Geology of the Caspiche Porphyry Gold-Copper Deposit, Maricunga Belt, Northern Chile*

RICHARD H. SILLITOE,1,† JUSTIN TOLMAN,2,** AND GLEN VAN KERKVOORT3,***

1 27 West Hill Park, Highgate Village, London N6 6ND, England
2 Exeter Resource Corporation, Suite 1660 - 999 W. Hastings St., Vancouver, BC V6C 2W2, Canada
3 Exeter Resource Corporation, Suite 701, 121 Walker St., North Sydney, NSW 2060, Australia

Abstract

The Caspiche porphyry gold-copper deposit, part of the Maricunga gold-silver-copper belt of northern Chile, was discovered in 2007 beneath postmineral cover by the third company to explore the property over a 21-year period. This company, Exeter Resource Corporation, has announced a proven and probable mineral reserve of 1.091 million tonnes (Mt) averaging 0.55 g/t Au, all but 124 Mt of which also contain 0.23% Cu, for a total of 19.3 Moz of contained gold and 2.1 Mt of copper.

The deposit was formed in the latest Oligocene (~25 Ma) during the first of two volcanic and corresponding metallogenic epochs that define the Maricunga belt. The gold-copper mineralization is centered on a composite diorite to quartz diorite porphyry stock, within which five outward-younging phases are routinely distinguished. The centrally located, early diorite porphyry (phase 1) hosts the highest-grade ore, averaging ~1 g/t Au and 0.4% Cu. The subsequent porphyry phases are quartz diorite in composition and characterized by progressively lower gold and copper tenors. Stock emplacement was both pre- and postdated by the generation of large-volume, andesite-dominated breccias, with tuffaceous matrices, which are believed to be shallow portions of diatremes. The deposit is characterized by a central gold-copper zone and partially overlapped but non-economic molybdenum halo. The gold-copper mineralization in the lower half of the deposit accompanies quartz ± magnetite-veined, potassic-altered rocks, whereas the shallower mineralization occurs within quartz-kaolinite–dominated, advanced argillic alteration. Upper parts of the advanced argillic zone are characterized by siliceous ledges, some auriferous, composed of vuggy residual quartz and/or silicified rock. The chalcopyrite-pyrite mineralization in the potassic zone was partially transformed to high sulfidation-state sulfides and sulfosalts during the advanced argillic overprint, although the underlying chalcopyrite-bornite assemblage was mainly too deep to be affected. The deposit terminates downward in a sulfide-deficient, potassic-calcic zone defined by K-feldspar, actinolite, and magnetite, which formed at the expense of biotite. A relatively minor, shallowly inclined zone of intermediate sulfidation epithermal gold-zinc mineralization, comprising narrow veinlets and disseminations, abuts the late-mineral diatreme contact. Supergene sulfide oxidation throughout the deposit is relatively shallow, and chalcocite enrichment extremely minor.

The Caspiche deposit is thought to have been emplaced at relatively shallow paleodepths, within the southern, flat-bottomed part of the premineral diatreme vent. Earliest porphyry system development, probably north of the present deposit, appears to have been aborted by diatreme formation. Much of the gold and copper in the Caspiche deposit was introduced during the potassic alteration stage, with the highly telescoped, advanced argillic overprint being responsible for only minor redistribution of the two metals, and the addition of arsenic. The late-mineral diatreme was emplaced west of the Caspiche deposit, and caused destruction of only its uppermost peripheral parts. The late-mineral diatreme was both pre- and postdated by advanced argillic alteration. Finally, the intermediate sulfidation epithermal gold-zinc zone was localized by the enhanced permeability provided by intense fracturing along the underside of the upward-flared, late-mineral diatreme contact.

Introduction and Exploration History

THE CASPICHE porphyry gold-copper deposit is the latest discovery in the Maricunga metallogenic belt, located between latitudes 26° and 28°S in the high volcanic Andes of the Atacama Region, northern Chile (Fig. 1). The belt, some 200 km long and 30 km wide, is an N-trending alignment of latest Oligocene to Miocene volcanic complexes and comagmatic subvolcanic stocks associated with porphyry gold ± copper and high sulfidation epithermal gold ± silver deposits and prospects (Vila and Sillitoe, 1991; Mpodozis et al., 1995; Fig. 2). The alignment of mineralized centers continues to the south, via the Caserones (formerly Regalito) porphyry copper deposit (Perelló et al., 2003) and nearby prospects, to the El Indio belt, where high-grade vein (e.g., El Indio) and bulk-tonnage (e.g., Pascua-Lama, Veladero), high sulfidation epithermal gold ± silver deposits predominate (e.g., Maksaev et al., 1984; Jannas et al., 1999; Chouinard et al., 2005; Fig. 1). Miocene porphyry gold prospects also occur farther east, in westernmost Argentina, where they were generated in the backarc to the Maricunga belt.
The Maricunga belt was defined during the mid- to late 1980s during a regional exploration program of areally extensive alteration zones for gold and silver conducted by Minera Anglo American Chile Ltda. and joint-venture partners. However, it was not until one of these zones, the host to the Marte deposit (Fig. 2), was systematically explored that the presence of porphyry-type mineralization was first recognized (Vila and Sillitoe, 1991; Vila et al., 1991). The porphyry deposits, including those at Marte, Lobo, Refugio, La Pepa, and Volcán (Fig. 2), typically contain gold as the only economically extractable metal, whereas those at Caspiche and Cerro Casale (Fig. 2) contain gold plus by-product copper potential.

Caspiche is located at 4,200 to 4,560 m above sea level, immediately east of the topographically and visually prominent Santa Cecilia alteration zone, from which it is separated by a 250-m-wide valley (Fig. 3). Santa Cecilia was extensively

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**Fig. 1.** Location of the Caspiche porphyry gold-copper deposit in the Maricunga belt with respect to its southern continuation—the El Indio belt—and some key deposits. Area shown in Figure 2 is marked.

**Fig. 2.** Location of the Caspiche porphyry gold-copper deposit in the Maricunga belt, showing the two ages of mineralized volcanic rocks and the main porphyry and epithermal deposits. The underlined deposits accompanied the younger volcanism. Compiled from Kay et al. (1994).
investigated, but with only limited success, by Anglo American from 1985 to 1990 under an option agreement with a Chilean mining entrepreneur. At the same time, Anglo American also claimed surrounding open ground, within which the company recognized and then explored the Caspiche prospect, with a focus on the prominently exposed, gold- and silver-bearing, siliceous ledges of high sulfidation epithermal type (Fig. 3). Anglo American collected 22 rock-chip samples from the ledges during the 1985 to 1986 summer field season, obtaining gold values ranging from 0.5 to 4 g/t. Grid talus-fines geochemistry and more detailed rock-chip sampling were followed by 12 50-m air-track holes during the 1986 to 1987 season. Based on the reasonably encouraging results from two of the holes (including 48 m at 1.03 g/t Au), detailed geologic mapping and six deeper (150–200 m) reverse-circulation holes were completed in the 1989 to 1990 season, but the best intercept was 148 m at 0.49 g/t Au. A preliminary resource of 6.3 million tonnes (Mt) averaging 0.45 g/t Au was estimated, leading to all work at Caspiche being terminated.

The Caspiche prospect lay fallow for six years before Minera Newcrest Chile Ltda. entered into a purchase option agreement with Anglo American, with the aim of following up the low-grade, disseminated gold intercepts obtained previously as well as testing the possibility that a “microdiorite” intrusion present at depth alongside the main siliceous ledge might contain higher-grade, structurally controlled gold ore. During the 1996 to 1997 season, Newcrest conducted detailed geologic mapping, rock and trench geochemical sampling, and an induced polarization-resistivity survey over the Caspiche and newly pegged contiguous claims, preparatory to drilling 12 reverse-circulation holes to a nominal depth of 300 m at Caspiche. The results suggested the presence of bulk-tonnage, high sulfidation epithermal gold mineralization grading 0.3 to 0.6 g/t, but one of the holes, collared in an area of post-mineral cover between the siliceous ledges (Fig. 3), reportedly intersected potassic-altered “microdiorite porphyry” averaging 0.73 g/t Au and 0.23% Cu from 232 to 326 m, with values increasing near the bottom of the hole. Later in 1997, a district-wide, helicopter-borne aeromagnetic survey was flown, resulting in definition of a prominent magnetic high centered immediately south of the previously drilled area.

Newcrest geologists appreciated that the 94-m gold intercept was of porphyry rather than epithermal style, and recommended follow-up core drilling to test the gold-copper mineralization beneath the covered area farther south and west and at greater depth. Eventually, only two reverse-circulation holes, totaling 532 m, were drilled on the porphyry gold-copper target during the 1997 to 1998 season, both
designated to test the magnetic high. The best results, 224 m averaging 0.14 g/t Au, were discouraging and led to the option being terminated, but without it being appreciated that the holes had penetrated a weakly mineralized, intermineral porphyry intrusion (see below).

Following an additional eight years of inactivity, the property was again optioned by Anglo American, this time to Exeter Resource Corporation, a Toronto-listed junior explorer. During the 2005 to 2006 field season, Exeter conducted geologic mapping, rock-chip sampling, and a controlled source audio-frequency magnetotelluric (CSAMT) survey, followed in early 2007 by reverse-circulation drill testing of high sulfidation targets beyond the immediate Caspiche porphyry prospect. As documented more fully by Van Kerkvoort et al. (2009), only at the very end of the 2006 to 2007 season was it elected to drill the Caspiche prospect itself, with time remaining for just one hole, which returned 304 m averaging 0.90 g/t Au and 0.26% Cu. In early 2008, this discovery hole was followed up with a campaign of core drilling, with the third hole reporting 793 m at 0.96 g/t Au and 0.40% Cu (Van Kerkvoort et al., 2009). By the beginning of 2012, ~63,000 m of core drilling had been completed at Caspiche, the results of which, coupled with engineering studies, enabled estimation of a proven plus probable oxide reserve of 967 Mt grading 0.57 g/t Au and 0.23% Cu, using an economic cutoff formula based on recovery, mining cost, and other parameters, but approximating 0.3 g/t Au equiv. To this should be added an overlying proven plus probable oxide reserve of 124 Mt averaging 0.38 g/t Au, at a 0.18 g/t Au equiv cutoff. The reserves contain a total of 19.3 million ounces of gold and 2.1 Mt of copper (Exeter Resource Corporation press release, 17 January 2012).

This paper describes the geologic setting, alteration-mineralization characteristics, and evolutionary history of the completely concealed Caspiche porphyry gold-copper deposit over its known 1,400-m vertical extent, with particular emphasis on a spectrum of variably mineralized breccias. The geologic description and interpretation, based on logging of all drill core, reflects the latest version of the model that has guided the exploration program; it complements the detailed discovery case history presented elsewhere (Van Kerkvoort et al., 2009).

Regional Setting

The Maricunga belt, situated along the southwestern edge of the Altiplano-Puna plateau, spans the boundary between the currently active Central Volcanic Zone of the Andes and, to the south, the nonvolcanic segment between 28° and 33°S—a change caused by the transition from moderate- to flat-slab subduction (Thorpe et al., 1982; Cahill and Isacks, 1992; Kay and Mpodozis, 2002). Arc magmatism in the Maricunga belt was initiated in the late Oligocene to early Miocene, at ~26 Ma, when reorganization of plate motions beneath the Pacific Ocean led to breakup of the Farallon plate into the Nazca and Cocos plates (Lonsdale, 2005). These processes were accompanied by increased oceanic crust generation at the East Pacific Rise (Conrad and Lithgow-Bertelloni, 2007) and acceleration of plate convergence at the Peru-Chile trench (Pardo-Casas and Molnar, 1987).

The basement to the Maricunga belt comprises metasedimentary and felsic volcanic rocks and graniteoids of late Paleozoic age, like those that form large tracts of the Cordillera Frontal farther east in Argentina (Mpodozis and Ramos, 1990). These rocks are capped by Triassic bimodal volcanic and sedimentary rocks deposited in extensional rift basins and Jurassic to Early Cretaceous marine and continental sedimentary rocks that accumulated in a backarc basin developed throughout northern Chile (Mercado, 1982; Mpodozis et al., 1995; Conrcejo et al., 1998; Iriarte et al., 1999; Arriagada et al., 2006). Late Cretaceous to Eocene arc to backarc volcanic rocks and continental redbeds formed after the tectonic inversion of the basin and eastward migration of the Andean arc (Conrcejo et al., 1998; Iriarte et al., 1999; Mpodozis and Clavero, 2002). In the southern Maricunga belt, between Caspiche and Cerro Casale (Fig. 2), as well as farther east and south, the Paleocene volcanic units are covered by Oligocene continental sedimentary sequences, composed of red sandstone, siltstone, and conglomerate, and including evaporitic horizons (Mpodozis and Kay, 2003). The siliciclastic redbeds, which crop out west of Caspiche and are a major host rock to the porphyry deposit at depth (see below), are most likely Oligocene in age because, farther south, they unconformably overlie Eocene redbeds and volcanic rocks (Mpodozis et al., 1991; C. Mpodozis, written comm., 2011).

The late Oligocene and Miocene Maricunga volcanic rocks, predominantly medium- to high-K calc-alkaline andesite to dacite in composition (Kay et al., 1994; Mckee et al., 1994; Mpodozis et al., 1995), are chiefly the products of extinct stratovolcanoes and volcanic dome complexes, which display varied degrees of erosional dissection (Vila and Sillitoe, 1991; Kay et al., 1994; Mpodozis et al., 1995). The porphyry and high sulfidation epithermal deposits, closely linked in places (e.g., Caspiche, La Pepa: Fig. 2), have been shown by K-Ar and 40Ar/39Ar dating (Sillitoe et al., 1991; Mpodozis et al., 1995) to have been generated beneath both these main volcanic landforms during two principal metallogenic epochs: latest Oligocene to earliest Miocene (26–21 Ma) and mid-Miocene (14–10 Ma). The Caspiche deposit is assigned to the older of these two epochs on the basis of an Re-Os age for molybdenite of 25.38 ± 0.09 Ma (H. Stein, unpub. report for Gold Fields Chile S.A., 2009; see online Supplementary Data), which was determined using the methodology described by Zimmerman et al. (2008). Caspiche is penecontemporaneous with and probably genetically related to the contiguous Santa Cecilia alteration zone (Fig. 3), which is hosted by a stratified volcanic sequence, including ignimbrite flows, and at least one dacite dome. Santa Cecilia is known to host minor, albeit locally high grade, high sulfidation epithermal gold mineralization, which returned essentially identical K-Ar ages of 24.3 ± 0.7 and 24.1 ± 0.8 Ma for hydrothermal sericite and alunite, respectively (Sillitoe et al., 1991).

The latest Oligocene to earliest Miocene (26–21 Ma) volcanic activity and precious and base metal mineralization likely took place in a neutral to weakly extensional tectonic setting, which gave way to contraction consequent upon initial slab flattening between 20 and 18 Ma (Mpodozis et al., 1991, 1995; Kay et al., 1994, 2008; Kay and Mpodozis, 2001). The contraction resulted in diminished volcanism, compressive deformation, and crustal thickening (Kay et al., 1994; Mpodozis et al., 1995). The gold-deficient Caserones porphyry copper-molybdenum deposit and nearby prospects,
immediately south of the Maricunga belt (Fig. 1), were generated during this compressive event (Mpodozis and Kay, 2003; Perelló et al., 2003; Sillitoe and Perelló, 2005). Volcanic activity under more extensional conditions was again widespread and voluminous between 17 and 12 Ma, an interval that concluded with the second precious and base metal mineralization event. This was followed by renewed contractional tectonism and marked geographic restriction of volcanism between 11 and 5 Ma, when all volcanic activity ceased in the Maricunga belt prior to reestablishment at the site of the present-day magmatic arc, some 60 km farther east (Kay et al., 1994, 2008; Mpodozis et al., 1995). Throughout the Maricunga belt, the volcanic centers and associated mineralization that formed during both of the noncompressive epochs display a clear control by steep, NW-, NE-, and E-striking faults, particularly the first of these (Mpodozis et al., 1995; Fig. 2); however, E-striking faults are most prominent in the Caspiche area (Mpodozis et al., 1991). Glaciation affected the higher parts of the Maricunga belt during the Plio-Pleistocene, giving rise to the final exhumation stages of the late Oligocene to mid-Miocene alteration zones and any contained mineralization.

Deposit Geology

The principal rock types defined at Caspiche may be assigned to four broad units: premineral sedimentary host rocks; volcanic breccia, which also predate all the potentially economic mineralization; five discrete porphyry intrusions, spanning the alteration-mineralization sequence; and a late-mineral diatreme breccia (Figs. 4, 5). To these may be added relatively small volumes of hydrothermal breccia.

Sedimentary rocks

Sedimentary rocks surround the composite Caspiche porphyry stock on all sides below elevations ranging from 3,870 to 3,700 m above sea level, which is roughly 500 to 750 m below the surface (Figs. 4, 5). The rocks typically comprise a monotonous sequence of black, hornfelsed, and highly altered sandstone and siltstone, which may display little obvious textural variation over tens of meters. In places, however, shallowly dipping, relict bedding is observed, confirming their sedimentary origin (Fig. 6a). If, as seems probable, these siliciclastic rocks are correlative with the nearby redbed sequence of inferred Oligocene age (see above), the original diagenetic hematite was transformed to magnetite consequent upon the hornfelsing and pervasive potassic alteration, which also gave rise, in places, to a prominent, mottled texture produced by biotite clots. Notwithstanding the ubiquitous presence of magmatic-hydrothermal anhydrite throughout the deeper parts of the Caspiche deposit (see below), concentrations of centimeter-sized anhydrite nodules in several thin siltstone horizons may be evaporitic in origin, possibly formed.

Fig. 4. Geologic level plan at 3,700-m elevation of the Caspiche porphyry gold-copper deposit. Note that the porphyry phases tend to become progressively younger outward from the early phase 1 diorite porphyry, which constitutes the high-grade core to the system. Projections of drill holes also shown.
during diagenesis (e.g., Dean et al., 1975) in a former playalake environment (cf. Mpodozis and Kay, 2003).

The deeper parts of the sedimentary sequence, beneath approximately 400 m of the sandstone and siltstone, include two sedimentary breccia horizons (Fig. 6b). The thicker (~100 m), upper horizon has a deposit-wide, ~2-m-thick bed of calcareous rock, transformed to garnet-diopside-epidote skarn, at its base. Correlation of these marker horizons over distances of several hundred meters confirms that the sedimentary sequence is essentially flat lying (Fig. 5). The breccias, transitional to conglomerate in places, contain abundant clasts of distinctive rhyolite porphyry, almost certainly derived from the late Paleozoic and Triassic basement, in which such felsic volcanic rock types are widespread (e.g., Mpodozis and Ramos, 1990; see above). The lower sedimentary breccia horizon is directly underlain by andesitic volcanic rocks, chiefly flows (Fig. 5).

Minor bodies of probable andesite porphyry, characterized by centimeter-sized plagioclase phenocrysts in a black, fine-grained, and highly altered groundmass, cut the siliciclastic sedimentary rocks locally, particularly near their upper contact. The bodies are clearly intrusive because of the presence of chilled margins, but it is still uncertain if they constitute sills, dikes, or a combination thereof.

Fig. 5. Representative geologic section through the Caspiche porphyry gold-copper deposit, showing all the main rock types recognized. Section line shown in Figure 4.
FIG. 6. Selected rock and alteration types from the Caspiche porphyry gold-copper deposit. a. Intensely biotitized, siliciclastic sedimentary wall rock from below 3,800-m elevation. Stratification is highlighted by more intense biotitization of siltstone than of sandstone beds. b. Sedimentary breccia, containing large rhyolite clast of probable late Paleozoic or Triassic age, from biotitized siliciclastic sedimentary wall-rock sequence at ~3,400-m elevation. Note that veinlets cut the breccia. c. Premineral volcanic breccia, inferred to be part of an early diatreme, displaying patchy texture and advanced argillic alteration. The patchy texture, including the amoeboid clast form, is inherited from the original fragmental rock texture. Clasts are altered to kaolinite and pyrite, whereas the matrix is pervasively silicified. d. Potassic-altered part of the same premineral volcanic breccia unit as depicted in c, containing flattened and aligned andesite porphyry clasts (fiamme) interpreted as former magma blobs or pumice. e. Potassic-altered, premineral volcanic breccia containing an A-type quartz (Qz) veinlet xenolith indicative of a preexisting porphyry system. Note the typical concentration of hydrothermal biotite (black) in the clasts and K-feldspar in the matrix. f. Early phase 1 diorite porphyry affected by intense K-feldspar-dominant potassic alteration and associated magnetite and A-type quartz veinlet stockwork. g. Potassic-altered, early intermineral phase 2 quartz diorite porphyry cut by weakly developed A-type quartz veinlet stockwork, and containing quartz (Qz) veinlet xenolith derived from nearby phase 1 diorite porphyry. Note prominent quartz (Qz) phenocryst. h. Potassic-altered, early intermineral phase 2 quartz diorite porphyry intrusion breccia developed near contact of the quartz diorite porphyry with sedimentary wall rocks. Sandstone and siltstone clasts are biotitized, whereas the quartz diorite porphyry cement is K-feldspar rich. Note D-type pyrite veinlet at top of image. i. Late-mineral, polymict hydrothermal breccia from peripheral chlorite-sericite alteration zone. The breccia contains abundant silicified, veinlet quartz (Qz), and quartz-veined clasts in a silicified rock-flour matrix. j. Late-mineral, polymict hydrothermal breccia displaying advanced argillic alteration, and cemented by alunite (al) and kaolinite (ka). Note quartz (Qz)-veined clast. k. Late-mineral diatreme breccia containing polymict clast population, including vuggy residual quartz (Qz), silicified, and pyrite (py)-veined clasts. Matrix is dominated by dacitic tuff. l. Phase 2 quartz diorite porphyry, from ~3,400-m elevation, affected by potassic-calcic alteration. The veinlet contains actinolite (Ac)-magnetite (Mg) and quartz (Qz)-K-feldspar (Kf)-rich segments, and has a K-feldspar alteration halo.
Volcanic breccia

Throughout the prospect area, the siliciclastic sequence is overlain by a 500- to 750-m-thick volcanic breccia (Fig. 5), which has an apparently restricted areal extent of approximately 5 km².

The breccia is polymict and mainly composed of rounded to subangular clasts surrounded by an obscure, highly altered, fine-grained, fragmental matrix, which is suspected to be dominated by a tuff component (Fig. 6c-e). The clasts are typically 1 to 4 cm in size, with isolated examples attaining 10 cm, but with no hint of bedding or size sorting. In parts, some of the clasts have an amoeboid shape defined by cuspate margins (Fig. 6c), and, very locally, aligned, lenticular clasts (fiamme in a descriptive sense; Bull and McPhie, 2007) are prominent, some up to 8 cm long (Fig. 6d). The fiamme are either magma blobs or pieces of pumice flattened by compaction and, along with the cuspate clasts, are considered juvenile in origin. Intense alteration of the breccia precludes certain identification of most component clast rock types, but the remanent textures and characteristic absence of magmatic quartz grains suggest that andesite/diorite predominates. Clasts of hornfelsed siliciclastic sedimentary rock and, very locally, the intrusive andesite porphyry are particularly prominent in the lower parts of the breccia, within ~50 m of contacts with these rock types, although suspected sedimentary clasts also occur elsewhere in the breccia. The youngest zircon population in a representative breccia sample yielded a U-Pb age of 24.7 ± 0.7 Ma (V. Valencia, unpub. report for Exeter Resource Corporation, 2010; see online Supplementary Data), determined using the laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) method detailed by Chang et al. (2006). This age is essentially the same, within experimental error (2σ), as the Caspiche molybdenite age (25.38 ± 0.09 Ma; see above).
The breccia clasts typically display different alteration minerals to the matrix (Fig. 6c-e; see below), thereby enhancing appreciation of the fragmental texture. Although most clasts are internally homogenous, recognition of veinlets confined to a few of them is important because it confirms that some hydrothermal activity took place prior to breccia formation. The isolated, clast-confined veinlets comprise hydrothermal biotite, specularite, or granular A-type quartz (as defined by Gustafson and Hunt, 1975). In addition, isolated clasts of either A-type veinlet quartz (Fig. 6c) or silicified dioritic/anidesitic material are also widespread, particularly in the lowermost 100 m or so of the breccia.

The origin of this volcanic breccia remains to be fully revealed, but it seems most likely to be part of a small, localized volcanic center that overlapped both spatially and temporally with development of the Caspiche porphyry gold-copper deposit. In combination, the textural homogeneity, lack of bedding and size sorting over several hundred vertical meters, and localized presence of mineralized material would appear to preclude accumulation of the breccia in stratovolcano or ash-flow caldera settings. A local origin is also supported by the appearance of clasts of the underlying rock types on approach to its basal contact. The breccia throughout much of the deposit area overlies a low-relief surface (Fig. 5), which gives way northward to a much steeper slope, as implied by the presence of the breccia below 3,700-m elevation. This depressed area could be interpreted as one sector of an upward-flared vent, which fed a restricted basin, although an incised paleosurface cannot yet be discounted.

Porphyry intrusions

Two main porphyry intrusions, early and early intermineral in timing (phases 1 and 2), constitute the well-mineralized part of the composite Caspiche stock, which is abutted to both east and west by a late intermineral phase 3 (Figs. 4, 5). In contrast, the two late-mineral phases 4 and 5 have so far only been encountered farther west (Fig. 4). Together, the well-mineralized phases 1 and 2 measure roughly 500 × 500 m in plan view (Fig. 4), with little appreciable change in size over their defined 1,400-m vertical extent (Fig. 5).

The early phase 1 porphyry is dioritic in composition and contains sparse, 1-mm-sized quartz phenocrysts. Larger plagioclase and biotite phenocrysts are abundant and accompanied by subordinate hornblende. The original texture of the phase 1 porphyry is partly obliterated by intense alteration and veining (Fig. 6f), the latter dominated by a multidirectional, A-type quartz veinlet stockwork, which, near the apex of the intrusion, constitutes >50% of rock volume.

The other four intrusions, phases 2 to 5, are quartz diorite porphyries. The intermineral phases 2 and 3 are texturally better preserved and coarser grained than the dioritic phase 1; they contain prominent quartz, besides plagioclase, biotite, and hornblende phenocrysts (Fig. 6g). The phase 3 porphyry is noticeably coarser grained and contains larger quartz phenocrysts than the better-mineralized phase 2. The latter is cut by abundant, relatively narrow (mostly <1 cm), A-type quartz veinlets (Fig. 6g), but truncates many of the A-type quartz veinlets in the phase 1 diorite porphyry, including all those with widths of 2 to 4 cm. In several places, the peripheral parts of the phase 2 porphyry body comprise intrusion breccia:

- abundant phase 1 diorite porphyry or sedimentary wall-rock clasts and quartz veinlet fragments in a porphyry rock matrix (Figs. 4, 5, 6h). In contrast, the phase 3 quartz diorite porphyry is only weakly veined, and displays low alteration intensity and partial preservation of magmatic biotite and magnetite. The late-mineral phase 4 and 5 quartz diorite porphyries are texturally well preserved and nearly veinlet free. The earlier phase 4 displays extremely weak potassic alteration, whereas phase 5 is characterized by intense propylitic alteration; both contain <0.02 g/t Au and <100 ppm Cu.

The composite porphyry stock has a highly irregular form in plan and is associated with a number of dikes, which together suggest both northwest and northeast structural controls on its emplacement (Fig. 4). The phase 1 diorite porphyry, constituting the core of the stock, occurs as a ~500-m-long, sigmoidal body ranging from ~50 to 150 m wide (Fig. 4), but is blind and concealed beneath up to 150 m of premineral volcanic breccia (Fig. 5). The phase 2 quartz diorite porphyry, comprising at least two discrete pulses, occurs as a discontinuous shell around phase 1; however, the largest volume of phase 2 occurs as an NE-trending, 400-m-long body along the southeastern side of phase 1 (Fig. 4). The internal position of the phase 1 porphyry relative to the enveloping phase 2 is unusual and, in map pattern, might be taken to suggest that the former is younger than the latter. Nonetheless, the reverse is amply confirmed by the higher veinlet intensity and metal content in phase 1 as well as the truncation of some A-type quartz veinlets by, and presence of A-type quartz veinlet fragments within, phase 2 (Fig. 6c). The form and diameter of phase 1 is roughly the same irrespective of whether it is enveloped by the sedimentary basement or phase 2 quartz diorite porphyry (Fig. 5), implying that little or no phase 1 porphyry was assimilated or otherwise removed during phase 2 emplacement. The phase 3 quartz diorite porphyry intrusion measures at least 400 m in a northeast direction, and is nested into the western margin of phase 2 (Fig. 4). The phase 4 quartz diorite porphyry locally truncates the western side of phase 2 and, in turn, is cut by phase 5 quartz diorite porphyry, which also occurs as large blocks in the late-mineral diatreme (Fig. 5).

Hydrothermal breccias

Several, volumetrically minor hydrothermal breccias are present at Caspiche, chiefly in the peripheral and shallow parts of the deposit (Figs. 4, 5). The best-defined breccias are clearly dike like and <10 m wide. All the breccias are polygonic and contain a variety of veined and mineralized clasts, which range from angular to subrounded in form.

The peripheral breccias are mainly cemented by fine-grained quartz (Fig. 6i) or chlorite, whereas the shallow examples, within the advanced argillic zone (see below), are characterized by alunite ± kaolinite cement accompanied locally by minor pyrite and enargite (Fig. 6j). Most of the breccias are largely barren, reflecting their late timing, although those that display the advanced argillic alteration can contain minor copper and gold.

Late-mineral diatreme

A large breccia body, which dips west at approximately 30° to 40° and then steepens downward, truncates the western
side of the Caspiche porphyry deposit at shallow levels (Figs. 4, 5). The breccia extends for a distance of at least 1,100 m in a north-south direction and has a maximum drilled thickness of 700 m. The east-west dimension remains undefined, although the breccia is anticipated to underlie the full width of the valley that separates Caspiche from the Santa Cecilia alteration zone (Fig. 3).

The breccia is highly polymict, matrix supported, and contains abundant mineralized clasts in proximity to its contact with the Caspiche porphyry deposit. Besides quartz-veined clasts and quartz-veinlet fragments, there are also prominent pieces of vuggy residual quartz (Fig. 6k), showing that brecciation postdated development of some of the high sulfidation epithermal ledges (see below). Away from the contact zone, tuffaceous material, apparently compositionally similar to the late-mineral phase 5 quartz diorite porphyry, is readily recognizable as a matrix to texturally varied andesite and andesite porphyry clasts. The breccia contains blocks of phase 5 porphyry, up to ~50 m in size, some of them displaying intense epidote-rich, propylitic alteration (Figs. 5, 7). Many of the blocks were also brecciated in situ, with the introduced matrix comprising fine-grained, hematite-impregnated quartz.

![Diagram](image.png)

**Fig. 7.** Alteration section showing the spatial relationships between the principal alteration assemblages and the rock types depicted in Figure 5, Caspiche porphyry gold-copper deposit. The positions of the base of the leached capping (base of supergene sulfide oxidation), sulfate front (base of anhydrite and gypsum removal), and bornite front (top of megascopically visible chalcopyrite-bornite assemblage) are also shown. Note confinement of vuggy residual quartz ledges to shallow parts of the system.
Although much of the breccia is nonbedded and nonsorted, there are local intervals of normally graded, silt- to pebble-sized material, which are interpreted as surge deposits. One such interval has abrupt contacts against the nonbedded breccia, suggesting an origin as a sunken block derived from subaerial tuff accumulations (cf. Sillitoe, 1985; Davies et al., 2008), whereas other bedded intervals may have formed in place.

On the basis of these characteristics and close similarities to late diatreme breccias in porphyry systems elsewhere (e.g., Sillitoe, 1985), it seems clear that the breccia fills a diatreme vent. To date, only the upward-flared, eastern contact has been partly defined, with the bulk of the body, including the throat of the vent, lying farther west. The diatreme is a late, but not the final manifestation of the Caspiche system because it not only contains clasts of ledge material but is also cut by a few residual vuggy quartz ledges, one at least 300 m long.

Hypogene Alteration and Mineralization Features

Five alteration types are depicted in Figure 7: potassic, propylitic, potassic-calcic, chlorite-sericite, and advanced argillic, with the first and last of these being by far the most widely developed and economically important. Because the alteration zones overprint one another, commencing with the potassic and ending with the advanced argillic, combinations of alteration types are commonplace, although, for mapping purposes, the predominant assemblage everywhere takes precedence.

Potassic Alteration

Potassic alteration becomes progressively more widespread downward in the Caspiche system, and is essentially the only alteration type present between the ~3,600- and 3,400-m elevations (Fig. 7). The potassic zone comprises two distinct alteration assemblages, the earlier biotite dominated and the younger containing K-feldspar, albite, and subordinate biotite (Fig. 7). Both contain >5 vol % of hydrothermal magnetite where not appreciably overprinted by the later alteration types. The biotite-rich type dominates the hornfelsed siliciclastic sedimentary rocks (Fig. 6a) as well as affecting many clasts in the volcanic breccia (Fig. 6e). The K-feldspar-rich potassic alteration is widely developed in the early and intermediate porphyries as well as in the matrix to the volcanic breccia (Fig. 6d-h). K-feldspar flooding is far more abundant than is its confinement to veinlet selvages. The potassic zone is characterized by widespread quartz ± magnetite veinlets, the quartz being granular and, hence, typical of A-type veinlet generations (Gustafson and Hunt, 1975; Fig. 6f, g). Sulfide-free, magnetite-only veinlets predate most of the A-type veinlet generations. Banded quartz veinlets, typical of the Maricunga porphyry gold deposits (Vila and Sillitoe, 1991; Muntean and Einaudi, 2000), are absent.

The potassic alteration contains extremely fine grained chalcopyrite and subordinate pyrite in its shallower parts, with the pyrite/chalcopyrite ratio decreasing gradually downward and increasing outward. At a depth of about 700 m in the phase 1 diorite porphyry and its immediate wall rock, visible pyrite disappears entirely from the potassic alteration and bornite becomes progressively more abundant, although everywhere subordinate to chalcopyrite (chalcopyrite/bornite ~7). The bornite front is marked in Figure 7. The sulfide minerals occur as disseminated grains in the quartz ± magnetite veinlets as well as throughout the surrounding rock. A wide variety of pyrite-dominated veinlets, some having sericitic halos (D-type; Gustafson and Hunt, 1975), cut the potassic alteration and quartz ± magnetite veinlet stockwork, as do late-stage anhydrite veinlets, some containing a few grains of pyrite, chalcopyrite, and/or molybdenite, but others completely barren.

Propylitic Alteration

Propylitic alteration was encountered by drilling 600 m west of the mineralized Caspiche stock (Fig. 7), and is expected to completely encircle it at depth, but also occurs as the earliest recognizable alteration type in the late-mineral, phase 5 quartz diorite porphyry and parts of the late-mineral diatreme breccia (Fig. 7). The alteration is characterized by chlorite replacement of mafic minerals, epidote after plagioclase phenocrysts, and several percent of magnetite. The epidote content is >5 vol %, with both veinlets and dispersed grains being commonplace. The pyrite content also exceeds 5 vol % in the propylitic halo, but attains only 1 to 2 vol % in the late-mineral porphyry and diatreme breccia.

The peripheral propylitic alteration, most prominently the contained epidote veinlets, overprints the fringe of the potassic zone, although the two alteration types are assumed to be broadly contemporaneous. A similar situation was reported from the Bajo de la Alumbre porphyry copper-gold deposit, Argentina (Proffitt, 2003).

Potassic-calcic Alteration

Potassic-calcic alteration, defined by the presence of K-feldspar and actinolite and largely lacking biotite, is mainly confined to the central parts of the early intermineral, phase 2 quartz diorite porphyry and its host rocks below ~3,400-m elevation, although it is not widely developed in the part of the deposit depicted in Figure 7. The downward change from potassic to potassic-calcic assemblages takes place relatively abruptly, over just 10 to 20 m. The potassic-calcic zone is characterized by actinolite intergrown with 10 vol % magnetite as veinlets, clots, and disseminations. The wider veinlets, up to 2 cm across, tend to be segmented, with alternation of actinolite-magnetite and granular quartz intervals (Fig. 6l). The K-feldspar forms prominent veinlet halos, some of it as centimeter-sized crystals, as well as occurring as a groundmass alteration product. Diopside, albite, calcite, anhydrite, chalcopyrite, and trace bornite are subsidiary veinlet components. Some of the calcite fills numerous fractures in coarse-grained diopside.

In the transition between the potassic-calcic and overlying potassic zones, the actinolite and magnetite are observed to overprint and destroy preexisting biotite, a process that also eliminates most of the contained chalcopyrite and bornite, although minor amounts of these sulfide minerals are retained in the wider actinolite-magnetite-quartz veinlet. Consequently, there is a marked drop in both total sulfide and corresponding gold and copper contents on passing from the potassic to potassic-calcic zones, with the latter averaging 0.13 g/t Au and 0.06% Cu.
Chlorite-sericite alteration occurs marginal to the potassic core of the system, beyond the gold-copper orebody, but internal to the propylitic zone (Fig. 7). The late intermineral, phase 3 quartz diorite porphyry is particularly susceptible to this alteration type. Mafic minerals are transformed to chlorite and plagioclase to illite and/or sericite (fine-grained muscovite). The dominance of illite over sericite was confirmed using a portable spectrometer. Pyrite was also introduced in both veinlet and disseminated forms.

The upper parts of the potassic zone in both the volcanic breccia and porphyries have been partially overprinted by illite ± smectite, the latter causing the sawn drill core to take on a yellow stain after only a few months of storage (Fig. 6g). The main effects of this overprint are to convert plagioclase to illite and magnetite to hematite, the latter in the form of both martite and accompanying specularite. Much of the biotite remains stable, although it is locally retrograded to chlorite. Carbonate is also present in places. Only below the top of the zone containing unaltered magnetite is the K-feldspar-rich potassic zone relatively free from the effects of the illite overprint.

Where the chlorite-sericite/illite alteration is strongest, it is mapped separately (Fig. 7), although it is commonly extensively overprinted by kaolinite and, hence, included in the advanced argillic zone. This progression is recorded by plagioclase phenocrysts that have illite cores and irregular kaolinite rims.

Advanced argillic

The shallower parts of the Caspiche system, to an average depth of 300 to 400 m, but a maximum depth of approximately 1,000 m (3,400-m elevation) within steep fractures, are overprinted by advanced argillic alteration dominated by a quartz-kaolinite assemblage; however, it also contains widespread albite subordinate pyrophyllite and dickite as well as trace diaspore (Fig. 7). Tiny (1 mm), disseminated rosettes of bluish-colored dumortierite occur as a widespread accessory mineral in the deeper parts of the advanced argillic zone, but give way to black, centimeter-sized rosettes of black tourmaline (schorl) closely associated with kaolinite, sericite, chalcopyrite, and pyrite at the base of the central portion of the advanced argillic zone. The martite and specularite, products of the illite overprint, along with any remnant magnetite, are entirely converted to pyrite.

Where advanced argillic alteration affects the volcanic breccia, patchy texture is developed as a result of replacement of the clasts by kaolinite and pyrite and the matrix by extremely fine grained, gray-colored chaledony (Fig. 6c; cf. Yanacocha; Gustafson et al., 2004). The patchy texture mimics the similar texture developed during the preceding potassic alteration, in which biotite-rich clasts are surrounded by K-feldspar-rich matrix (Fig. 6d, e; see above). Such inheritance of patchy-textured advanced argillic alteration from a preexisting alteration type affecting fragmental rock is also described from the Oyu Tolgoi porphyry copper-gold deposit, Mongolia (Khashgerel et al., 2008).

The advanced argillic alteration contains a high sulfidation-state sulfide assemblage in which chalcopyrite and pyrite are rimmed and, possibly, partially replaced by complex, microscopic intergrowths of enargite, luzonite, tennantite, bornite, digenite, chalcocite-group minerals, and covellite (Fig. 8). The chalcocite group and covellite are both hypogene and should not be confused with the minor chalcocite resulting from supergene enrichment (see below). This dominantly disseminated, high sulfidation sulfide assemblage is largely confined to the mineralized porphyry stock and its immediate wall rocks.

Siliceous ledges occur within the quartz-kaolinite zone at shallow depths, generally above 4,000-m elevation (Fig. 7), where they represent the main upflow conduits within the advanced argillic lithocap. The drilled ledges, up to 35 m wide, comprise silicification, vuggy residual quartz, and/or semi-massive pyrite and marcasite where unoxidized. Enargite, orpiment, and native sulfur can occur as paragenetically later additions in unoxidized parts of the ledges. Several ledges are auriferous whereas others are totally barren. Some of the ledges have prominent, but typically narrow (<5 cm) alunite halos, although these can coalesce locally into broader quartz-alumite zones where ledges are closely spaced along the southern margin of the system (see below). The alunite, like the kaolinite, replaces plagioclase phenocrysts. Dickite is most evident as a final fill of quartz-pyrite ± enargite veins interpreted as the roots of the siliceous ledges.

The surface exposures (Fig. 3) and information from above 4,200-m elevation suggest that the siliceous ledges are preferentially developed around the periphery of the Caspiche porphyry deposit, particularly to the south. However, it is suspected that ledge development simply penetrated more deeply around the system margins, thereby leading to earlier erosional removal of the ledges that once capped the central parts of the system.

Advanced argillic alteration, including siliceous ledges, is developed far beyond the Caspiche deposit, at least 3 km east and 500 m north, and to depths of at least 400 m in places. Some of the ledges are irregularly mineralized with enargite, luzonite, and associated gold. Late-stage addition of orpiment...
is also widespread in some of these peripheral ledges, accounting for arsenic contents of several percent in places.

**Late-stage gold-zinc mineralization**

Scattered quartz ± calcite veinlets, containing straw-colored, low-iron sphalerite, galena, chalcopyrite, and pyrite, cut a spectrum of alteration types, ranging from pyrite-rich, quartz-kaolinite to pyrite-poor, illite-overprinted, potassic assemblages. The veinlets lack megascopically observable associated alteration. Along with accompanying sulfide disseminations, they are particularly concentrated and gold rich in a shallowly dipping zone that abuts the eastern flared contact of the late-mineral diatreme breccia. A few such veinlets also cut overlying parts of the breccia, thereby confirming that the gold-zinc zone is the product of an end-stage hydrothermal event.

**Hypogene Metal Distribution**

**Porphyry deposit**

The Caspiche deposit displays a classic hypogene metal zoning pattern over its known 1,400-m vertical extent (Figs. 9, 10). Gold and copper contents correlate well, with the highest average tenors (~1 g/t Au, 0.4 % Cu) being largely confined to the phase 1 diorite porphyry intrusion and its immediate wall rocks (Fig. 9a, b). The phase 2 and 3 quartz diorite porphyries are characterized by roughly 50 and 20%, respectively, of the phase 1 diorite porphyry grades. Notwithstanding the unusually high Au/Cu ratio at Caspiche, the close Au/Cu correlation is typical of that observed in most gold-rich porphyry copper deposits (e.g., Sillitoe, 2000, 2010). At depth in the phase 1 diorite porphyry intrusion, where bornite accompanies chalcopyrite (Fig. 7), copper contents increase, as

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**FIG. 9.** Element distribution contour plots for the same Caspiche section shown in Figures 5 and 7. a. Gold. b. Copper. c. Arsenic. d. Zinc. Note the central, broadly coincident positions of gold and copper and shallow concentration of arsenic associated with the advanced argillic alteration overprint. Appreciable zinc is confined to the gold-zinc zone immediately beneath the eastward-flared, late-mineral diatreme contact. Background geologic outline taken from Figure 5.
Peripheral gold-zinc zone

West of the main Caspiche deposit, the drilling defined an ovoid, shallowly W dipping zone of elevated (locally >1 g/t) gold values, which coincides with and is enveloped by a similarly shaped, 500-m-long zone of high zinc values, typically in the 500 to 1,000 ppm range, but with isolated values attaining >2,000 ppm (Fig. 9d); lead and copper can also attain several hundred ppm locally. This zone, lying immediately beneath and parallel to the W-dipping contact of the late-mineral diatreme breccia (Fig. 9a, d), coincides with the greatest concentration of the auriferous sphalerite-galena-chalcopyrite mineralization noted above.

Supergene Effects

Sulfide oxidation

The supergene profile at Caspiche is relatively thin (Fig. 7), in common with those developed over most deposits in the Maricunga belt (Vila and Sillitoe, 1991). The leached capping is typically thickest over the core of the system, where it is hosted by the uppermost parts of the advanced argillic zone, but tends to shallow progressively northward from 150 to 200 m in the southeast to 40 m in the northwest. All pyrite and other sulfide minerals, including any contained copper, have been completely removed from the oxidized rock, whereas the gold remains largely in situ within derivative jarosite to constitute the oxide gold reserve cited above. The acidic solutions generated by the pyrite oxidation produced an unquantified amount of supergene kaolinite, although most of this is impossible to distinguish from the preexisting hypogene component.

Most of the copper leached from the oxidized zone appears to have been lost to the paleoground-water system, but a thin (<30 m) zone of incipiently developed chalcocite enrichment was intersected by a few, centrally located drill holes.

Sulfate front

In common with most porphyry copper deposits, all the defined alteration zones at Caspiche formerly contained a few percent of hypogene anhydrite, much of it confined to the A-type quartz and late pyrite-bearing veinlets as well as occurring as the end-stage, anhydrite-only veinlets. The former presence of this anhydrite is shown by characteristic open spaces present in many of the veinlets.

The anhydrite was removed by ingress of cool groundwater after erosion had exhumed the porphyry gold-copper mineralization. Gypsum formed as an initial hydration product of the anhydrite, but was then completely dissolved. The resultant sulfate front, present at depths of 600 to 900 m below the surface within the deposit but locally much shallower on the margins (Fig. 7), is the level beneath which the rocks retain their calcium sulfate content. This is in the form of supergene gypsum and residual hypogene anhydrite in proximity to the front, but exclusively as anhydrite at depth. The sulfate front is typically sharp, but uncommon patches of sulfate-cemented rock also remain stranded hundreds of meters above it.

Genetic Considerations

The Caspiche porphyry gold-copper deposit shares many geologic features with gold-rich porphyry deposits elsewhere in the world (e.g., Sillitoe, 2000), with metal contents being closely similar to those of the nearby Cerro Casale deposit, where an extensive advanced argillic lithocap is also partially preserved (Vila and Sillitoe, 1991; Fig. 2). Interestingly, as noted above, Cerro Casale is part of the mid-Miocene metallogenic epoch in the Maricunga belt and, therefore, some 12 m.y. younger than Caspiche.
Caspiche is unique among well-described porphyry deposits in that intrusion of the composite diorite to quartz diorite porphyry stock and gold-copper mineralization is bracketed by emplacement of large-volume vent breccias, interpreted here as diatremes (Fig. 11); the products of phreatomagmatic (hydrovolcanic) eruptive activity caused by interaction between subsurface magma and external water (e.g., Sheridan and Wohletz, 1983; Lorenz, 1986). Although late-stage diatreme formation is a relatively widespread phenomenon in gold-rich porphyry copper deposits (Sillitoe, 1985), premineral volcanic vents are uncommon, albeit well documented (e.g., MacDonald and Arnold, 1994; Braxton et al., 2008).

Premineral development

The up to 750-m-thick volcanic breccia that hosts the upper half of the Caspiche porphyry stock and its associated gold-copper mineralization is best interpreted, for the reasons outlined above, as the southern manifestation of a diatreme vent, the center of which seems likely to be situated north of Caspiche (Fig. 12a). The near synchronism of the U-Pb zircon age of the volcanic breccia (24.7 ± 0.7 Ma) and Re-Os age of Caspiche molybdenite (25.38 ± 0.09 Ma) adds further weight to a genetic connection between breccia accumulation and the porphyry system and, by the same token, argues against an external source for this thick but apparently localized volcaniclastic accumulation.

This genetic connection is further strengthened by the evidence, in the form of veined and altered clasts (Fig. 6e; see above), for at least minor porphyry copper formation before the volcanic breccia was generated (Figs. 11, 12a). This evidence may further imply that initial porphyry copper formation was aborted by the catastrophic brecciation event, only to be resumed farther south at the site of the Caspiche deposit following completion of diatreme emplacement (Figs. 11, 12b). This early porphyry copper system appears to have been aborted relatively early in its development, judging by the absence of any pyrite-bearing clast material in the volcanic breccia. The close temporal association between the Caspiche deposit and the volcanic breccia that hosts its upper half further suggests that the gold-copper mineralization took place in a relatively shallow setting, possibly beneath only a few hundred meters of extant volcanic cover (Fig. 12b-d).

Perhaps the most enigmatic aspect of the volcanic breccia, in the context of a diatreme model, is its subhorizontal base throughout much of the Caspiche deposit and its immediate surroundings, which implies accumulation within a flat-bottomed, basin-like depression rather than an upward-flared, cone-shaped vent. However, evidence from several porphyry copper-related diatremes elsewhere, including the late-mineral examples at Lepanto-Far Southeast, Philippines (Garcia, 1991), and Río Blanco-Los Bronces, Chile (J.C. Toro, pers. comm., 2010; E. Wettke, pers. comm., 2011), as well as the premineral example at Resolution, Arizona (G. Zulliger and R.H. Sillitoe, unpub. data, 2006; Hehnke et al., 2012), suggests that thick, basin-like tuff and breccia accumulations above restricted and, in some cases, poorly documented vents may be more common than previously thought. The shallow portions of diatreme vents tend to approximate broad, bowl-shaped and flat-bottomed structures, rather than being steeply conical in form, where enclosing wall rocks are relatively incompetent (e.g., Auer et al., 2007), which may have been the case of the fine-grained sedimentary strata of Oligocene age at Caspiche. Furthermore, such thick but areally restricted tuff and breccia accumulations could also represent the transitions between true diatremes and small calderas (Lipman, 1997).

Porphyry gold-copper formation

The main stages of gold and copper introduction at Caspiche accompanied the potassic alteration that spanned emplacement of phases 1 and 2 of the five readily recognizable porphyry intrusions (Figs. 11, 12b, c). With only few exceptions, the highest-grade ore occurs within the centrally positioned, phase 1 diorite porphyry and its immediate wall rocks: the volcanic breccia and, at depth, siliciclastic sedimentary sequence. Nonetheless, the encircling phase 2 quartz diorite porphyry, in particular its interior parts, also hosts a substantial part of the orebody, albeit generally with lower average grades. Minor metal introduction followed intrusion of the phase 3 quartz diorite porphyry, but had essentially ceased by the time the late-mineral, phase 4 and 5 quartz diorite porphyries were emplaced (Figs. 11, 12d, e).

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**Fig. 11.** Schematic time line diagram to show the relative age relationships between the main brecciation, porphyry intrusion, hydrothermal alteration, and metal introduction events at Caspiche. Note that the average gold grades in the two earliest porphyries (phases 1 and 2) are cumulative rather than being the products of only the host intrusions. Widths of bars approximate the importance of events. IS = intermediate sulfidation epithermal, QDP = quartz diorite porphyry.
FIG. 12. Schematized evolution of the Caspiche porphyry gold-copper deposit. a. Formation of the premineral diatreme, showing the possible prediatreme position of weakly developed porphyry-type mineralization. b. Emplacement of the early phase 1 diorite porphyry, with associated potassic and advanced argillic alteration, into the southern part of the premineral diatreme breccia. c. Emplacement of the early intermineral phase 2 quartz diorite porphyry and continued potassic and advanced argillic alteration. d. Emplacement of the three later quartz diorite porphyries, phases 3, 4, and 5, following appreciable erosion and initiation of telescoping. e. Continued erosion and telescoping resulting in massive overprinting of the advanced argillic lithocap over the porphyry intrusions and potassic alteration, leading to high sulfidation-state gold-copper mineralization. f. Emplacement of the late-mineral diatreme, localized advanced argillic alteration within it, and intermediate sulfidation gold-zinc mineralization beneath the flared contact. The diatreme breccia covered and helped to preserve the deposit, with its lower contact inferred to have been subhorizontal. The blue line approximates the present erosion surface, at which the porphyry intrusions and potassic alteration are largely blind. Note that sections a and b are oriented north-south, with b offset to the south of a, whereas c-f are east-west. See text for further discussion.
There is a crude outward decrease, most pronounced to the west, in the relative age of the Caspiche porphyry intrusions from the phase 1 diorite to the propylitized, phase 5 quartz diorite, the latter emplaced after potassic alteration had completely ceased. This intrusion sequence is the opposite of that observed in many gold-rich porphyry copper deposits, in which the porphyry phases tend to become progressively younger inward (e.g., Panguna, Papua New Guinea, Batu Hijau, Indonesia, and Bajo de la Alumbrera, Argentina; Clark, 1990; Clode et al., 1999; Proffett, 2003).

Notwithstanding the unusually high Au/Cu ratio at Caspiche compared to most gold-rich porphyry copper deposits, the observed close correlation of the gold and copper contents and the external but partly overlapped position of the main molybdenum concentration are typical features of the deposit class (Figs. 9a, b, 10). This lateral metal zoning is widely observed in gold-rich porphyry copper deposits, including Bajo de la Alumbrera (Proffett, 2003), Esperanza, Chile (Pereló et al., 2004), and elsewhere (Sillitoe, 2000, 2010), and suggests control by outward temperature decline and/or different metal complexing of molybdenum compared to that of copper and gold (e.g., Ulrich and Mavrogenes, 2005).

The bottom of the Caspiche ore zone is defined by the abrupt transition from potassic to potassic-calcic alteration, the latter being sulphide and gold deficient, albeit substantially richer in magnetite. The potassic-calcic alteration is tentatively considered to have followed emplacement of the phase 2 quartz diorite porphyry intrusion, and to have caused biotite and copper-bearing sulphide destruction. The downward termination of the Caspiche ore zone as a result of increased magnetite at the expense of sulphide contents markedly differs from that described from the Batu Hijau gold-rich porphyry copper deposit, Indonesia, where downward grade decrease corresponds to increased pyrite/chalcopyrite ratios (Setyandhaka et al., 2008). In the context of a magmatic versus external basal brine origin for actinolite-rich alteration assemblages in porphyry copper deposits (e.g., Seedorff et al., 2005; Sillitoe, 2010), the deep potassic-calcic assemblage at Caspiche might be assigned either to the former, in view of its confinement to the deep core of the system, or to the latter because of the sedimentary host rocks, which potentially could have acted as a connate brine source; however, in view of the elevated potassium content, in the form of K-feldspar, the first of these alternatives is preferred.

The gold grade at Caspiche remains approximately constant over ~1,000 vertical meters, without any noticeable change where copper contents increase on passing from the chalcopyrite-only to deeper bornite-bearing zones (Figs. 7, 7a). This situation is contrary to that predicted experimentally, whereby higher gold contents in the high-temperature precursor to bornite than in intermediate solid solution—the high-temperature chalcopyrite precursor—should be reflected by increased gold tenors with greater bornite abundance (Kesler et al., 2002). However, the vertical constancy of the gold grade combined with the clear gold-copper correlation may be taken as further support for relatively shallow emplacement of the Caspiche deposit (Fig. 12), which would have favored coprecipitation of gold and copper from a buoyant, sulfur-rich vapor plume as a result of depressurization (Murakani et al., 2010). The uncommonly high Au/Cu ratio at Caspiche was likely dictated by the subjacent magma column, possibly as a result of preferential copper sequestration by magmatic sulfides (Simon et al., 2010; Audéat and Simon, 2012).

Late-stage evolution

Advanced argillic lithocap development in the shallower parts of the Caspiche system is assumed to have commenced once potassic alteration was initiated at depth (Figs. 11, 12b, c; Sillitoe, 2010). Nonetheless, much of the preserved advanced argillic zone, which overprints and obliterates preexisting potassic assemblages over the uppermost 300 to 400 vertical meters (Fig. 7), formed later in system development during extreme telescoping. This is believed to have been a direct consequence of progressive but rapid erosional degradation of the paleosurface (Figs. 11, 12d, e), leading to an equally rapid transition from ductile to brittle conditions within and around the porphyry stock. A similar situation exists at the Marte porphyry gold deposit farther north in the Maricunga belt (Sillitoe, 1994; Fig. 2).

This progressive overprinting of potassic by advanced argillic alteration caused total to partial destruction of the intermediate sulfidation-state chalcopyrite ± pyrite assemblages in the upper parts of the potassic zone by high sulfidation-state copper ± iron sulfides and copper-arsenic sulfosalts (Fig. 8). This reconstitution of the potassic zone and its contained mineralization was effective notwithstanding the relatively low temperature, probably not much greater than ~200°C (Hedenquist et al., 1996; Seedorff et al., 2005), implied by the dominant quartz-kaolinite alteration assemblage. The arsenic, absent from the pristine potassic zone, must have been introduced by the fluid responsible for the advanced argillic overprint, whereas much of the gold and copper appear to have been recycled from the preexisting sulfide assemblages (cf. Brimhall, 1979). The latter conclusion is supported by the general coincidence between the highest-grade gold and copper mineralization in the advanced argillic zone and the phase 1 diorite porphyry intrusion and its related high-intensity quartz veinlet stockwork. Nonetheless, several prominent exceptions to this generalization appear to require at least local redistribution of gold and copper.

Hydrothermal breccias at Caspiche are typically small and commonly of dike-like form, in common with those in many other gold-rich porphyry copper deposits (Sillitoe, 2000). The brecciation, whether within (Figs. 5, 6j) or beneath (Fig. 5, 6i) the advanced argillic zone, took place relatively late in system evolution (Fig. 11), as evidenced by the abundance of mineralized clasts and paucity of crosscutting veinlets (Fig. 6i, j). The breccias are consistently barren, and ascribed to phreatic brecciation processes instigated by either late-mineral porphyry intrusion or, within the lithocap, by localized fluid overpressuring (Sillitoe, 1985, 2010).

Development of the Caspiche system concluded with emplacement of the late-mineral diatrime along its western side. Although the diatrime breccia contains abundant wall-rock clasts, including previously mineralized material, the breccia in the western, deeper known parts of the vent has a more obvious juvenile tuffaceous matrix and, hence, is more clearly phreatomagmatic (hydrovolcanic) in origin. The magma chamber from which the juvenile component was erupted is inferred to be that from which the phase 5 quartz diorite
porphyry was also derived, a proposal supported by the pyrite-poor, propylitic alteration affecting both the breccia and phase 5 porphyry. Groundwater ingress to this late-mineral porphyry stock could have been the trigger for the phreatomagmatic activity (e.g., Sheridan and Wohletz, 1983). The upward- and eastward-decreasing angle of the diatreme contact suggests that it may have approached horizontal over the Caspiche deposit, in common with the situation described above for the premineral diatreme (Fig. 12a, f). The subside block of subaerial surge deposits recognized in the diatreme breccia implies that the vent may formerly have been surmounted by a tuff ring or tuff cone (cf. Lorenz, 1986).

Late-mineral diatreme formation overlapped in time with the waning stages of advanced argillic lithocap development (Fig. 11), which resulted in fault-controlled, quartz-kaolinite alteration and localized siliceous ledge formation within the breccia. The final hypogene event at Caspiche was introduction of the gold-zinc-(lead-copper) mineralization, the main concentration of which was localized by the heavily fractured volcanic breccia immediately beneath the eastward-flared, late-mineral diatreme contact. The relatively impermeable nature of the diatreme breccia may have acted as an aquitard (cf. Davies et al., 2005), thereby impeding upward fluid flow and facilitating gold, zinc, and subordinate lead and copper precipitation along the diatreme margin. The zinc, lead, and carbonate contents of the mineralization and low-iron composition of the sphalerite combine to suggest that this end-stage mineralization is of intermediate sulfidation epithermal affinity (Einaudi et al., 2003). Similar late-mineral diatreme contacts in gold-rich porphyry copper systems elsewhere also localized gold-bearing mineralization of high and/or intermediate sulfidation epithermal type (e.g., Lepanto, Philippines, and Wafi-Golpu, Papua New Guinea; Garcia, 1991; Sillitoe, 1999).

Conclusions

Caspiche is the latest discovery in the Maricunga gold-silver-copper belt of northern Chile, with its delayed recognition being due to the concealment by postmineral cover. The deposit provides an excellent example of the full vertical alteration-mineralization zoning sequence in a telescoped, gold-rich porphyry copper deposit, from the high sulfidation, advanced argillic top through the potassic central parts to the metal-deficient, potassic-calcic roots. The ore zone, largely blind at the bedrock surface as well as concealed beneath postmineral cover, extends over approximately 1,000 vertical meters. Early- and late-stage diatremes generated little, if any, mineralization, although part of the former did act as the host rock for the upper half of the Caspiche deposit, and the latter helped localize the end-stage, intermediate sulfidation epithermal gold-zinc mineralization.

A notable feature of Caspiche is the diversity of pre-, syn-, and postmineral fragmental rocks, which need to be correctly distinguished in drill core in order to properly map, understand, and interpret system evolution. The earliest of these are the thick, flat-lying sedimentary breccia horizons in the deeper drilled parts of the siliciclastic wall-rock succession (Figs. 5, 6b), which were followed by the thick, monotonous volcanic breccia package ascribed to early diatreme formation (Figs. 5, 6c-e). Breccias generated during deposit formation comprise the intrusion breccia, developed locally in marginal parts of the phase 2 quartz diorite porphyry (Fig. 6h), and several texturally and mineralogically distinct, late-stage hydrothermal breccias (Fig. 6i, j). Brecciation processes concluded with emplacement of the late-stage diatreme breccia along the western side of the deposit (Figs. 4, 5), within which a variety of mineralized clasts are commonplace near its eastern contact (Fig. 6k). To these may be added a number of steep zones of tectonic brecciation caused by relatively minor postmineral faulting (Figs. 4, 5).

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