PGC PUBLISHING

Masterman G.J., Cooke, D.R. and Moore, R.L., 2005 - Geology and Discovery of Porphyry Cu-Mo-Ag Deposits in the Collahuasi District, Northern Chile; *in Porter, T.M. (Ed.), Super Porphyry Copper & Gold Deposits: A Global Perspective*; PGC Publishing, Adelaide, v. 1, pp 175-188.

GEOLOGY AND DISCOVERY OF PORPHYRY Cu-Mo-Ag DEPOSITS IN THE COLLAHUASI DISTRICT, NORTHERN CHILE

[1,2]Glenton J. Masterman, [1]David R. Cooke and [3]Richard L. Moore

[1]*Centre for Ore Deposit Research, University of Tasmania, Hobart, Australia*
[2]*Bolnisi Gold NL, Chihuahua, México*
[3]*Consulting Geologist, Toronto, Ontario, Canada*

Abstract - The Collahuasi district is located in northeastern Chile, approximately 200 km southeast of the port of Iquique. It defines an area of 1200 km^2 in the Western Cordillera of the Andes Mountains, between altitudes of 4000 and 5000 m above sea level. The district hosts a cluster of mineralised centres that currently comprise three porphyry copper, associated high level epithermal vein, and palaeogravel-hosted exotic copper deposits. The Quebrada Blanca, Ujina and Rosario porphyry copper deposits are currently in production, as are the Huinquintipa exotic copper accumulations. The Collahuasi porphyry deposits are spatially associated with the West Fissure/Domeyko Fault System and appear to have been emplaced during a period of dextral transpression between 35-34 Ma.

Two major faults have segmented the Collahuasi district into three principal tectonic units. The central uplifted block of Collahuasi Formation is made up of Permian to Triassic andesite, dacite and rhyolite with small porphyry intrusions. The central block is separated from Jurassic sedimentary and volcanic rocks of the Cerro Empexa and Quehuita Formations to the west by the West Fissure, and is overlain to the east and north by extensive sheets of Cenozoic ignimbrites. To the east, the Collahuasi Formation is truncated by the Loa Fault that is a splay of the West Fissure Fault System.

The Quebrada Blanca, Rosario and Ujina porphyry centres define a broad east-trending corridor between the West Fissure and Loa Faults. At Rosario, high-grade massive sulphide (Cu-Ag-Au) veins overprint porphyry-style copper-molybdenum mineralisation. Similar high-sulphidation veins occur in the La Grande and Poderosa areas southwest and southeast of Rosario respectively. Intermediate-sulphidation Ag mineralisation occurs in a long (3 to 5 km), semi continuous quartz vein in the Monctezuma Fault. West of the Rosario porphyry centre are several palaeochannel systems containing exotic copper mineralisation. The present drainage system has dissected the original deposit resulting in preservation of several isolated mineralised bodies know as the Huinquintipa deposits.

Mining in the Collahuasi district commenced with the Incas around 1400 A.D. and continues to the present day. During the early 1970s Anacaonda recognised that the geology and altered rocks at Quebrada Blanca were consistent with porphyry-style copper mineralisation. However, Quebrada Blanca was not delineated until the Superior Oil/Falconbridge Group optioned the property from the Chilean authorities in the late 1970s. The Rosario porphyry copper-molybdenum-silver deposit was discovered in 1979, but it took another 12 years for the Falconbridge, Shell Chile and Chevron joint venture consortium to discover the economically significant Ujina porphyry Cu-Mo deposit.

Introduction

The Collahuasi District (20°58' S and 68°43' W) is located in the high Andes in the First Region of northern Chile, 15 km from the Bolivian border (Figs. 1 and 2). The deposits are located at altitudes which vary from 4200 to 5000 m above sea level. Road systems connect the project with Chuquicamata, 150 km to the south and with the Pacific coast port city of Iquique, 200 km to the northwest.

Historically, mining activity focused on the Cerro La Grande, Poderosa and Monctezuma areas where high-sulphidation Cu-Ag-Au and intermediate-sulphidation Ag cropped out in high-grade veins (Fig. 4). Up to 300 000 tonnes, grading 25% Cu, 180 g/t Ag and 2 g/t Au, were mined from these veins up to 1930. With predominantly hypogene sulphide reserves of 1094 Mt @ 1.03 % Cu (Moore and Masterman, 2002), Rosario constitutes an excellent example of an environment in which major high-sulphidation Cu-Ag veins have developed in a porphyry system. These veins account for approximately 10 % of the hypogene Cu ore at Rosario (Dick *et al.,* 1994). Mineral reserves (plus production) at the Ujina deposit, 7 km east of Rosario, which include hypogene and supergene ore, are 741 Mt @ 0.81% Cu (Moore and Masterman, 2002). La Profunda, a hydrothermally-altered intrusion intersected by drilling <2 km southeast Ujina has been tentatively identified as a further centre of mineralisation (Fig. 4). The Quebrada Blanca deposit, situated 8 km southwest of Rosario, contains reserves of 281 Mt @ 1.23 % Cu. The Rosario and Ujina deposits are jointly owned by the consortium Falconbridge (44%), Anglo American (44%) and Mitsui (12%). Quebrada Blanca is owned 76.5% by Aur Resources, 13.5% by Sociedad Minera Pudahuel LTDA and 10% by Enami. Together, the deposits of the Collahuasi district comprise total reserves (plus production) of 2.2 Gt at 0.90% Cu.

This manuscript describes the geology of the Collahuasi district and provides brief descriptions of the main deposits. We also summarise the mining history and give an overview of the modern exploration that led to the discovery of three world class copper deposits between 1977 and 1991. This paper has been modified from the Moore and Masterman

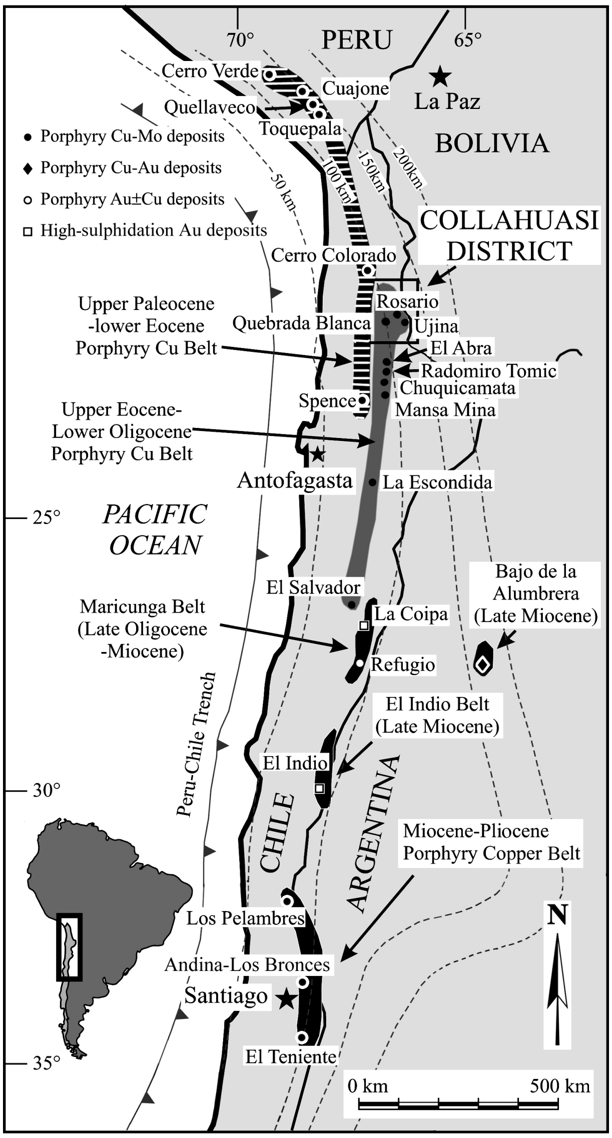


Figure 1: ***Map showing the location of the Collahuasi district*** relative to other major copper and gold deposits in Chile and western Argentina. Metallogenic belts representing the five major copper provinces are also shown. Dashed contour lines are the depths to the Wadati-Benioff zone. *Modified from Muntean and Einaudi (2000).*

(2002) manuscript published in the extended abstracts volume "Giant Ore Deposits: Characteristics, genesis and exploration", CODES Special Publication 4, Hobart, June, 2002.

District Geology

At Collahuasi, the north-trending Domeyko and Loa Faults (Fig. 2) separate three principal stratigraphic domains. In the west, Cretaceous continental volcanic and arenitic rocks (Cerro Empexa Formation) overlie deep to shallow marine Jurassic sedimentary rocks (Quehuita Formation). Both formations unconformably overlie continental to shallow marine volcanic and sedimentary rocks of the Permo-Triassic Collahuasi Formation. Extensive Cenozoic ignimbrite covers the basement stratigraphy in the northern part of the district. Chains of Miocene-Pliocene andesite stratovolcanoes, defining the Western Cordillera, occur east of the Collahuasi Formation near the north-trending Loa Fault. The upper Eocene-lower Oligocene Rosario and Ujina porphyry Cu deposits occur along the trace of a significant northwest-trending photogeologic lineament in the uplifted Collahuasi Formation (Fig. 2).

Collahuasi Formation

Permian to Triassic andesite, dacite and rhyolite, and small porphyry intrusions characterise the geology of the Collahuasi Formation (Fig. 3; Vergara and Thomas, 1984). Volcanic units are intercalated with arenites (of andesitic origin) and rare limestone lenses. The Domeyko Fault System defines the western edge of the Collahuasi Formation (Bisso *et al.,* 1998). The eastern edge of the Collahuasi Formation is not exposed, but is probably the Loa Fault. The northern termination of the Collahuasi Formation is poorly defined as the sequence is buried beneath the Huasco Ignimbrite (Vergara and Thomas, 1984). The Collahuasi Formation extends south to Chuquicamata, but is absent beyond Calama (Figs. 1 and 2).

The Collahuasi Formation was emplaced onto Proterozoic to early Palaeozoic basement of the Arequipa Terrane during the late Palaeozoic (Shatwell, 1995). Deposition occurred in a continental setting, characterised by dacitic and minor andesitic volcanism. The topography of the Permo-Triassic landmass facilitated deposition of volcano-sedimentary rocks in fluvial basins and lakes (Vergara and Thomas, 1984).

Quehuita Formation

Sedimentary rocks of the Quehuita Formation, unconformably overlie the Collahuasi Formation (Figs. 2 and 3), and are extensively exposed west of the Domeyko Fault. They consist of a lower member of deep marine mudstone and siltstone, and an upper member of shallow marine to subaerial continental limestones, calcareous sandstones, arenites and conglomerates (Vergara, 1978; Vergara and Thomas, 1984). Limestones and deep marine units in the lower marine member contain fossil associations that indicate a Jurassic age (Vergara and Thomas, 1984; Munchmeyer *et al.,* 1984). Growth faults in both members indicate deposition occurred in an extensional setting that was initially deep water but gradually shallowed upward during seawater regression. Quehuita Formation sedimentation is associated with back-arc extensional basins that formed during development of the Jurassic arc in northern Chile.

Cerro Empexa Formation

The Cerro Empexa Formation is a north-trending, elongate sequence of andesite and dacite lavas, volcanic breccias, and interbedded red-bed arenites and conglomerates (Figs. 2 and 3; Vergara and Thomas, 1984). The Domeyko Fault System defines the eastern contact of the Cerro Empexa Formation. To the west, the Cerro Empexa Formation unconformably overlies the Quehuita Formation (Fig. 2). Granite stocks, dated at 95 Ma, have intruded the Cerro Empexa Formation and led Vergara and Thomas (1984) to assign a Cretaceous age for these units. Continental deposition of the Cerro Empexa Formation consisted of andesitic-dacitic volcanic rocks and simultaneous emplacement of red bed deposits in an environment similar to the modern arc of the Eastern Cordillera.

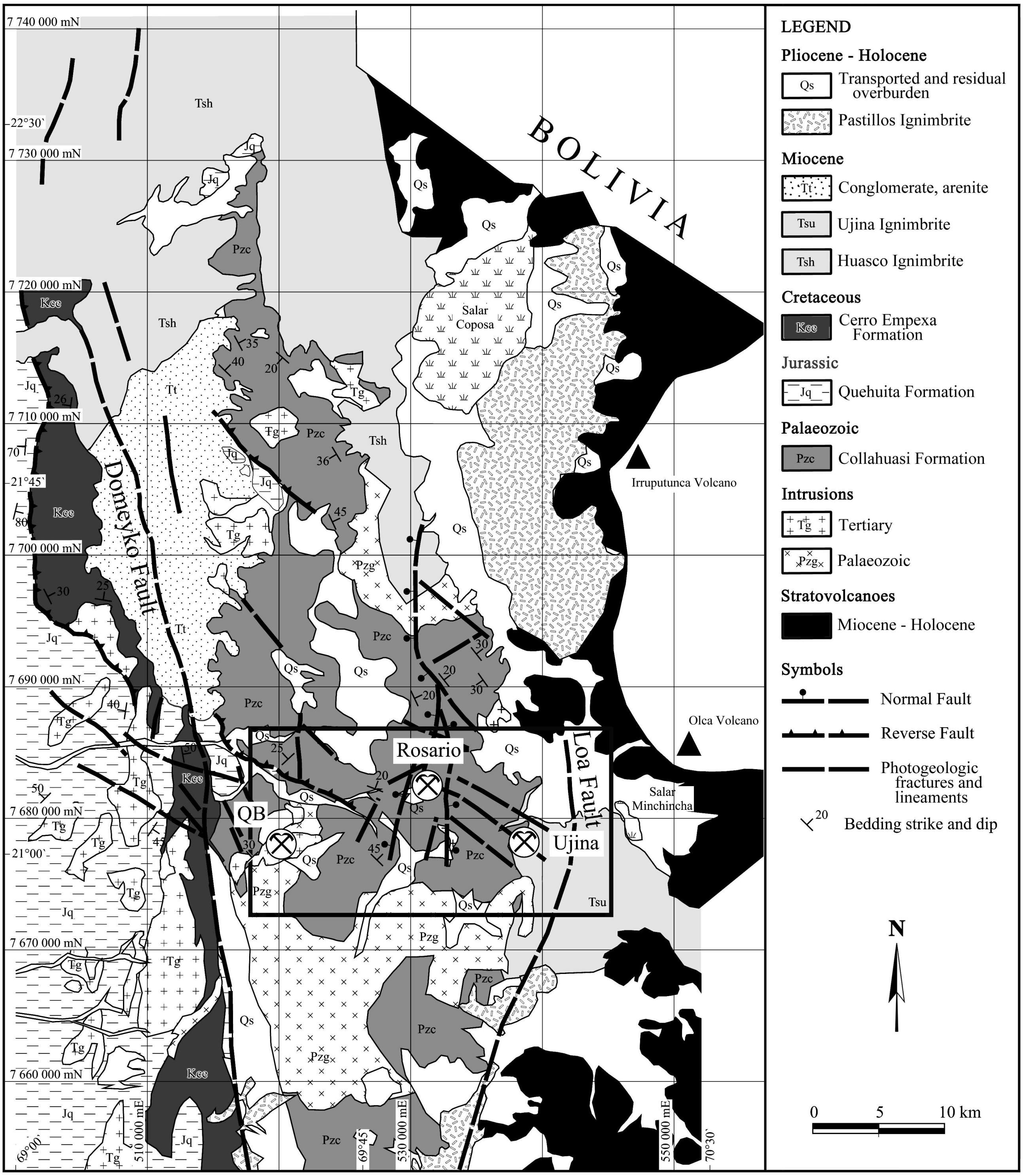


Figure 2: ***Simplified geological map of the Collahuasi district.*** The Rosario, Ujina and Quebrada Blanca (QB) deposits occur in the Collahuasi Formation bound on the east and west by the Loa and Domeyko faults respectively. Note that the Rosario and Ujina deposits occur on a northwest-striking photogeologic lineament interpreted from merged LandSat-SPOT imagery. The outline box shows the outline of Figure 3. *Geology modified from Vergara and Thomas (1984), reproduced from Masterman et al., (2003).*

Cenozoic Rocks

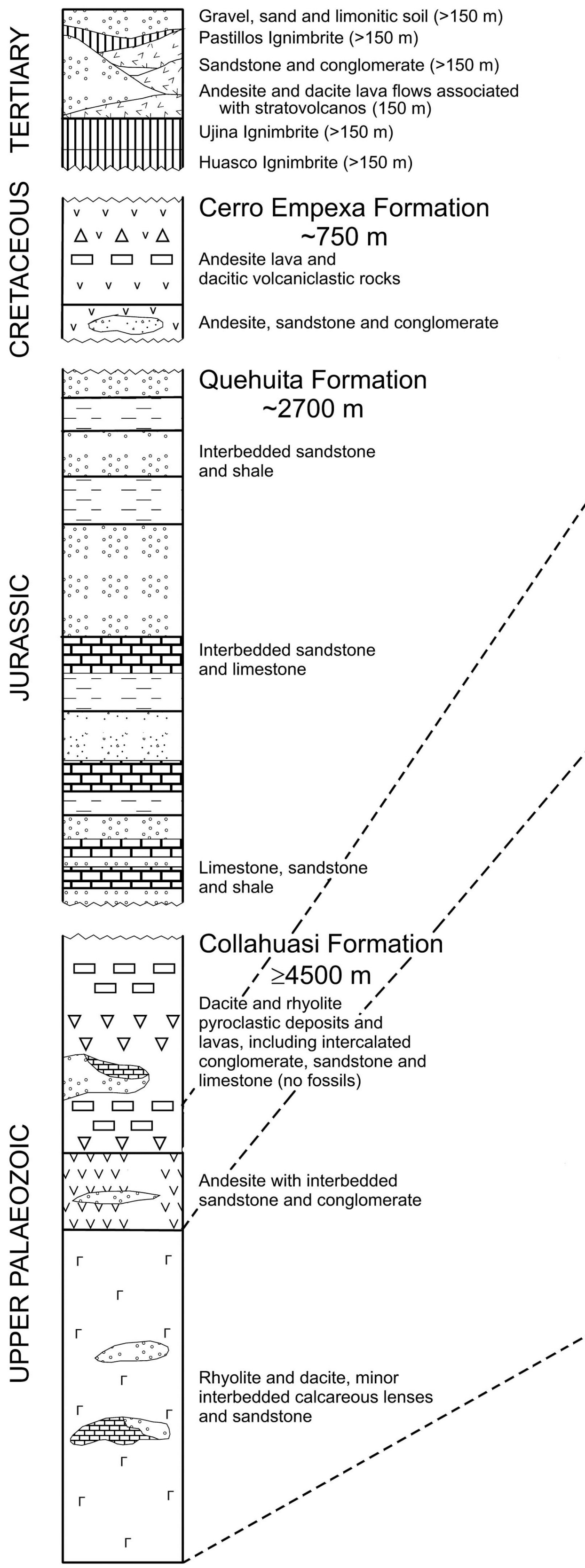
Three discrete ignimbrite bodies, the Huasco, Ujina and Pastillos Ingimbrites, occur in the northern and eastern parts of the Collahuasi district (Figs. 2 and 3). They have been dated by Vergara and Thomas (1984) at 17.1, 9.3 and 0.75 Ma, respectively. Recent andesite flows erupted between 7.4 and 3.4 Ma (Vergara and Thomas, 1984), and originated from stratovolcanoes that mark the position of the modern arc.

Intrusive rocks

Intrusive bodies ranging in composition from diorite to monzonite, granodiorite and granite occur throughout the Collahuasi district (Fig. 2; Munchmeyer *et al.,* 1984; Vergara and Thomas, 1984). Pre-continental arc Palaeozoic granite and granodiorite are restricted to the Collahuasi Formation. Late Cretaceous – early Tertiary quartz diorite and granodiorite occur throughout the Cerro Empexa, Quehuita and Collahuasi Formations. Late Eocene quartz-monzonite intrusions, related to porphyry copper mineralisation, were emplaced exclusively within the Collahuasi Formation (Munchmeyer *et al.,* 1984; Vergara and Thomas, 1984).

Structure

Two major faults have segmented the Collahuasi district into three principal tectonic units (Fig. 2). The central, uplifted block of Collahuasi Formation corresponds with



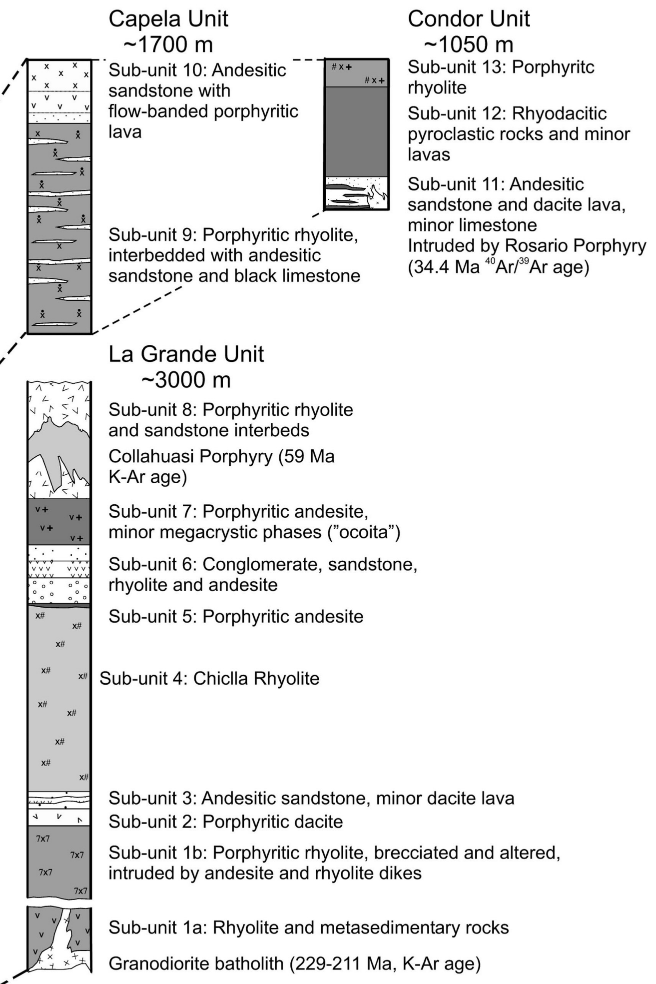


Figure 3: ***Collahuasi regional (left) and Rosario district (right) stratigraphic columns*** *(after Muchmeyer et al., 1984; Vergara and Thomas, 1984). Munchmeyer et al., (1984)* informally subdivided the Collahuasi Formation into thirteen sub-units based on their volcanic and sedimentary facies characteristics. The age of the Collahuasi Formation has been constrained by a late Triassic granodiorite pluton (229-211 Ma) that intruded the base of the volcanic and sedimentary sequence. Ore grade copper at Rosario is localised in the Rosario Porphyry, a monzonite stock, which has been emplaced at the base the Condor Unit.

the northward continuation of the Domeyko Cordillera that is bound to the west by the Domeyko Fault. At Collahuasi, the eastern edge of the Domeyko Cordillera is defined by the active volcanic front of the Western Cordillera. West of the Domeyko Fault System, sedimentary and volcanic units of the Cerro Empexa and Quehuita Formations are folded isoclinally and dip steeply into the Longitudinal Valley.

The Loa Fault is defined by a series of concave to the west arcuate faults (inverted basin structures). These structures, although not well exposed, extend north along the trace of the Loa River. At Collahuasi, the Loa Fault passes to the east of Ujina beneath the Ujina Ignimbrite. Several Collahuasi drill holes have intersected the Loa Fault, where it cuts the La Profunda Granite. Dick et al. (1994) and Clark et al. (1998) proposed that the Loa Fault splayed from the Domeyko Fault System north of El Abra.

Folding

Open, upright NW-trending folds have developed in the Collahuasi Formation. Vergara and Thomas (1984) interpreted the long wavelength north-trending fold at Quebrada Blanca to be related to doming by the Quebrada Blanca plutonic complex. The age of the oldest intrusive rocks at Quebrada Blanca is late Triassic-middle Jurassic, indicating that at least one of the folding events recorded in the Collahuasi Formation occurred during the Mesozoic. Tight north-trending anticlines and synclines, partitioned into the Quehuita and Cerro Empexa Formations, are characterised by subvertical and locally overturned fold limbs, some of which are related to reverse faults. The sub-horizontal strata of the Cenozoic volcanic and sedimentary rocks have not been folded.

Regional-Scale Faults

Palaeozoic basement rocks of the Collahuasi Formation have been thrust over Mesozoic rocks west of the Collahuasi District along several northwest- trending reverse faults (Fig. 2). In addition, Quehuita Formation has been overthrust by Cerro Empexa Formation along the high-angle Copaquire Fault west of Quebrada Blanca. The Copaquire Fault cuts the Malta Granite (Fig. 2) which has been dated at 45 ± 5.2 Ma (Vergara and Thomas, 1984). However, further south, the Copaquire Fault is intruded by Malta Granite (Fig. 2), suggesting syn-tectonic magmatism along this structure (Vergara and Thomas, 1984).

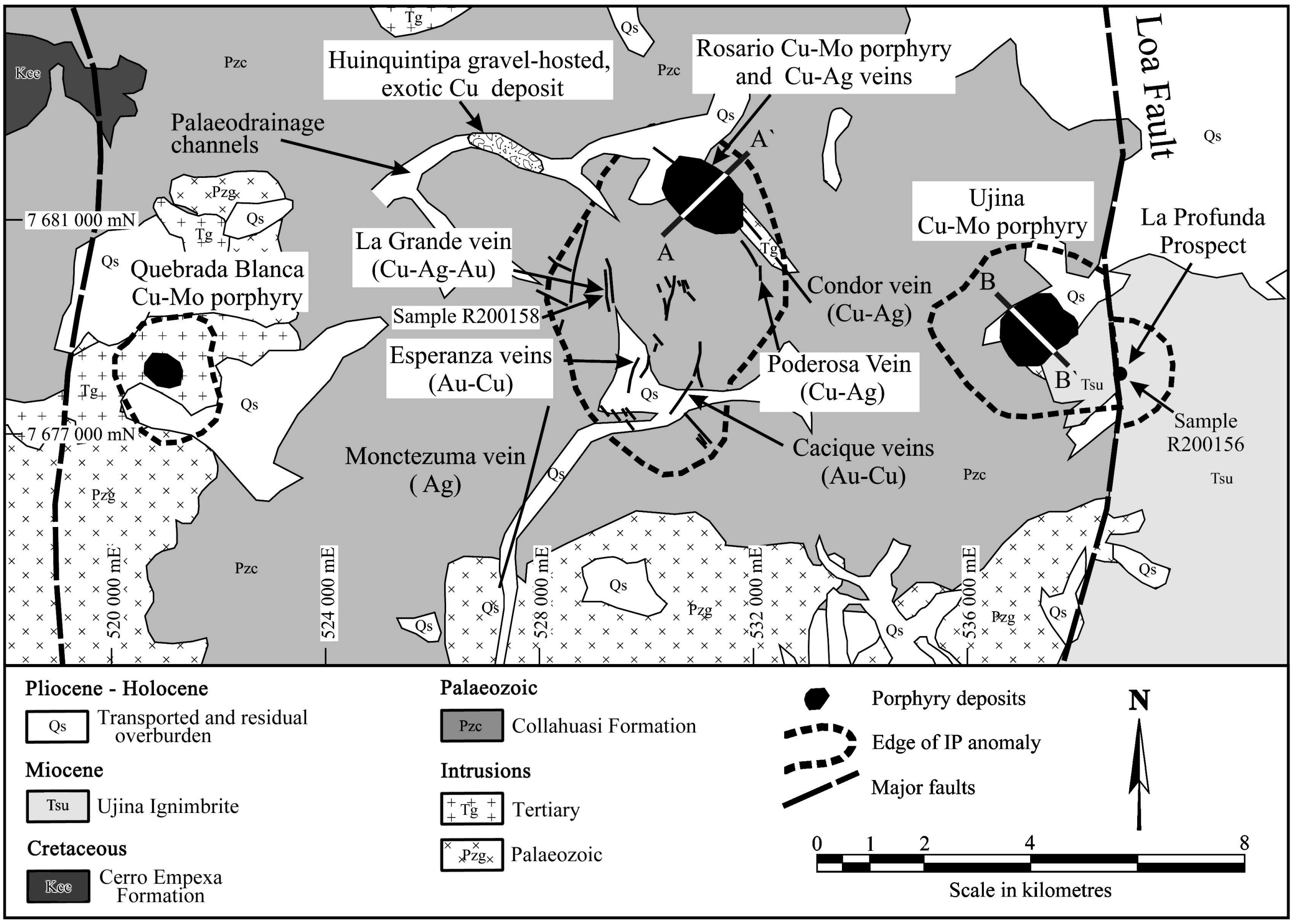


Figure 4: ***Schematic map showing the distribution of porphyry deposits and epithermal veins in the Collahuasi district.*** The induced polarisation (IP) anomalies surrounding each of the porphyry centres are interpreted to delimit the extent of hydrothermal alteration. The shaded areas represent the mineralised zones. Precious metals in late-stage high-sulphidation veins are zoned from Cu-Ag rich at Rosario to Au-Cu rich in the Cerro La Grande area (e.g., the La Grande vein). Vein morphology (banded and comb textures) and ore and gangue mineralogy of the Monctezuma Ag vein are characteristic of low-sulphidation mineralisation (e.g., Hedenquist, 1987; White and Hedenquist, 1990; 1995). The gravel-hosted Huinquintipa exotic copper deposit occurs in a palaeodrainage system that originated at Rosario. Present drainage systems south of Cerro La Grande contain placer gold. Section lines A-A' and B-B' indicate the locations of cross sections through the Rosario and Ujina deposits, respectively (Figs. 4 and 5). *Modified from Dick et al., (1994), reproduced from Masterman et al., (2003).*

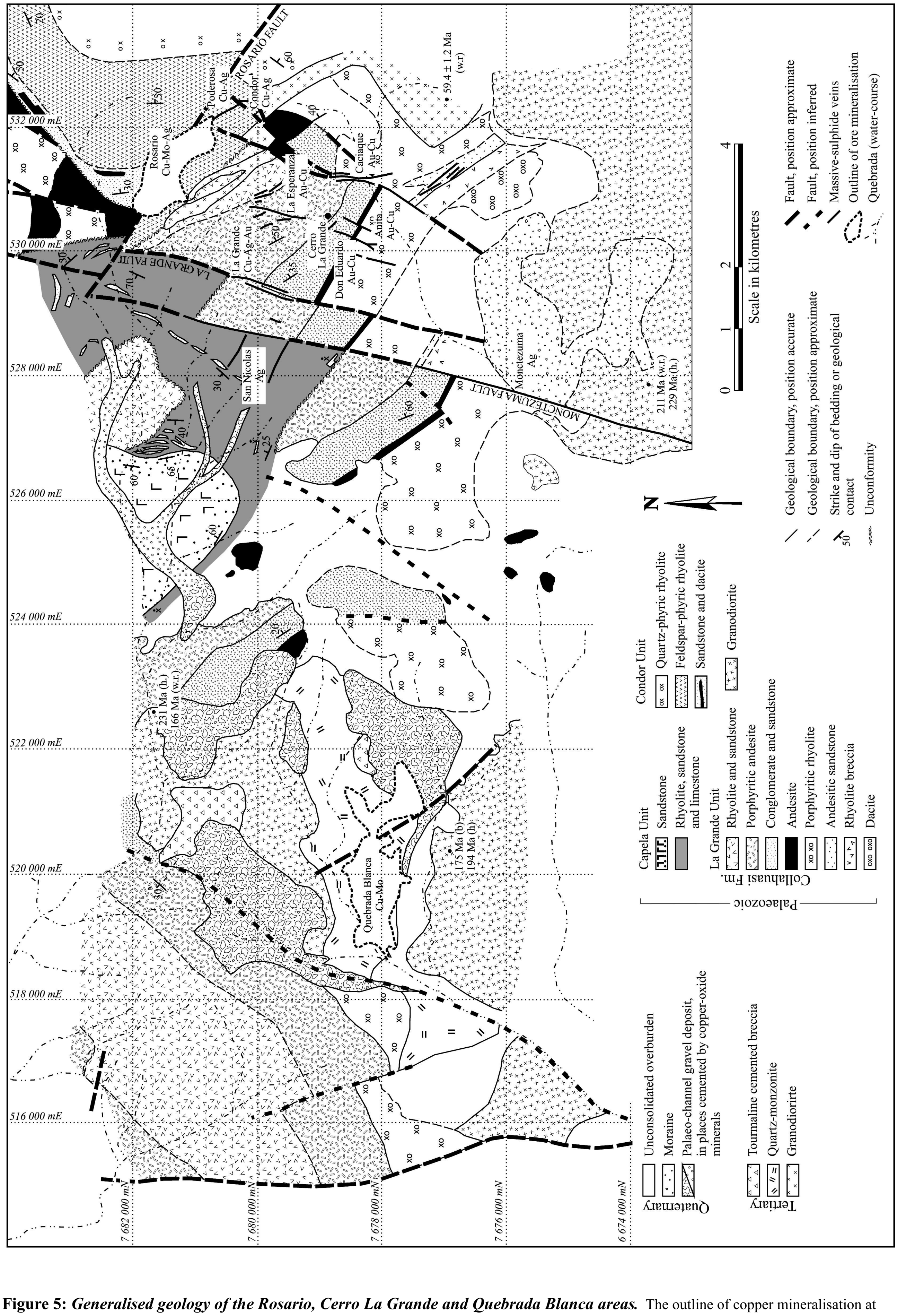


Figure 5: ***Generalised geology of the Rosario, Cerro La Grande and Quebrada Blanca areas.*** The outline of copper mineralisation at the Rosario and Quebrada Blanca porphyry centres is shown, as well as vein-hosted Cu-Ag-(Au) massive sulphide occurrences at Poderosa and Cerro La Grande. High-grade silver occurs in a laminated quartz vein at Monctezuma. *From Munchmeyer et al., (1984).*

Sinistral offset of the Copaquire Fault north of Quebrada Blanca (Fig. 2), indicates that strike-slip movement along the Domeyko Fault occurred after the middle Eocene. The northern extension of the Domeyko Fault beyond the Collahuasi district is buried beneath Miocene-Pliocene ignimbrite and unconsolidated sedimentary rocks (Fig. 2), indicating that this strand of the Domeyko Fault System has not been reactivated since the Neogene.

District-Scale Faults

A system of north-south to north-northeast-trending, subvertical faults has cut the volcanic stratigraphy south of Rosario (Fig. 4). Some of these faults have localised high-grade Cu-Ag-Au veins. Munchmeyer *et al.,* (1984) suggested that development of the La Grande and Monctezuma fault systems was related to strike-slip movement on the Domeyko Fault. A second group of faults striking northwest (dipping 45°-60° SW) have also localised high-grade Cu-Ag-Au mineralisation at the Rosario Cu-Mo-Ag deposit (Dick *et al.,* 1994; Lee, 1994; Masterman, 2003).

At Quebrada Blanca, a series of shallow southwest-dipping faults has imposed structural control on late hydrothermal veins (Hunt *et al.,* 1983; Rowland and Wilkinson, 1998). This orientation corresponds with the SW-dipping fault system at Rosario. The NE-trending Quebrada Blanca Fault cuts porphyry-style mineralisation (Fig. 4), but may have developed before intrusion of the complex and influenced its emplacement (Johny Bonilla, Chief Geologist Compañia Minera Quebrada Blanca S.A., pers. com. 2000).

Quebrada Blanca Porphyry Cu-Mo Deposit

Geological Relationships

The Quebrada Blanca intrusive complex is hosted by a Permian granite batholith that intruded a north-trending anticline of folded Collahuasi Formation volcanic units (Fig. 5; Munchmeyer *et al.,* 1984; Rowland and Wilkinson, 1998). The volcanic stratigraphy consists of several andesite flows interfingered with epivolcaniclastic sandstone of andesitic origin. Rhyolitic and dacitic pyroclastic rocks overlie the andesite and sandstone units (Hunt *et al.,* 1983). The mineralised intrusions define an ENE-trend that cuts the axis of the anticline. Copper mineralisation is associated with several generations of igneous activity.

Alteration and Mineralisation

At Quebrada Blanca, copper ore is mined predominantly from the supergene zone. A detailed description of hypogene mineralisation styles is presented in Rowland (1998). Early chalcopyrite-bornite mineralisation at Quebrada Blanca is associated with a quartz monzonite stock and a porphyry dyke suite, whereas late chalcopyrite-molybdenite-pyrite mineralisation is associated with cross-cutting igneous and hydrothermal breccia bodies (Rowland, 1998; Rowland and Wilkinson, 1998; Hunt *et al.,* 1983). Quebrada Blanca vein and alteration paragenesis is detailed in Table 1.

The Quebrada Blanca stock is intensely biotite altered along its northern contact. Hunt *et al.,* (1983) defined this facies as a discrete mafic (diorite) intrusion. Disseminated bornite-chalcopyrite mineralisation is spatially associated with potassic alteration in the granodiorite core of the quartz monzonite intrusion. The highest molybdenite grades occur along the Quebrada Blanca Fault. Potassic alteration grades out to chlorite-epidote in the southern sector of the deposit (Hunt *et al.,* 1983). A funnel-shaped zone of pervasive sericite alteration surrounds the vuggy hydrothermal breccia unit (Rowland, 1998). Secondary copper-arsenic oxide minerals occur at the top of the hydrothermal breccia body in the supergene zone (Johny Bonilla: chief geologist CMQB, pers. com. 2000) suggesting they were derived by oxidation of primary copper-sulphosalt minerals. The vuggy breccia zone and associated copper-sulphosalts may have originated from hydrothermal fluids of high-sulphidation character.

At least two tourmaline breccia bodies containing chalcopyrite are defined on the northern and eastern margins of the intrusive complex (Rowland and Wilkinson, 1999). Their relationship to breccia bodies in the central mineralised zone at Quebrada Blanca is unclear, although Hunt *et al.,* (1983) speculated that tourmaline breccias postdate igneous breccias in the core of the Quebrada Blanca complex.

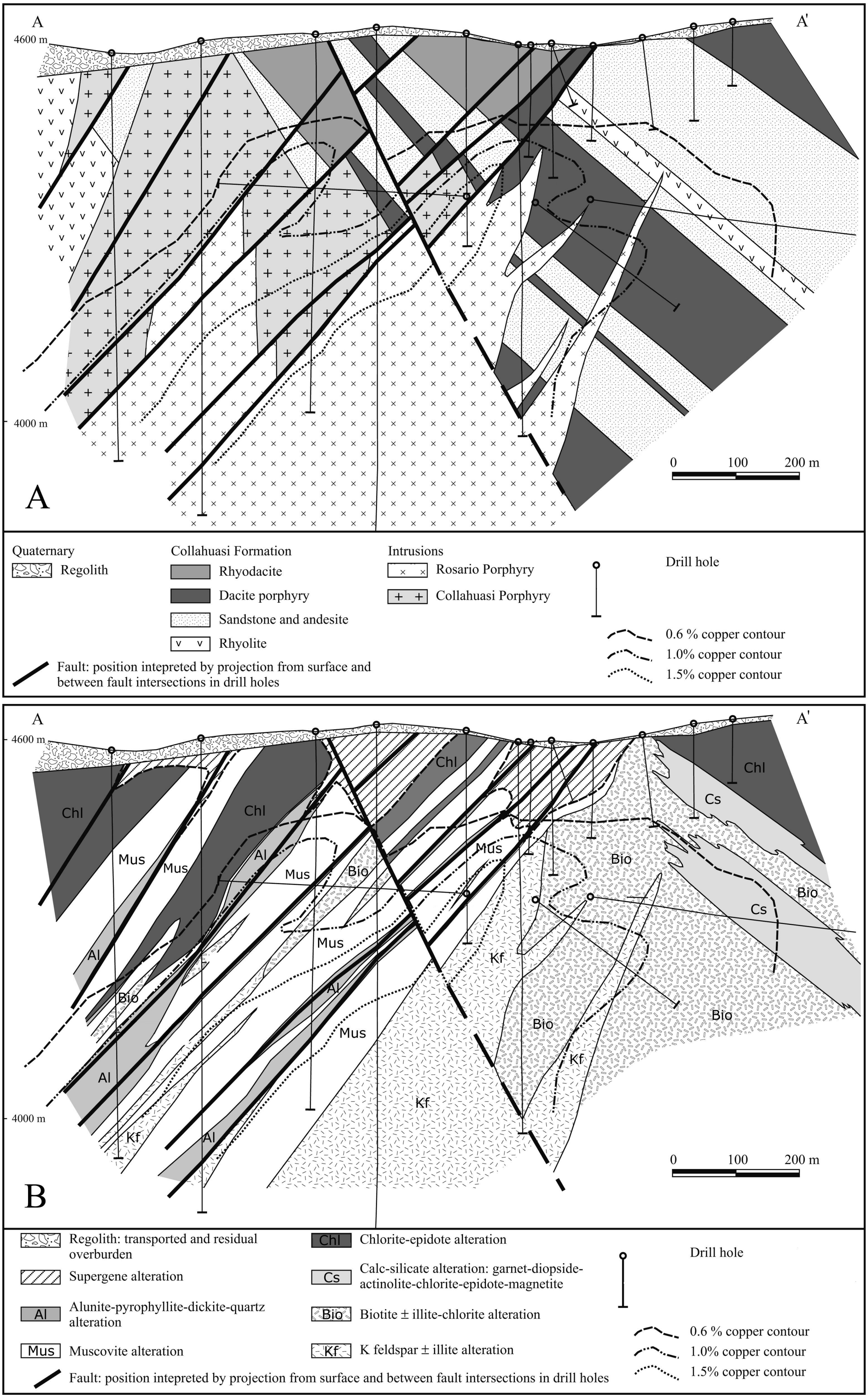
Rosario Porphyry Cu-Mo-Ag Deposit

Geological Relationships

The Rosario porphyry deposit is hosted in andesitic to rhyolitic volcanic units of the Collahuasi Formation. The volcanic rocks are interbedded with volcaniclastic sandstone and minor limestone (Fig. 6a; Dick *et al.,* 1994;

Stage	Vein mineralogy	Alteration zone
Pre-ore	Biotite-magnetite	± potassic halo
Early	Quartz-k feldspar-anhydrite-magnetite-sulphides	± potassic or sericitic halo
	Quartz	± potassic/sericitic halo
Hydrothermal breccias	Quartz-molybdenite-chalcopyrite ± anhydrite	± sericitic halo
Tourmaline breccias	Tourmaline-chalcopyrite-bornite-molybdenite-pyrite	Tourmaline
Late	Pyrite > quartz	Strong sericitic to argillic halo

Table 1: ***Summary of vein paragenesis at Quebrada Blanca*** (after Rowland and Wilkinson, 1999; Hunt *et al.,* 1983).


A
A'
4600 m
4000 m
0 100 200 m
A
Quaternary
Regolith
Collahuasi Formation
Rhyodacite
Dacite porphyry
Sandstone and andesite
Rhyolite
Intrusions
Rosario Porphyry
Collahuasi Porphyry
Drill hole
0.6 % copper contour
1.0% copper contour
1.5% copper contour
Fault: position intepreted by projection from surface and between fault intersections in drill holes
A
A'
4600 m
4000 m
Chl
Mus
Al
Bio
Kf
Cs
0 100 200 m
B
Regolith: transported and residual overburden
Supergene alteration
Alunite-pyrophyllite-dickite-quartz alteration
Muscovite alteration
Chl Chlorite-epidote alteration
Cs Calc-silicate alteration: garnet-diopside-actinolite-chlorite-epidote-magnetite
Bio Biotite ± illite-chlorite alteration
Kf K feldspar ± illite alteration
Drill hole
0.6 % copper contour
1.0% copper contour
1.5% copper contour
Fault: position intepreted by projection from surface and between fault intersections in drill holes

Lee, 1994; Masterman, 2003). A southwest-dipping system of brittle faults (the Rosario Fault System) cuts the intrusions that host copper mineralisation. Lee (1994) and Dick *et al.,* (1994) recognised that the Rosario Fault System was an important control on high-grade hypogene copper mineralisation and also served to localise overprinting supergene mineralisation (Fig. 6a).

There are two main feldspar-quartz-biotite porphyritic intrusions showing discordant contact relationships (Fig. 6a). A granodiorite dyke, the Collahuasi Porphyry, was intruded by a quartz monzonite known as the Rosario Porphyry (Lee, 1994). A third porphyritic unit, the Inés Porphyry, has been interpreted by previous workers as a pre-mineralisation dacitic intrusion with a sill-like geometry (Munchmeyer *et al.,* 1984; Lee, 1994; Bisso *et al.,* 1998; Clark *et al.,* 1998). The northwest-trending Collahuasi Porphyry is between 50 and 300 m wide and has a strike length of 8 km (Munchmeyer *et al.,* 1984). Its southeastern end is situated 3 to 4 km beyond the limit of the Rosario hydrothermal system. The northwest-trending Rosario Porphyry is 300-500 m wide and up to 1500 m long and has been delineated to a depth of 1000 m. Low-grade, veinlet and disseminated porphyry-style copper-molybdenum mineralisation is centred in and around the Rosario Porphyry (Lee, 1994; Masterman, 2003). In contrast, high-sulphidation copper-silver massive sulphide veins are localised in the Rosario Fault System, which cuts porphyry-style copper-molybdenum ore in the centre of the Rosario Porphyry (Fig. 6a; Dick *et al.,* 1994; Lee, 1994). Hypogene copper grades are high in the Collahuasi and Inés porphyries near the Rosario Fault System, although copper grades and the intensity of hydrothermal alteration decrease outward from the Rosario Porphyry (Masterman, 2003).

Alteration and Mineralisation

The history of hydrothermal activity at Rosario was first described in a detailed study by Lee (1994). A revision of his alteration-mineralisation paragenesis is provided in Masterman (2003) and Masterman *et al.,* (in press). Multiple, overprinting generations of mineralisation and alteration are grouped in Table 2, modified from the main paragenetic classifications of Lee (1994). Early-, transitional- and intermediate-stage veins constitute the porphyry-related mineralisation at Rosario, while late-stage, massive sulphide veins belong to the high-sulphidation-style mineralisation. The distribution of the alteration zones is illustrated in cross section in Fig. 6b.

The earliest alteration, apparently barren, is dominated by disseminated and veinlet-style magnetite, in varying proportions. Chalcopyrite-bornite mineralisation occurs in early-stage quartz-biotite-albite and quartz-K feldspar veins that cut the magnetite veining (Masterman, 2003). These early-stage veins are associated with biotite-albite-K feldspar alteration within and around the Rosario Porphyry (Fig. 6b). The greatest proportion of biotite-albite alteration occurs in the country rocks surrounding the Rosario Porphyry, with only a small amount within the intrusion itself. Molybdenite is found in transitional veins as flaky aggregates intimately intergrown with anhedral quartz and variable amounts of K feldspar. These transitional veins cross-cut all early-stage veins, and in turn, have been overprinted by intermediate-stage veins. The intermediate-stage veins, corresponding to the Group 2 veins of Lee (1994), consist of quartz, pyrite and chalcopyrite, with illite-chlorite alteration envelopes.

Late-stage, high-sulphidation copper-silver veins are localised by the southwest-dipping Rosario Fault System and define a zone of high copper grades, locally greater than 10 wt. percent (Fig. 6b; Dick *et al.,* 1994; Lee 1994). Sulphide and sulphosalt minerals in the late-stage veins include tennantite and accessory enargite, chalcocite, covellite, mawsonite ($Cu_6Fe_2SnS_8$) and colusite [$Cu_3(As,Sn,V,Fe)S_4$] in addition to pyrite, bornite and chalcopyrite. Quartz-alunite-pyrite alteration proximal to late-stage veins has been overprinted by an alteration assemblage of pyrophyllite-dickite (Masterman, 2003). This envelope of advanced argillic alteration passes out through muscovite-quartz-pyrite to illite-smectite altered rocks, distal to the veins. The muscovite-quartz-pyrite assemblage is interpreted to have formed contemporaneously with the pyrophyllite-dickite assemblage.

Huinquintipa Exotic Cu Deposit

The exotic copper mineralisation within the east-west striking Huinquintipa palaeodrainage system originates from the Rosario mineralised centre. Gravels were transported from the east and impregnated with exotic copper oxide minerals following deposition in the palaeochannel (Munchmeyer, 1996). The present drainage system has dissected the original deposit, dividing the remaining preserved mineralisation into several isolated bodies (Munchmeyer *et al.,* 1984). Economic copper mineralisation at Huinquintipa occurs over an area of 1 km by 150 m, averaging 10 m in thickness (Figs. 4 and 5). Zonation of exotic copper species and hydrothermal alteration minerals is evident along the 6 km length of the palaeochannel (Munchmeyer, 1996). Near Rosario, the gravels are unaltered and cemented by abundant limonite. Approximately 2 km from Rosario, pervasively kaolinised gravel fragments are cemented by copper wad and kaolinite.

Figure 6: Northeast-southwest section through the Rosario deposit *from Masterman et al., (2004; see Fig. 3 for the location of the section)*:

- **A** - ***Geological cross section***. Hypogene copper grade contours are shown at the 0.6, 1.0 and 1.5 wt. percent levels. The highest copper grades (>1.5 wt. % Cu) occur in the late-stage veins associated with the southwest dipping Rosario fault system. The 1 wt. % Cu contour closely follows the outline of the Rosario Porphyry.
- **B -** ***Cross section showing alteration.*** The Rosario fault system has imposed strong structural control on late-stage alunite-pyrophyllite-dickite-quartz alteration. This facies grades outward to muscovite-quartz alteration. Relict lenses of early-stage magnetite, biotite-albite and K feldspar altered rock have been preserved in the hanging wall near the Rosario Fault, but these facies mostly occur in the footwall where the rocks are less affected by faulting. Illite-chlorite alteration has incipiently overprinted early-stage potassic alteration.

At Huinquintipa, weakly altered to unaltered gravel fragments are cemented by chrysocolla and accessory copper wad. The mineralised area terminated abruptly at the transition from the palaeochannel into a small palaeobasin (1.5 km wide, 100 m deep). Munchmeyer (1996) suggested that increasing pH (due to rock-fragment reaction and possibly fluid mixing) triggered deposition of exotic copper at Huinquintipa. The fluids were strongly diluted when they entered the palaeobasin preventing further significant copper precipitation.

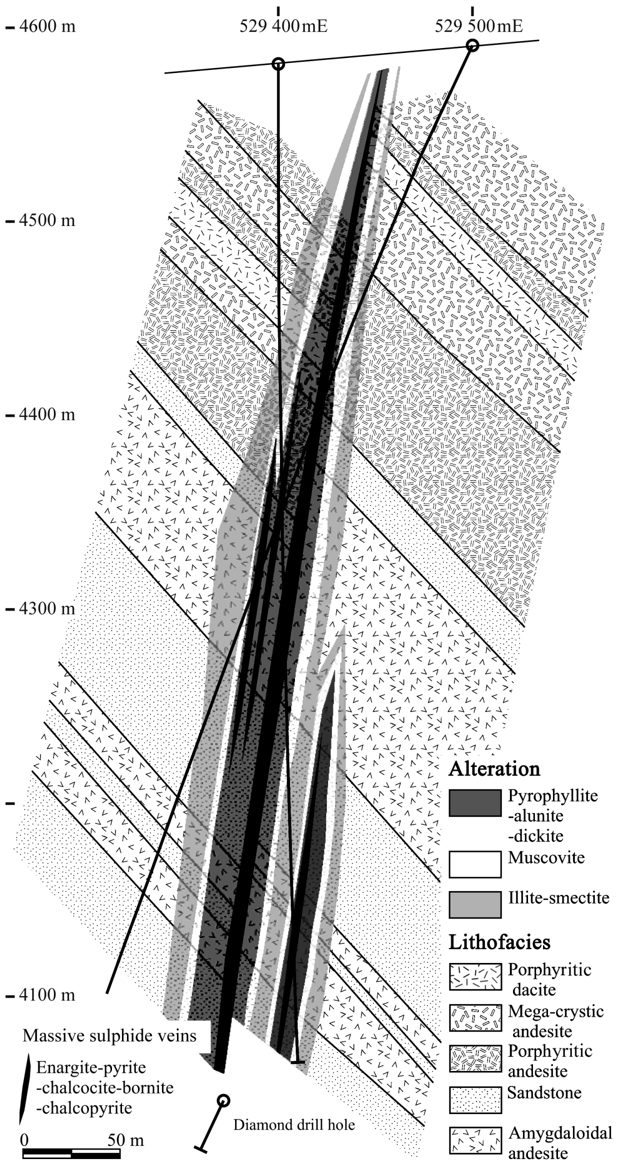


Figure 7: ***East-west cross-section through the La Grande veins*** *(from Masterman, 2003)*. The subvertical veins cut coherent volcanic rocks, interbedded with thick (10-50 m) sedimentary units. The rocks dip 40º to the northeast. Amygdaloidal andesite, interbedded with crystal-sandstone at the bottom of the sequence, are overlain by porphyritic and mega-crystic andesite, and porphyritic dacite. Hydrothermal alteration of the wall rocks is typically restricted to a zone, 25 m wide, either side of the veins, but reaches 50 m in the amygdaloidal andesite. Alteration zoning is characterised by pyrophyllite-alunite-dickite next to the vein, surrounded by muscovite that grades out to an illite-smectite fringe. The volcanic rocks are altered to epidote-chlorite beyond the zone of illite-smectite alteration. Vein minerals are pyrite, enargite, chalcocite, and bornite. The vein has a maximum thickness of 15 m, and averages 30 wt. % Cu, 70 g/t Ag and 0.8 g/t Au.

La Grande, Capela and Poderosa Cu-Ag-Au Veins

The mineralisation and alteration styles at La Grande, Capela and Poderosa are similar to the late-stage hydrothermal veins at Rosario. The distribution of these vein systems is shown in Figs. 4 and 5. At La Grande, massive sulphide veins consist of pyrite-bornite-chalcocite-enargite with accessory mawsonite and colusite (Masterman 2003). Alteration facies consist of proximal advanced argillic associations (pyrophyllite-alunite-dickite) that grade outward through sericite-quartz to epidote-chlorite alteration (Fig. 7; Masterman, 2003).

The Capela vein group occurs southeast of Rosario and is characterised by a series of massive pyrite veins, locally enriched in copper. The copper-silver veins at Poderosa lie along a NNW-trending structure that is rotated parallel to the Rosario Fault at the Rosario deposit. Vein sulphide associations consist of bornite-tennantite-chalcopyrite-enargite-pyrite (Munchmeyer *et al.,* 1984).

Monctezuma Ag Vein

The Monctezuma intermediate-sulphidation vein dips subvertically to the west and has been traced along surface and intersected in drill holes over a total strike length of 7 km. The vein varies from 1 to 5 m in width, and crops out as banded, cockade quartz that has been impregnated by manganese oxides and limonite. Below the base of surface oxidation, sphalerite, pyrite, galena and chalcopyrite are found, with accessory polybasite, argentopyrite, argentite, stephanite, tetrahedrite, and native silver and gold in a quartz-rhodochrosite gangue. In a 1 km segment of the vein, several Collahuasi drill holes have intersected a narrow (20 to 30m) vertical enrichment zone that occurs at the base of oxidation. This interval grades between 500 and 1000 g/t Ag, and passes down dip into hypogene mineralisation grading 200 to 500 g/t Ag. (Munchmeyer *et al.,* 1984).

Ujina Porphyry Cu-Mo Deposit

Geological Relationships

The host rocks at Ujina belong to the volcanic rocks of the Collahuasi Formation and are broadly correlated with those at Rosario. The Ujina stratigraphy consists of a thick basal andesite (possibly several flows) overlain by rhyolite and sedimentary breccia (Fig. 8a; Bisso *et al.,* 1998). Two principal feldspar-quartz-biotite porphyry intrusions are recognised at Ujina. The main host intrusion is the Ujina Porphyry which comprises a cylindrical granodiorite stock (1200 m in diameter) intruded by a series of north- and northwest-trending granodiorite dykes assigned to the Inca Porphyry unit (Bisso *et al.,* 1998). The relationship between the two intrusions is shown in cross section in Fig. 8a. The highest hypogene copper grades are associated with the Ujina Porphyry which is altered to K feldspar + biotite and muscovite-illite-quartz-chlorite-pyrite. The weakly mineralised Inca Porphyry is interpreted to have intruded the Ujina Porphyry before the cessation of hydrothermal activity.

Deposit	Stage	Vein fill	Wall-rock alteration halo
Rosario[1]	*Porphyry style*		
	Pre-ore	Magnetite	Disseminated magnetite
	Early stage (I)	Quartz + biotite + albite + chalcopyrite + pyrite	Biotite-albite
	Early stage (II)	Quartz + K feldspar + chalcopyrite + bornite ± biotite ± albite	K feldspar ± biotite ± albite
	Transitional	Quartz-molybdenite	
	Intermediate stage	Quartz + pyrite ± chalcopyrite	Illite-chlorite
	High-sulphidation epithermal style		
	Late stage (I)	Pyrite-quartz-alunite	Quartz-alunite
	Late stage (II)	Bornite + chalcopyrite + chalcocite	
	Late stage (III)	Tennantite + enargite	Pyrophyllite-dickite near veins; muscovite distal from veins
Ujina	*Porphyry style*		
	Early stage	Quartz + chalcopyrite + bornite	K feldspar ± biotite
	Intermediate stage	Quartz + molybdenite	White mica + quartz ± chlorite
	Late stage	Pyrite + chalcopyrite ± quartz	White mica + quartz

[1] Modified from Lee (1994).

Table 2: ***Vein and Alteration Mineral Paragenesis at Rosario and Ujina.***

Alteration and Mineralisation

The alteration and mineralisation paragenesis is presented in Table 2, while the distribution of alteration assemblages is shown in Fig. 8b. In contrast to Rosario, there are two main stages of hypogene mineralisation and alteration at Ujina. The early-stage potassic alteration, centred on the Ujina Porphyry, is characterised by a K feldspar core that passes out to biotite alteration (Fig. 8b). Accessory calcite has been recognised in association with hydrothermal biotite and K feldspar. Ore minerals associated with the potassic alteration include disseminated and veinlet-style chalcopyrite and bornite. Quartz-molybdenite veins, which lack recognisable alteration haloes, cut the early-stage veins and are themselves cut by the main-stage veins. The main-stage veins consist of pyrite-chalcopyrite-quartz surrounded by illite-chlorite alteration envelopes. Kaolinite and smectite occur in patches across the top of the Ujina alteration system, and are possibly supergene.

Hypogene sulphide mineralisation at Ujina is concentrically zoned about the Ujina Porphyry (Bisso *et al.,* 1998). DeBeer and Dick (1994) described a low-sulphide core of chalcopyrite-bornite grading outwards through chalcopyrite-pyrite to an outer pyrite shell. Hypogene copper distribution is also concentrically zoned, with the highest Cu grades forming an annulus about the low-sulphide potassic core (Fig. 8b; Bisso *et al.,* 1998). This high-grade zone coincides with the cylindrical contact between the Ujina Porphyry and the surrounding Collahuasi Formation host rocks (Fig. 8b).

Geochronology

New geochronologic data from Masterman *et al.,* (2004) constrain the ages of hydrothermal activity in the Rosario and Ujina deposits. An $^{40}Ar/^{39}Ar$ age of 34.4 ±0.3 Ma was obtained for igneous biotite in the Rosario Porphyry that hosts copper mineralisation at the Rosario deposit. Illite and hypogene alunite from separate overprinting alteration events yielded $^{40}Ar/^{39}Ar$ ages of 34.5 ±0.5 Ma and 32.6 ±0.3 Ma, respectively. A Re-Os age of 33.3 ±0.2 Ma for molybdenite at Rosario is slightly younger than the $^{40}Ar/^{39}Ar$ age of illite, but older than the alunite. An $^{40}Ar/^{39}Ar$ age of 32.7 ±1.6 Ma for hypogene alunite from the La Grande copper-silver-(gold) vein south of Rosario is indistinguishable from the age of Rosario alunite. At Ujina, the $^{40}Ar/^{39}Ar$ age of igneous biotite for the Ujina Porphyry that hosts copper mineralisation is 35.2 ± 0.3 Ma. By contrast, the post mineralisation Inca Porphyry yielded a biotite $^{40}Ar/^{39}Ar$ age of 34.7 ±0.3 Ma.

The age of igneous biotite in the Rosario Porphyry implies that porphyry-style ore and alteration minerals in the Rosario deposit had formed by 34.3 Ma. The ages of alunite at Rosario and La Grande indicate that a second discrete episode of hydrothermal activity was superimposed, 1.8 ±0.4 m.y. later, overprinting the earlier-formed porphyry Cu system. Hydrothermal activity at Ujina is constrained by the $^{40}Ar/^{39}Ar$ ages of igneous biotite in the pre- and post-mineralisation intrusions and occurred during a minimum interval of 0.5 ±0.4 m.y. The biotite granite at La Profunda, 1.5 km east of Ujina, has an igneous biotite age of 81.2 ±2.9 Ma, indicating that this intrusion is unrelated to the mineralised Eocene-Oligocene porphyry intrusions at Ujina, Rosario and Quebrada Blanca.

Historical Mining

Evidence of the earliest exploitation of copper at Collahuasi was identified during environmental baseline studies (von Fersen, 1993). Archaeologists identified an important Inca settlement, probably dating from around 1400 A.D., just a few kilometres from Collahuasi. Within these ruins a copper smelting facility was located, along with crude copper jewellery.

The first recorded production comes from the 1890's when 20 000 tonnes of silver ore were mined and shipped from the Monctezuma veins. Underground mines were developed at La Grande in 1899 and shortly afterwards at the copper-rich Poderosa vein system (Figs. 4 and 5). Ore grades from the La Grande and Poderosa vein systems

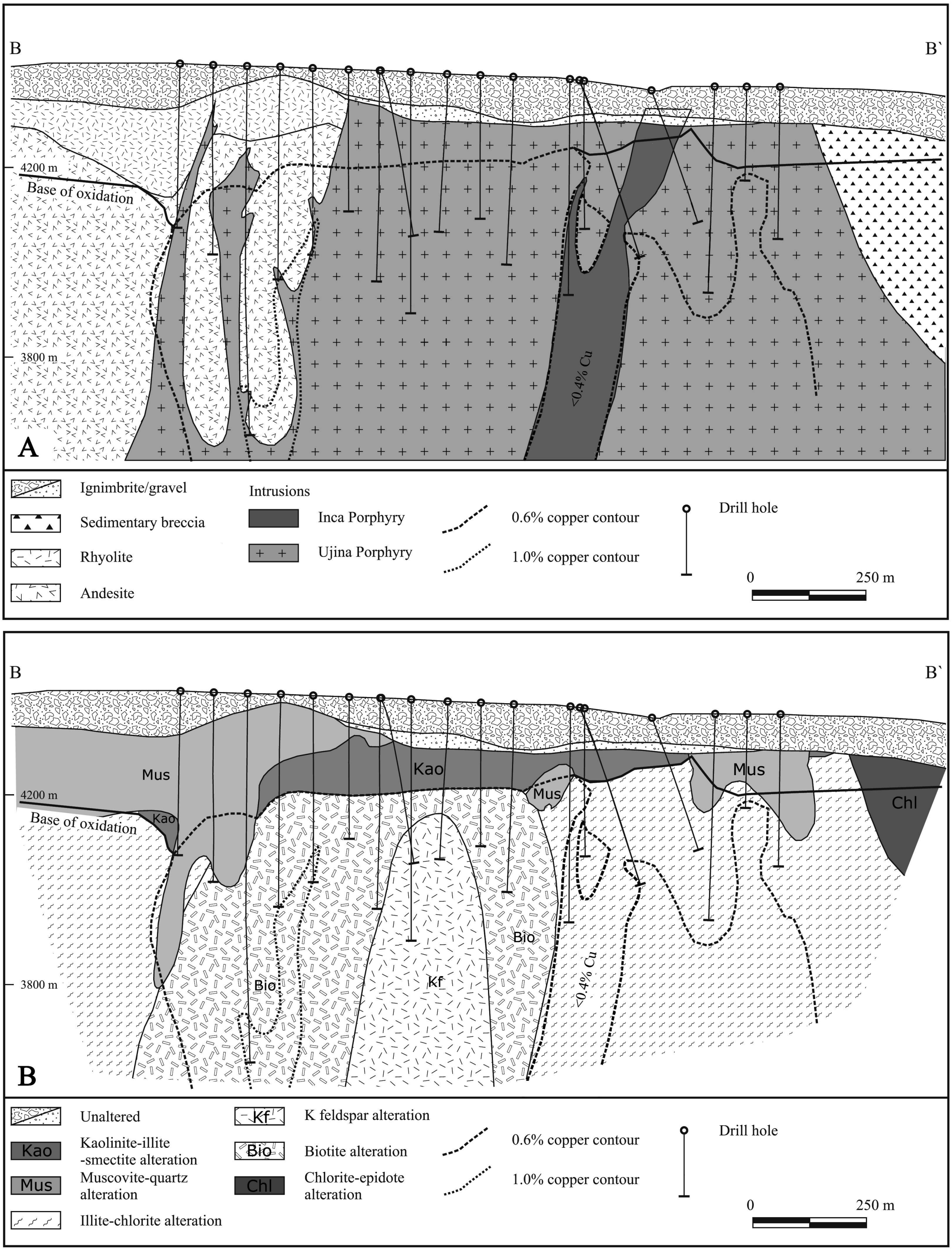


Figure 8: ***Northeast-southwest section through the Ujina deposit.***

A - ***Geology*** *modified from Bisso et al. (1998)*. The highest hypogene copper grades occur in the Ujina Porphyry, whereas the lowest grades (< 0.4% Cu) are spatially associated with the post-mineralisation Inca Porphyry. This has resulted in reverse copper grading, with the highest grades around the edges of the Ujina Porphyry.

B - ***Alteration*** *(Compañia Minera Doña Inés de Collahuasi, 1993, Collahuasi prefeasability study, Internal Report, Compañia Minera Doña Inés de Collahuasi, Santiago, 27 p.)*. Early biotite and K feldspar alteration, preserved on the northwest edge of the Ujina Porphyry, coincides with the highest grades. White mica-chlorite alteration has overprinted biotite and K feldspar altered rocks. Chlorite-epidote altered rocks occur on the margins of the intrusive centre.

averaged between 23 and 32% Cu plus 200 to 300 g/t (7 to 10 ounces/ton) Ag. A spur line to Poderosa and La Grande from the Antofagasta-Bolivia railroad was completed in 1907. At this time, more than 15 companies were exploring and developing vein type mineralisation in the district. Because of the continuity of the Poderosa vein, it became the largest producer in the district, and in 1910, produced 23 241 tonnes grading 21.5% Cu and 200 g/t (7 oz/ton) Ag. In the same year the total district production was 41 237 tonnes grading 22.65% Cu, accounting for 25% of the entire annual Chilean output. During the height of activity between 1907 and 1920, over 2000 people lived and worked at Collahuasi.

During the early part of the Twentieth Century, the underground mines at La Grande and Poderosa were operated by French and English companies. In 1923 the operations were merged to form the Poderosa Mining Company which continued to extract copper ore until 1930, when, due to low prices brought on by the depression, the mines were forced to close. Until that time, the copper veins at Collahuasi represented the third most important copper producer in Chile.

The Quebrada Blanca area was worked for gold by artisanal miners in the period from 1905 to 1930, during the heyday of the Poderosa Mining Company at Collahuasi. However, it was not until the late 1950's that significant attention returned to the Quebrada Blanca area when the Chilean subsidiary of Anaconda, the Chile Exploration Company, pegged claims over the area (Hunt and Bratt, 1981). The target was chosen for follow-up on a regional airborne colour photography survey along the West Fissure Fault System. Geologists from the Chile Exploration Company produced the first geological maps and predicted the existence of a secondary enrichment blanket (Hunt and Bratt, 1981).

Modern Exploration

In 1973, the Chilean government invited the Superior Oil/ Falconbridge group to consider investing in the copper industry, and provided a group of eight prospects from which to choose. A joint venture controlled by Superior Oil was formed and in 1977 the Quebrada Blanca deposit was chosen for detailed investigation, based on the results of previous work by Anaconda. Although Codelco drilled the first hole into Quebrada Blanca, the deposit was not delineated until the Superior Oil/Falconbridge Group optioned the property from the Chilean authorities. The Rosario and Ujina areas were optioned from private interests and exploration subsequently led to the discovery of the Rosario porphyry system in 1979. In response to corporate restructuring and difficult economic times, the project was recast as a joint venture between Falconbridge, Shell Chile and Chevron. This joint venture was operated by a management company which was controlled by Chevron and Shell Chile and it conducted the exploration that eventually led to the discovery in 1991 of the economically important Ujina porphyry deposit. The main exploration tools used were induced polarisation, surface mapping, and reverse circulation drilling.

Discussion and Conclusions

The Collahuasi deposits, situated at the northern end of the late Eocene-early Oligocene porphyry belt, are spatially associated with the Domeyko Fault System, although their emplacement was not directly controlled by this structure. Instead, the Quebrada Blanca and Ujina porphyry centres were formed contemporaneously on the western and eastern edges respectively of the Palaeozoic basement horst between the West-Fissure-Domeyko and Loa Faults. This was followed by formation of the Rosario Porphyry in the centre of the basement horst, suggesting that the emplacement mechanism was controlled by the evolution of district-scale brittle structures within the Collahuasi district during the late Eocene-early Oligocene.

Early potassic and late low pH hydrothermal alteration at Rosario-La Grande clearly indicate a significant contribution from a magmatic-hydrothermal reservoir. No data are currently available that indicate external fluids contributed significantly to the metal budgets of the Collahuasi porphyry deposits. The superimposition of a late advanced argillic assemblage onto early potassic alteration indicates that they were discrete events (Masterman, 2003; Masterman *et al.,* 2004). Telescoped epithermal mineralisation required rapid exhumation of the Rosario intrusive complex to the crustal level of the epithermal environment. Exhumation and erosion of the overlying pile at Quebrada Blanca and Ujina to depths of the epithermal environment are interpreted to have been a district-wide event that was contemporaneous with epithermal mineralisation at Rosario. Certainly, the Ujina deposit had been eroded to at least the top of the hypogene sulphides by the middle Miocene, as oxidation of pyrite is inferred to have formed alunite, thus providing a minimum age of 15 Ma for the supergene enrichment in the Collahuasi district.

The discovery of the Collahuasi district porphyry copper deposits resulted from the consistent use of a well established mineral deposit model along the structural extension of a significantly mineralised district. Quebrada Blanca, the best exposed was discovered first. Rosario, which is more deeply buried, took longer to be recognised, while Ujina, that was partially obscured by recent gravels and ignimbrite, and which exhibited the fewest clues, was found last. The discovery of all three deposits could have been accomplished without high technology tools such as IP and Landsat images, but these tools added a layer of information to the geological observations that validated the working model.

Acknowledgements

We are grateful to the Centre for Ore Deposit Research (CODES) Special Research Centre, AMIRA International, CSIRO Exploration and Mining, and Compañia Minera Doña Inés de Collahuasi (CMDIC) for providing financial, logistical and technical support for this project. We gratefully acknowledge CMDIC SCM for provision of field support and access to the Collahuasi deposits, with special thanks to Manuel Durán, Héctor Lagunas, Ryan Crosbie, Claudio Bisso and Luciano Malhue.

References

Bisso, C.B., Duran, M. and Gonzales, A.A., 1998 - Geology of the Ujina and Rosario copper porphyry deposits Collahuasi district, Chile: *in* Porter, T.M. (Ed.), Porphyry and Hydrothermal Copper and Gold Deposits: A Global Perspective, *PGC Publishing,* Adelaide, pp. 133-148.

Clark, A.H., Archibald, D.A., Lee, A.W., Farra, E. and Hodgson, C.J., 1998 - Laser probe $^{40}Ar/^{39}Ar$ ages of early- and late-stage alteration assemblages, Rosario porphyry copper-molybdenum deposit, Collahuasi District, I Region, Chile: *Economic Geology,* v. 93, pp. 326-337.

DeBeer, L.J. and Dick, L.A., 1994 - Development of the Collahuasi copper deposits, a world class copper project in the Andes of Northern Chile: Proceedings Volume, Mining Latin America, Santiago, Chile, 1994, *Institute for Mining and Metallurgy,* pp. 181-195.

Dick, L.A., Chavez, W.X., Gonzales, A. and Bisso, C., 1994 - Geologic setting and mineralogy of the Cu-Ag-(As) Rosario vein system, Collahuasi District, Chile: *Society of Economic Geologists Newsletter,* pp. 1, 6-11.

Hedenquist, J.W., 1987 - Volcanic-related hydrothermal systems in the Circum-Pacific basin and their potential for mineralisation*: Mining Geology,* v. 37, pp. 347-364.

Hunt, J.P. and Bratt, J.A., 1981 - Quebrada Blanca Chile: An Enriched Porphyry Copper Deposit. Presentation to the AIME Annual Meeting Chicago, Illinois, February 22-26, 1981.

Hunt, J.P., Bratt, J.A. and Marquardt, L., 1983 - Quebrada Blanca, Chile: an enriched porphyry copper deposit: *Mining Engineering,* v. 35, pp. 636-644.

Lee, A.W., 1994 - Evolution of the Rosario copper-molybdenum porphyry deposit and associated copper-silver vein system, Collahuasi District, I Region, Northern Chile: *Unpub. Masters thesis, Queen's University, Kingston, Ontario,* Canada, 75p.

Masterman, G.J., 2003 - Structural and geochemical evolution of the Rosario Cu-Mo porphyry deposit and related Cu-Ag veins, Collahuasi district, Northern Chile: *Unpub. PhD thesis, University of Tasmania,* Tasmania, Australia, 253p.

Masterman, G.J., Cooke, D.R., Berry, R.F., Clark, A.H., Archibald, D.A., Mathur, R., Walshe, J.L. and Duran, M., 2004 - $^{40}Ar/^{39}Ar$ and Re-Os geochronology of porphyry copper-molybdenum deposits and related copper-silver veins in the Collahuasi district, northern Chile: *Economic Geology,* v. 99, pp 673-690.

Masterman, G.J., Cooke, D.R., Berry, R.F., Walshe, J.L., Lee, A.W. and Clark, A.H., in press - Fluid Chemistry, Structural Setting and Emplacement History of the Rosario Cu-Mo Porphyry and Cu-Ag-Au Epithermal Veins, Collahuasi District, Northern Chile: *Economic Geology*, v. 99, pp. 673-690.

Mathur, R., Ruiz, J. and Munizaga, F., 2000 - Relationship between copper tonnage of Chilean base-metal porphyry deposits and Os isotope ratios: *Geology,* v. 28, pp. 555-558.

Moore, R.L. and Masterman, G.J., 2002 - The geology and corporate discovery history of the Collahuasi district porphyry copper deposits, Chile: Giant Ore Deposits: Characteristics, genesis and exploration, *CODES Special Publication 4, University of Tasmania,* Hobart, Australia, pp. 23-50.

Munchmeyer, C., 1996 - Exotic deposits: products of lateral migration of supergene solutions from porphyry copper deposits, *in* Camus, F., Sillitoe, R. H., and Petersen, R., (Eds.), Andean Copper Deposits: New Discoveries, Mineralization, Styles and Metallogeny: *Society of Economic Geologists,* Special Publication No. 5, pp. 42-58.

Munchmeyer, C., Hunt, J.P. and Ware, H., 1984 - Geologia del Distrito de Collahuasi y del porfido cuprifero Rosario: *Internal Report, Compania Dona Ines de Collahuasi,* Santiago, 84p.

Muntean, J.L. and Einaudi, M.T., 2000 - Porphyry gold deposits of the Refugio district, Maricunga Belt, Northern Chile: *Economic Geology,* v. 95, pp. 1445-1472.

Rowland, M.G., 1998 - The role of magmatic processes in the development of hypogene mineralization at Quebrada Blanca, northern Chile: *Unpub. PhD thesis, University of London*, England, 240p.

Rowland, M.G. and Wilkinson, J.J., 1998 - A hybrid origin for porphyritic magmas sourcing mineralizing fluids, *in* Hudson, A., (Ed.), Water-Rock Interaction: *Balkema,* Rotterdam, pp. 569-573.

Rowland, M.G. and Wilkinson, J.J., 1999 - Significance of intermediate stage veins at Quebrada Blanca, Chile, *in* Stanley, C.J. *et al.,* (Eds.), Mineral Deposits: Processes to Processing: *Balkema,* Rotterdam, pp. 99-102.

Shatwell, D., 1995 - Accreted terranes and porphyry copper deposits in the Central Andes: Pacific Rim Congress 1995, Sydney, *AusIMM,* Melbourne, pp. 515-520.

Vergara, H., 1978 – Cuadrangulo Ujina, Region de Tarapacá, Carta Geológica de Chile, Escala 1:50,000; Santiago, *Instituto de Investigaciones Geológicas*, 63p.

Vergara, H.L. and Thomas, A.N., 1984 - Hoja Collacagua, Region de Tarapaca, Carta Geologica de Chile, Escala 1:250 000: *Servicio Nacional de Geologia y Mineria,* Santiago, 79p.

von Fersen, N., 1993 - A discovery history of Collahuasi. Presentation to the Prospectors and Developers Association Convention, Toronto, Canada, March 1993.

White, N.C. and Hedenquist, J.W., 1990 - Epithermal environments and styles of mineralization: variations and their causes, and guidelines for exploration, *in* Hedenquist, J.W., White, N.C. and Siddeley, G., (Eds.), Epithermal Gold Mineralization of the Circum-Pacific: Geology, Geochemistry, Origin and Exploration, II. *Journal of Geochemical Exploration,* v. 36, pp. 445-474.

White, N.C. and Hedenquist, J.W., 1995 - Epithermal gold deposits: Styles, characteristics and exploration, *Society of Economic Geologists Newsletter,* v. 23, pp. 1, 9-13.