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DISCOVERY OF THE AGUA RICA PORPHYRY Cu-Mo-Au DEPOSIT, CATAMARCA PROVINCE, NORTHWESTERN ARGENTINA.

PART I: EXPLORATION AND DISCOVERY

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PART 2: GEOLOGY

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Abstract: The Agua Rica deposit consists of two porphyry copper centres (Quebrada Seca-Trampeadero and Melcho) associated with several porphyritic stocks and hydrothermal breccias of late Miocene-early Pliocene age that intrude a basement of ?Precambrian to early Palaeozoic metasedimentary rocks and Palaeozoic granitoids. Hypogene Cu-Au mineralization is present in porphyry-style and epithermal assemblages. Main-stage Cu-Au mineralization is of epithermal, high-sulphidation type and associated with pyrite-rich associations of covellite, chalcopyrite, bornite, and enargite emplaced in advanced argillic alteration. The alteration is dominated by sericite, pyrophyllite, zunyite, dickite, kaolinite, alunite, vuggy silica, and silicification. Supergene Cu-Au mineralization is present in an immature chalcocite blanket that consists of an upper part rich in chalcocite underlain by a covellite-bearing zone.

Hypogene Cu-Au mineralization at Agua Rica formed over a period of 1.4 m.y. between 6.29 and 4.88 Ma. Syn-mineralization uplift and erosion, induced by regional tectonism, caused the superposition of main-stage Cu-Au mineralization over higher-temperature, deeper-seated K silicate alteration-mineralization assemblages. Supergene chalcocite formation, dated at 3.9 Ma, was favoured by the pyrite-rich, main-stage Cu-Au mineralization and advanced argillic alteration associated with hydrothermal telescoping, and the pluvial regime of the elevated topography of the area.

Twenty-nine years elapsed between when the existence of porphyry copper mineralization was first recognised in the area and when the real dimensions of the system were realised. Geological mapping, coupled with rock chip geochemistry and relict sulfide studies, resulted in the siting of the discovery holes. The commitment and tenacity of the exploration team and the backing of company management at a time when results were discouraging played an important role.

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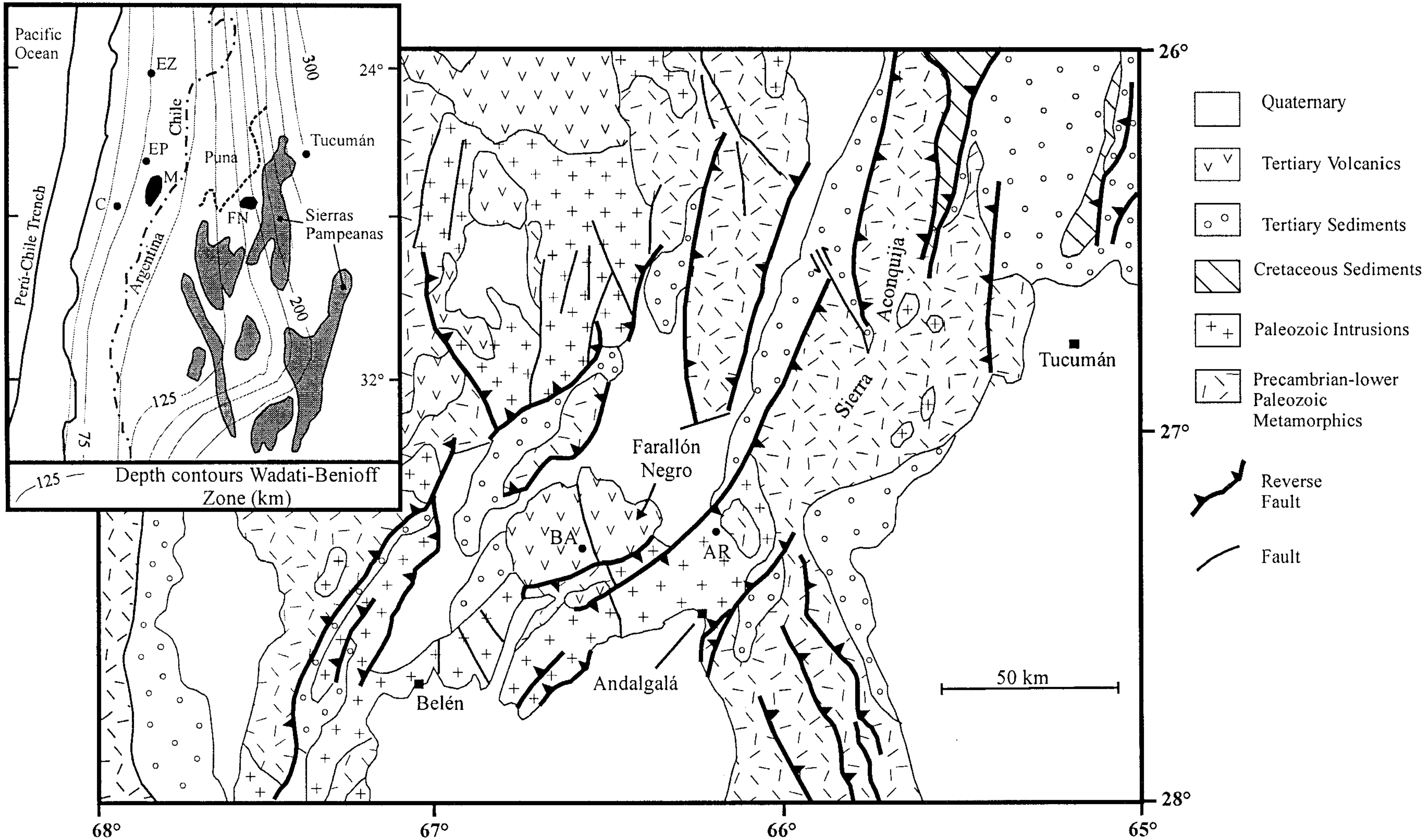

Figure 1. Location of the Agua Rica Deposit and Farallón Negro district in the regional geological context of northwestern Argentina. Regional geology simplified from Allmendinger et al. (1983). Contours on the Wadati-Benioff zone after Isacks (1998). Abbreviations: AR = Agua Rica; BA = Bajo de la Alumbrera; C = Candelaria; EP = El Salvador-Potrerillos; EZ = Escondida-Zaldivar; FN = Farallón Negro; M = Maricunga belt.

INTRODUCTION

The Agua Rica deposit (27°45' S Lat.; 66° 20' W Long.) is located in the Farallón Negro region of Catamarca province, approximately 25 km north of the town of Andalgalá, northwestern Argentina (Fig. 1). The project area, at an average altitude of 3,100 m, is characterized by the steep, rugged topography of the Sierra de Aconquija, which locally attains elevations of up to 5,500 m above sea level. The deposit is held in a joint venture between BHP Minerals (70%) and Northern Orion Explorations Ltd. (30%), and operated by BHP Copper, a business group of the Broken Hill Proprietary Company Limited (BHP).

The Farallón Negro region (Fig. 2) hosts one of the largest concentrations of mineral deposits known in Argentina, including at least nine porphyry copper centers and three epithermal base and precious metals deposits (Caelles et al., 1971; Sillitoe, 1973; Sasso and Clark, 1998). Bajo de la Alumbrera (780 million tonnes containing 0.52% Cu and 0.67g/t Au; Mining Journal Ltd., 1997) and Agua Rica (750 million tonnes containing 0.62% Cu; 0.037% Mo; 0.23g/t Au; see below) are among the largest copper resources known in Argentina.

The present contribution on Agua Rica outlines the exploration and discovery history, reviews the regional geology and metallogenesis, describes the deposit's geology, alteration and mineralization, and presents an interpretation of its evolution in the geologic context of the region. Comparisons with other deposits are made. This paper builds on the geological work by the authors during the early exploration phase by BHP that led to the discovery of the deposit (Hoyt and Rojas, 1993; Perelló, 1994; Rojas et al., 1994) and incorporates descriptions by Koukharsky and Mirré (1976) and post-discovery in-house work by BHP geologists (Fava and Etchart, 1995; Bratt, 1996; Marcet, 1996). A complete, up-to-date geological description of the deposit's geology will be the subject of a future contribution by the Agua Rica project staff.

PART I. EXPLORATION AND DISCOVERY

Historical Aspects

A minor tonnage of copper oxides was mined from small diggings on the Agua Rica property by a British company at the beginning of the century (1900-1915) and small amounts of high-grade material were hauled by mule to Andalgalá to be refined in artisanal smelters. Between 1918 and 1950 the area was referred to variably as Mina El Negro, Montenegro, and Cerro Rico by different geologists and considered to lack commercial interest.

In 1950, H. Navarro, a geologist from the nearby Capillitas mine visited the area during a guanaco hunting excursion and noticed the presence of covellite within altered rocks in the Quebrada Minas valley, close to the old workings. In 1959, miner and prospector F. Vera applied for a concession over the old workings, formed a small mining company and produced approximately 27 tonnes of hand-selected ore that was sold for smelting in Jujuy, northwestern Argentina. In 1963, in association with three friends, Vera founded the Compañía Minera Agua Rica and applied for claims Agua Rica I, II, and III around the old workings at Mina El Negro.

In 1965, Navarro returned from post-graduate training in Canada where he studied the geology of porphyry copper deposits. He revisited the area and confirmed the presence of an attractive porphyry system exposed in Quebrada Minas. In partnership with a group of friends and relatives, he then acquired Compañía Minera Agua Rica and renamed it Agua Rica Sociedad Anónima

Minera (ARSAM). He requested a further 24 exploitation concessions that he denominated Mi Vida (spanish for "My Life", an allusion that this would be the discovery of his life). ARSAM conducted some mapping and drilled six, small diameter core holes at Quebrada Minas that intersected only minor mineralization.

Early Exploration (1969-1973)

In 1969 ARSAM entered into agreement with the Argentinian subsidiary of Cities Service International Inc. (CITIES), a US based corporation, to explore the Mi Vida and Agua Rica claims. Between 1970 and 1972 CITIES conducted geological mapping and geochemical sampling over an area of 3x2 km, completed 140 m of underground workings, and drilled 38 helicopter-supported diamond drill holes totalling 8,000 m. The holes, mainly collared at the bottom of Quebrada Minas, intersected low-grade copper-molybdenum mineralization. In a small area at Quebrada Minas, three drill holes encountered a hydrothermal breccia with high-grade copper mineralization in the form of coarse, crystalline covellite and minor supergene chalcocite (Koukharsky and Mirré, 1976). The generally discouraging results together with the unstable political climate in Argentina at the time, led CITIES to withdraw from the project in 1973. During their exploration program, CITIES requested 34 new mining claims, a third of which was secured by ARSAM, who maintained control of the property for the next 20 years.

Modern Exploration

BHP established an exploration office in Argentina in 1986. Previous literature research by the geologist involved, identified Mi Vida as one of a number of prospects worth inspecting (Cabello, 1983), but this was not followed up at the time because of other exploration priorities.

In early 1992 Recursos Americanos Argentinos (RAA), a subsidiary of American Resources Corporation (ARC) of the U.S.A., signed an option agreement with ARSAM to acquire 100% of ARSAM's shares over a period of five years, for a total of US$ 9.5 million. Around the same time, the same BHP geologist visited the area with former CITIES geologist M. Koukharsky. He observed the favorable alteration and mineralization exposed along Quebrada Minas, and decided to apply for a 5,000 hectare exploration concession around the property maintained by ARSAM. This was done in September 1992 and title was granted to BHP in June 1993.

In early 1993, ARC approached several companies, including BHP, with a portfolio of several exploration projects in Argentina and Uruguay that included Mi Vida. The BHP geologist reviewed the literature and concluded that Mi Vida was the most attractive of all (Cabello, 1993). In May 1993, BHP and ARC professionals visited ten of the properties held by ARC in Argentina. Based on the field observations and on newer assays from some of the old CITIES drill holes, which showed several intervals with significant gold grades, it was concluded that Mi Vida was the only property of potential interest to BHP (Hoyt and Rojas, 1993).

A farm-in agreement was negotiated between BHP and ARC over the period June to September 1993 whereby BHP had two years to earn a 70% interest in the property. Field work by BHP staff commenced in October 1993 and consisted of geological mapping of an area of 3.5x2.5 km at 1:2,500 scale accompanied by rock chip geochemical sampling and relict sulfide studies. All available core from CITIES earlier work was re-logged and sampled. Approximately 6 km of mountain roads to access the property were constructed and a camp was established on site along with a support office in Andalgalá.

Collaborative efforts between BHP staffs from Argentina and Chile resulted in the identification of the main geological elements of the Agua Rica project and in a better definition of the main targets of significance for BHP, including the precious metal mineralization associated with epithermal assemblages in the then denominated Quebrada Seca Norte (now Quebrada Seca) and Trampeadero zones, and the porphyry-style mineralization in the Quebrada Seca Norte and Melcho zones (Perelló, 1994; Rojas, 1994). These targets were defined basically on geological and geochemical grounds. The original plan was to drill broadly spaced holes throughout the mapped area but, due to constraints on access and the high cost of road construction, it was decided that an initial round of drilling would first test the epithermal mineralization potential. This was also supported by the high copper and gold values obtained from the re-assayed CITIES core.

Six diamond drill holes (AR1 to AR6) totalling 2,013 m were completed between May and July 1994. Two of these holes failed to reach the target due to operational problems and three detected significant gold and copper values over short intervals (AR1, AR2 and AR6). The progress of work on site was reviewed during a visit in late May by BHP staff from the Argentina and Chile offices. The drilling results thus far, along with geometric considerations, suggested that the epithermal target was likely to be too small. It was also demonstrated that a large surface rock chip gold anomaly (0.3 ppm Au) over the previously identified Quebrada Seca Norte zone remained to be tested (Harman, 1995). This would necessitate further significant and expensive road construction.

In early August 1994 in BHP's Mendoza office, all the available geological, geochemical, and drilling data from the project were reviewed and interpreted cross-sections were drawn-up. These suggested that potential for a chalcocite blanket target, not previously identified, existed in the Quebrada Seca Norte zone. Two additional drill holes were proposed (Rojas et al., 1994) and received management endorsement. At the same time, 3D computer modelling of all available surface geochemistry and drilling information, helped to better define the size of the target.

Access road construction began in September and holes AR7 and AR8 were collared and completed in November 1994. Hole AR7 intersected 336 m averaging 0.7% Cu, 0.22 ppm Au and 0.058% Mo, and hole AR8 returned 108 m of 0.8% Cu, 0.52 ppm Au, and 0.031% Mo. Both holes intersected leached capping material that averaged 0.02% Cu, 0.59 to 0.69 ppm Au, and 0.021 to 0.024% Mo.

AR7 and AR8 are considered to be the discovery holes of Agua Rica and confirmed that a system of significant dimensions had been found. Work resumed with new roadwork in Quebrada Seca Norte to allow access for the drilling of hole AR9. This hole intersected 302 m of 0.93% Cu and 0.36 ppm Au below 20m of leached cap thereby confirming the discovery and upgrading the project. The exploration work was then expanded and considerable roadwork was completed over the Trampeadero zone. Further surface mapping, drilling, and geochemistry outlined the extent of the porphyry-style mineralization and led to an extensive drilling program. A low-level aeromagnetic survey was flown to outline the extent of the system.

By July 1995, 28 drill holes totalling 10,197 m had been completed and BHP had exercised its option with ARC. The project was then taken over by an advanced project team to complete

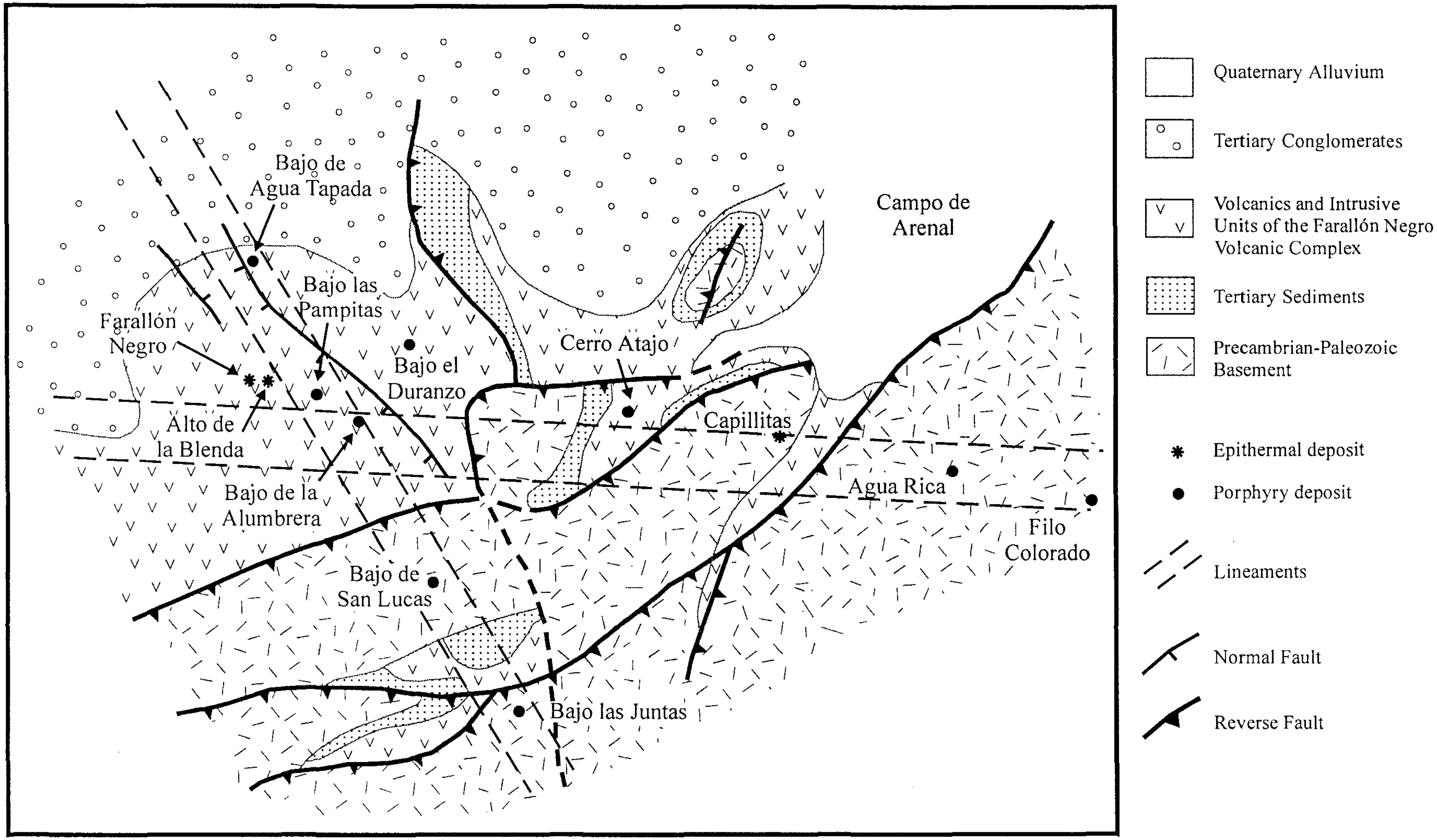

Figure 2. Simplified geologic map of the Farallón Negro region with location of ore deposits and prospects. Simplified from Sasso and Clark (1998).

delineation of resources and pre-feasibility studies. Also in 1995, Northern Orion Explorations Ltd. acquired 100% of RAA from ARC thereby becoming a 30% participating partner at Agua Rica.

Summary

Although the copper mineralization in the spectacular outcrops of the Agua Rica area was first detected early this century, the existence of porphyry copper mineralization was not recognized until 1965. Formal exploration was not conducted until three years later, when drilling targeted zones of favorable geological and geochemical characteristics that roughly coincided with areas of exposed mineralization. Although this early exploration effort identified evidence for supergene copper enrichment, the economic and political climate in Argentina along with the challenging location of the deposit, led to early curtailment of the program. Twenty more years then elapsed, before political, economic, and mining law reforms created a climate in which the real potential of the system was recognized. A submittal by a junior company related to an area which had already been identified from literature review and field inspection. Geological mapping and interpretation, especially of the crosscutting alteration events, rock types and leached capping, coupled with rock chip geochemistry and relict sulfide distribution, played an important role in deciphering the complex geology of the deposit and resulted in the siting of the discovery holes. Discovery was made partly because of the commitment and tenacity of the exploration team and the backing of company management to see the project through under extremely difficult topographic and access conditions. A critical step was the evaluation of all the relevant geological and geochemical data in light of BHP's target size at a time when drilling results were generally discouraging.

Current Status

Currently the project is undergoing pre-feasibility studies. Two tunnels for bulk sampling purposes totalling 350 m are in progress, together with environmental studies, metallurgical test work, geological block modelling, and water exploration. Approximately 67,700 m of diamond drilling have been completed. The sum of measured, indicated, and inferred mineral resources as of February 1998 have been estimated as follows:

% Cu cut-off	Million Tonnes	% Cu	% Mo	g/t Au
1.0	60	1.31	0.040	0.35
0.7	167	0.99	0.036	0.32
0.4	750	0.62	0.037	0.23
0.2	1,714	0.43	0.032	0.17

PART II. GEOLOGY

Regional Geology and Metallogenesis

The region lies in the Andean foreland, at the transition between two regional provinces of Neogene age, the Puna and the Sierras Pampeanas (Allmendinger et al., 1983; Jordan et al., 1983) along the ca. 27° S Lat. parallel (Fig. 1). This transition zone coincides with a north-south discontinuity of the Wadati-Benioff zone from steeply (ca. 30°) to shallowly-dipping (Barazangi and Isacks, 1976), as well as with major breaks in Mesozoic and Cenozoic Andean geology, geomorphology, and metallogenesis (Sillitoe, 1974; Sasso and Clark, 1998). The Sierras

Pampeanas, of which the Aconquija block constitutes their northernmost expression, is comprised of a series of high, discontinuous, fault-controlled, NS-trending mountain ranges of Precambrian and lower Paleozoic crystalline basement separated by wide, flat basins (Fig. 1). In the Sierra de Aconquija, this basement includes a series of schists and hornfelses of upper greenschist metamorphic facies (the Sierra de Aconquija complex; Koukharsky and Mirré, 1976), intruded by a multiple-phase, syenogranite to monzogranite batholith of peraluminous, calc-alkaline affinities and Ordovician-Silurian age (the Capillitas batholith; Caelles et al., 1971). The basins, blanketed by Quaternary deposits, locally expose Miocene-Pliocene continental terrigenous sequences with minor interbedded volcanic rocks, and Pleistocene boulder conglomerates (Allmendinger, 1986). Remnants of Miocene stratovolcanic edifices, including the Farallón Negro volcanic complex, are also a characteristic of the southern Puna region.

The Farallón Negro volcanic complex (Figs. 1 and 2), is characterized by multiple eruptive centers spread over an area of approximately 700 km^2 (Sasso and Clark, 1998). The complex is made up of several volcanic units, including lower basaltic, intermediate andesitic-dacitic, and upper pyroclastic members (Koukharsky and Mirré, 1976; Sasso and Clark, 1998), with ages between 12.56$\pm$0.36 and 6.72$\pm$0.08 Ma (Sasso and Clark, 1998). Stocks and dikes of dacitic to rhyolitic composition were emplaced between 8.56$\pm$0.48 and 5.16$\pm$0.05 Ma (Sasso and Clark, 1998). The volcanic units are shoshonitic or high-K calc-alkaline in composition (Allison, 1986).

The region is dominated by an array of NNE-trending, high-angle reverse faults of hundreds of kilometers along strike (Fig. 1) (Allmendinger et al., 1983). These faults, locally offset by NW-trending structures, control the present-day geomorphology of the region, including the up to 6,000 m high horsts of the Sierras Pampeanas. Regional NW-, NE-, and EW-trending lineaments are also apparent in the area (Fig. 2). Regional uplift and deformation commenced between 5 and 10 Ma (Allmendinger, 1986), continued between 2-3 Ma (Allmendinger, 1986), and remains active in the present (Jordan et al., 1983; Jordan et al., in press).

Porphyry copper and epithermal mineralization in the region is hosted by the Farallón Negro volcanic complex and its outliers (Fig. 2). The porphyry copper deposits of the Farallón Negro complex share a number of features, including their late Miocene age (between 8.56 and 6.75 Ma; Caelles et al., 1971; Sasso and Clark, 1998); an alteration-mineralization zoning consisting of a core of potassic alteration surrounded by phyllic and distal propylitic assemblages (Sillitoe, 1973; Sasso and Clark, 1998) that conforms closely to the porphyry copper geometry defined by Lowell and Guilbert (1970); hypogene copper mineralization associated with quartz-magnetite-chalcopyrite stockworks hosted by K-silicate alteration (Guilbert, 1995); anomalous to high gold contents in the copper ore (Sillitoe, 1979); cores of magnetite-rich assemblages (Sasso and Clark, 1998); and a general absence of economic supergene copper mineralization. Compared to other deposits of the district, the complex alteration-mineralization style, high molybdenum grades, and supergene copper mineralization at Agua Rica (see below) and the presence of large diatremes at Agua Rica and Capillitas, are distinct anomalies.

At the regional scale, hydrothermal deposits along the ca. 27° - 28° S Lat. host, over a length of >300 km, an unusual gold endowment by central Andean standards, including the progressively eastward-younging iron oxide copper-gold deposits of the early Cretaceous Candelaria-Punta del Cobre district; the gold-rich, late Eocene-early Oligocene porphyry copper and epithermal mineralization of the Potrerillos-El Hueso cluster; and the porphyry gold deposits of the early to middle Miocene Maricunga belt in Chile as well as the late Miocene-early Pliocene porphyry copper-gold and copper-molybdenum-gold mineralization of the Farallón Negro region, located approximately 500 km east of the Chile-Perú trench, in Argentina.

Agua Rica Geology, Alteration, and Mineralization

Geology

Two main porphyry copper systems are identified at Agua Rica (respectively Melcho and Quebrada Seca-Trampeadero) which are exposed over an area of approximately 2.5x2.0 km. They are located at the contact between two main basement units comprising the black schists and metasedimentary rocks of the Sierra Aconquija complex and a coarse-grained, microcline-rich, porphyritic granodiorite of the Capillitas batholith. Figure 3a portrays a simplified version of the geology of Agua Rica with emphasis on the main lithological units, structures, and porphyry copper centers. For simplicity, the Quaternary cover, dominated by colluvial sediments, soil, stream conglomerates (e.g., the Mi Vida Conglomerate of Koukharsky and Mirré, 1976), and ash-fall deposits, is omitted. Figure 4 is a simplified east-west cross-section through Quebrada Seca-Trampeadero.

The Melcho porphyry system is dominated by several porphyritic to equigranular intrusive phases described as syenodiorite and monzonite by Koukharsky and Mirré (1976). They have been field-termed amphibole-rich feldspar and quartz-feldspar porphyries and consist of plagioclase (~20-25%), amphibole (~10%), quartz (~10%), and locally large, up to 2 cm in size, K-feldspar poikilitic phenocrysts. Current understanding is that Melcho is made up of at least three phases of monzonitic composition (M. Leake, pers. comm., 1998).

The Quebrada Seca-Trampeadero system is made up of a series of porphyries that are roughly 0.5x0.5 km or smaller with an overall east-west alignment between the Quebrada Seca and Trampeadero areas. Multiple phases of both feldspar porphyry (FP) and quartz-feldspar porphyry (QFP) are apparent. Both FP and QFP phases display medium- to coarse-grained porphyritic textures dominated by plagioclase (~35%) with minor biotite and amphibole. QFP contains up to 20 vol. % quartz phenocrysts. An inter-mineral phase includes a coarse-grained hornblende-feldspar porphyry with conspicuous, up to 6 cm in length, subhedral to euhedral, poikilitic K-feldspar. Late-mineral phases possess coarse-grained porphyritic textures with abundant euhedral biotite. The groundmass of all FP and QFP phases is typically fine-grained to aphanitic. Contact relationships are complex in general, but evidence for continuity between porphyry phases of the two main areas of Figure 3a has been recently detected by deep drilling (>600 m; M. Leake, pers. comm., 1998). The presence of quartz, feldspars, and mafic minerals as principal phenocryst phases indicate an overall dacitic to monzonitic composition for the various porphyry intrusions.

Large volumes of hydrothermal breccias constitute an important feature of the geology of the Agua Rica deposit. These multiple-phase breccias (Perelló, 1994), originally interpreted as one body by Koukharsky and Mirré (1976), occur over an area of approximately 2 km^2 along a NW-trending axis parallel to the Quebrada Minas valley. Only the outline of the breccia complex is shown on Figure 3a. Main-stage breccia consists of several clast- and matrix-supported phases dominated by subangular blocks and rounded to subrounded, pebble- to boulder-size fragments. Where matrix-supported, the matrices are dominantly sand- to silt-size with minor tuffaceous material. Many fragments display "onion skin"-type hypogene exfoliation textures. Fragment

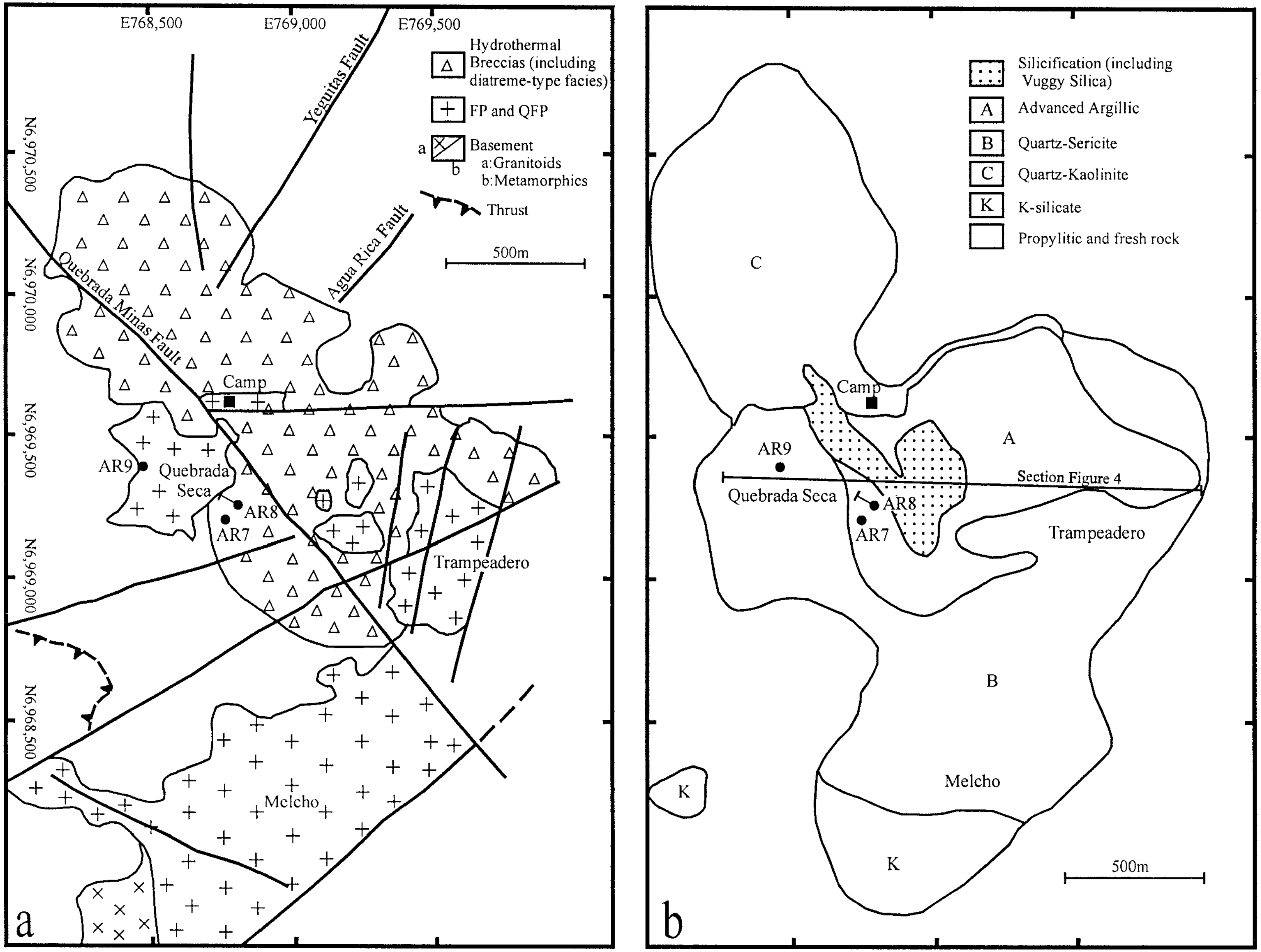

Figure 3. Simplified geology and alteration maps for the Agua Rica area. a) Geology; b) Hydrothermal alteration

composition varies according to host rock composition, including quartz-stockworked FP/QFP clasts in the vicinity of mineralized porphyries and metasedimentary clasts in proximity to basement rocks. Upward fragment transport is apparent in breccia phases that contain abundant, rounded, granitic fragments, which are probably derived from the Paleozoic granitic basement at depth. In general, the breccias display affinities with the magmatic-hydrothermal and phreatomagmatic categories of Sillitoe (1985).

Fine-grained clastic (tuffaceous?) dikes and pebble dikes of centimetric to metric dimensions are common. The fine-grained clastic dikes are dominated by a sand- to silt-size, locally laminated material. The pebble dikes display matrix-supported textures with subangular to rounded, spherical, heterogeneous clasts in the pebble to cobble size range, contained in a rock flour matrix. Similar facies dominate upstream exposures at Quebrada Yeguas, where a large breccia body consists dominantly of massive to thickly-bedded horizons with up to 20 vol. % pebble-size clasts of vein quartz, quartz-stockworked lithics, vuggy silica, and metasedimentary rocks, in a matrix of sand-size, clastic material with abundant disseminated pyrite. These breccia phases belong to the phreatic to phreatomagmatic, diatreme-type categories described by Sillitoe (1985). They typically crosscut FP, QFP, and the other breccia units described above, implying a late-mineral timing for their emplacement.

Structure

The Agua Rica area is characterized by a number of lineaments and poorly-constrained structures with dominant NW and NE directions. The most prominent structure is located along the relatively straight, N30°W- to N40°W-trending Quebrada Minas valley and several N30°E- to N45°E-oriented structures at Quebrada Yeguitas and Quebrada Agua Rica. More recently, several moderate- to low-angle thrusts (60°-25°) that apparently offset and repeat parts of the hydrothermal system and associated chalcocite blanket, have been identified (J. Bratt, pers. comm., 1996; M. Leake, pers. comm., 1998).

Hydrothermal Alteration

Early K-silicate and intermediate quartz-sericite assemblages are present at Melcho and Quebrada Seca-Trampeadero, whereas late, advanced argillic alteration is widespread at the latter. At the deposit scale, the overall zoning consists of a central area of advanced argillic alteration assemblages, with zones of vuggy silica and massive silicification, surrounded progressively outwards by zones of quartz-sericite and external propylitic alteration, with intervening zones of remnant K-silicate associations (Figs. 3b and 4b).

K-silicate alteration at Melcho is dominated by hydrothermal biotite, K-feldspar and magnetite, in which biotite totally to partially replaces original amphiboles. In the Quebrada Seca area, remnant K-silicate alteration consists of vague K-feldspar associated with patchy, fine-grained aggregates of pale brown biotite that replace former amphiboles. Biotite also occurs intimately associated with banded quartz-magnetite stockworks, in which much of the magnetite has undergone partial to total transformation to martite. Albite is also present. Early, irregular veinlets of translucent quartz and K-feldspar are common at Quebrada Seca and Melcho and are assigned to the A-type vein category of Gustafson and Hunt (1975).

Quartz-sericite assemblages are well developed at Melcho and Quebrada Seca-Trampeadero, in association with planar, quartz-sulfide veinlet stockworks and sulfide-only hairline fractures with sericitic alteration envelopes. The sericite of these assemblages includes both fine-grained micaceous and soapy illitic varieties, accompanied by rutile and minor tourmaline. Original rock textures are preserved at Melcho but totally destroyed at Quebrada Seca, where a mosaic of fine-grained quartz and sericite completely replaces original rock constituents.

Advanced argillic alteration assemblages dominate the center of the Quebrada Seca-Trampeadero system. They consist of one or more associations of quartz, sericite, pyrophyllite, zunyite, dickite, kaolinite, and alunite, with local andalusite and corundum (Koukharsky and Morello, 1995). This alteration type mainly affects the main-stage breccias described above. Central zones with vuggy silica and massive silicification are also present along structures and/or at lithologic contacts. Vuggy silica zones are bordered outwards by a proximal alunite-rich zone in which fine-grained, crystalline, hypogene alunite blades replace feldspar and mafic minerals, and by a distal kaolinite-sericite assemblage (Perelló, 1994). This array is similar to the zoning displayed by many high-sulfidation epithermal deposits (Stoffregen, 1986; White, 1991). Advanced argillic alteration is pervasive and texture-destructive, with fine-grained mosaics of quartz-pyrophyllite-sericite that completely replace original rock constituents. Open spaces in some breccia phases are also commonly lined by centimetric crystals and rosettes of alunite that characteristically are associated with native sulfur and copper sulfides (see below). Advanced argillic alteration assemblages are observed crosscutting earlier-formed K-silicate alteration, with transition zones including martitized magnetite and chlorite-illite±smectite associations.

External propylitic assemblages consist of calcium-bearing zeolites and epidote together with carbonates, chlorite, and minor albite. They affect mainly the granitic basement and, less intensely, the metamorphic country rocks.

Mineralization

Hypogene copper-molybdenum-gold mineralization at Agua Rica occurs in porphyry-type and epithermal assemblages at Melcho and Quebrada Seca-Trampeadero. Supergene copper mineralization occurs at Quebrada Seca-Trampeadero (Fig. 4b).

Early, K-silicate related, hypogene copper mineralization at Melcho is of low grade (0.2-0.3% Cu) and associated with sparse, multidirectional, planar to irregular, centimetric quartz veinlets with pyrite, chalcopyrite, magnetite, and rare bornite. At Quebrada Seca, K-silicate alteration is dominated by pyrite-rich assemblages with trace chalcopyrite hosted by translucent, irregular quartz veinlets of A-type (see above), which characteristically contain <0.1% Cu. Molybdenum mineralization at Quebrada Seca seems to be associated with quartz and K-feldspar veinlets that display crenulated plastic deformation textures comparable to the "brain-rock" textures from porphyry molybdenum deposits (D. Beane, pers. comm., 1998).

Intermediate stage porphyry-type mineralization at Melcho and Quebrada Seca-Trampeadero is molybedum-rich and associated with a stockwork of planar, comb-textured quartz veinlets with center lines of pyrite and selvages of banded molybdenite, in quartz-sericite alteration. These veins, that characteristically crosscut and offset earlier A-type veinlets, display similarities with the B-type veins of Gustafson and Hunt (1975). A chalcopyrite-bornite assemblage, present at Quebrada Seca in strongly quartz-sericite altered rocks (M. Leake, pers. comm., 1998), is tentatively assigned here to the intermediate stage of mineralization, and probably constitutes the main source of pre-epithermal, porphyry-style copper mineralization known at Agua Rica. Average grades for this assemblage are in the 0.6-0.7% Cu range.

Late-stage, hypogene copper mineralization, herein referred to as main-stage mineralization, is characteristic of the Quebrada Seca-Trampeadero system in which one or more Butte-type associations of covellite, chalcopyrite, bornite, and enargite, typically with several volume percent pyrite, occur as disseminations, hairline fractures, veinlets, breccia cement, and centimetric to decimetric open space-fillings in hydrothermal breccias. Marcasite, tetrahedrite-tennantite, chalcocite, sphalerite, galena, molybdenite, rhodochrosite, barite, gypsum, and native sulfur are common. Covellite is the principal copper sulfide of main-stage mineralization and occurs as well-terminated, bladed crystals averaging 1 cm in size (locally decimeter-size), mainly as open space-fillings. Covellite is also intergrown with hypogene alunite and locally is observed as inclusions in native sulfur crystals. This style was the original target pursued by previous exploration efforts in the area (Koukharsky and Mirré, 1976). Large, centimeter- to meter-wide massive pyrite-copper sulfide veins and quartz-pyrite veins with alteration haloes are also part of the mineralization in the Trampeadero area and belong to the D-vein category of Gustafson and Hunt (1975). Pyrite is also a main component of the copper-destructive, end-stage, phreatomagmatic, diatreme breccias and pebble dikes that cut through the Quebrada Seca-Trampeadero porphyry system. Copper grades associated with main-stage mineralization assemblages fall in the >1.5% Cu range.

Supergene copper mineralization at the Quebrada Seca-Trampeadero system consists of an immature, irregular, chalcocite blanket that occurs beneath a dominantly jarositic leached capping that is up to 150 m thick (Fig. 4b). The chalcocite blanket, which is up to 200 m in thickness, displays a crude vertical and lateral zoning with upper parts rich in chalcocite and lower parts dominated by supergene covellite. Copper grades average between 0.7-1.0% Cu in the blanket, with local zones exceeding 1.5% Cu. Incomplete replacement of sulfides is common, with supergene chalcocite and/or covellite characteristically occurring as thin coatings and films on disseminated and veinlet-controlled pyrite and copper sulfides. Minor neodigenite is also present (Koukharsky and Mirré, 1976).

Gold values of <0.1 ppm characterize K-silicate assemblages in both Quebrada Seca-Trampeadero and Melcho, whereas main-stage copper is typically associated with gold grades in the > 1ppm range. Gold grades in the supergene blanket typically range between 0.25 and 0.4 ppm and the leached capping zone typically returns between 0.3 and 0.4 ppm Au.

Age

A reconnaissance K-Ar study was carried out on selected samples from the Quebrada Seca and Trampeadero areas. The samples were analyzed at Amdel Ltd., Australia. The data support a late Miocene-early Pliocene age for the alteration associated with the copper-molybdenum-gold mineralization at Agua Rica, in agreement with the ages reported by Sasso and Clark (1988) for Agua Rica and the Farallón Negro cluster (Fig. 5).

The age of the Melcho system is constrained by the $^{40}Ar/^{39}Ar$ data of Sasso and Clark (1998). The monzonite stock, dated by them at 8.56±0.48 Ma, is here interpreted as a pre-mineral phase of the porphyry system, whereas K-silicate and quartz-sericite assemblages yield ages of 6.29±0.06 and 6.10±0.04 Ma, respectively.

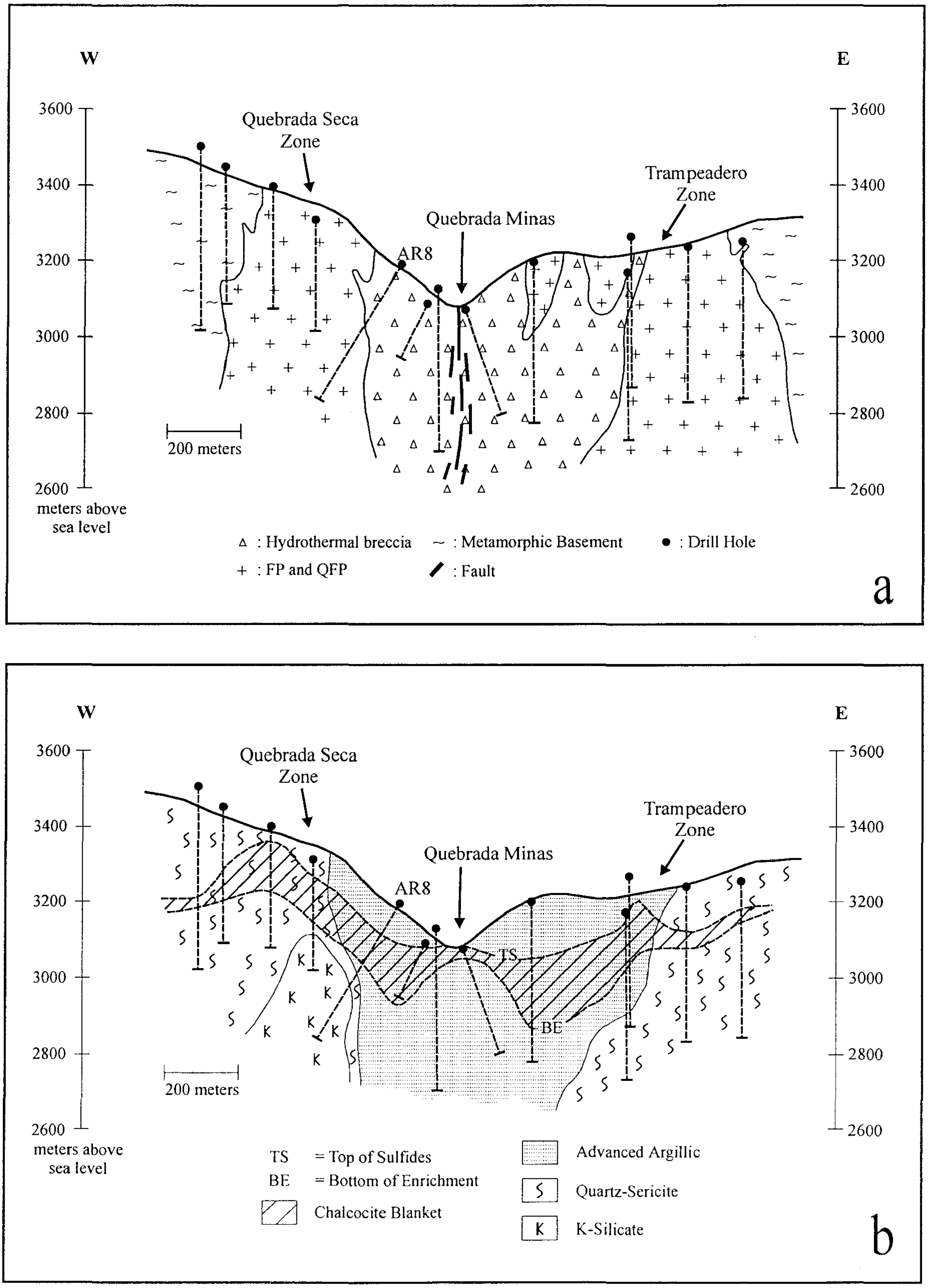

Figure 4. Simplified cross-section through the Quebrada Seca-Trampeadero system, Agua Rica. a) Geology; b) Hydrothermal alteration and location of the chalcocite blanket.

Data obtained from Quebrada Seca-Trampeadero show that the biotite-rich, K-silicate alteration from Quebrada Seca yields an age of 5.10±0.05 Ma. Crosscutting hypogene alunite, collected from the alunite zone around a vuggy silica ledge at Trampeadero and therefore of unambiguous high-sulfidation epithermal origin (Stoffregen, 1987; White, 1991), yields ages of 4.88±0.08 and 4.96±0.08 Ma. Additional ages obtained for sericite (5.38±0.05 Ma) and alunite (6.18±0.06 Ma), together with the age of the "late stage alteration" (5.35±0.04 Ma) reported by Sasso and Clark (1998) from the Quebrada Seca-Trampeadero system, may reflect the complex nature of the system and the continuous process of juxtaposition of alteration-mineralization events, rather than a hiatus of 2-3 m.y. as proposed by Sasso and Clark (1998).

A sample of alunite collected from a massive, centimetric, banded vein of probable supergene origin within the chalcocite blanket at Quebrada Seca, yields an age of 3.94±0.05 Ma. This is tentatively interpreted to record the age of the supergene oxidation and mineralization at Agua Rica. A biotite-rich ash-fall tuff from the Trampeadero zone yields an age of 0.52±0.02 Ma, which is interpreted to represent the age of the paleosurface in the area prior to canyon incision.

Considerations on a Genetic Model

At least five main events (Perelló, 1994) are interpreted to have combined to produce the complex geometry of the Agua Rica deposit: 1) Development of porphyry-style alteration-mineralization at Quebrada Seca-Trampeadero and Melcho associated with multiple-phase FP and QFP intrusions of dacitic to monzonitic composition. These systems evolved, apparently separately, from early, magnetite-rich K-silicate alteration to an intermediate quartz-sericite overprint associated with hydrothermal collapse; 2) Emplacement of the large, multiple-phase, main-stage breccia complex at Quebrada Seca-Trampeadero; 3) Overprinting of main-stage breccias by advanced argillic alteration. A series of vuggy silica ledges and associated alunite alteration, were emplaced as part of this event, in a classic, high-sulfidation epithermal environment; 4) Emplacement of main-stage copper-gold mineralization associated with a Butte-type, high-sulfur assemblage of covellite, chalcopyrite, bornite, and enargite with minor marcasite, copper sulfosalts, chalcocite, and molybdenite. This stage was emplaced in advanced argillic-stable conditions in a high-sulfidation epithermal environment; 5) Emplacement of post-mineralization pebble dikes, tuffaceous dikes, and diatreme-type breccias at Quebrada Seca-Trampeadero in an epithermal environment under phreatic to phreatomagmatic conditions.

Chalcocite blanket formation then took place under conditions of rapid tectonic uplift and intense seasonal rainfall.

Significant telescoping (Sillitoe, 1994) is inferred to have taken place during the evolution of Agua Rica judging by the crosscutting relationships between epithermal and porphyry assemblages (Perelló, 1994). By analogy with other deposits from elsewhere (Sillitoe, 1989; Hedenquist et al., 1998), the K-silicate and high-sulfidation epithermal associations at Agua Rica are interpreted to represent the end-members of the porphyry-epithermal environment, formed at depths of ~2 km and ~0.5 km, respectively. This implies that a vertical column of rock of ~1.5 km was removed by synmineralization erosion during a period of ~1.4 m.y., between the porphyry copper mineralization stage at Melcho (6.29 Ma) and the high-sulfidation epithermal conditions at Quebrada Seca-Trampeadero (4.88 Ma). In a similar scenario, the Quebrada Seca-Trampeadero system must have undergone even more dramatic synmineralization telescoping, considering that only ~200,000 years elapsed between K-silicate (5.10 Ma) and advanced argillic alteration (4.88

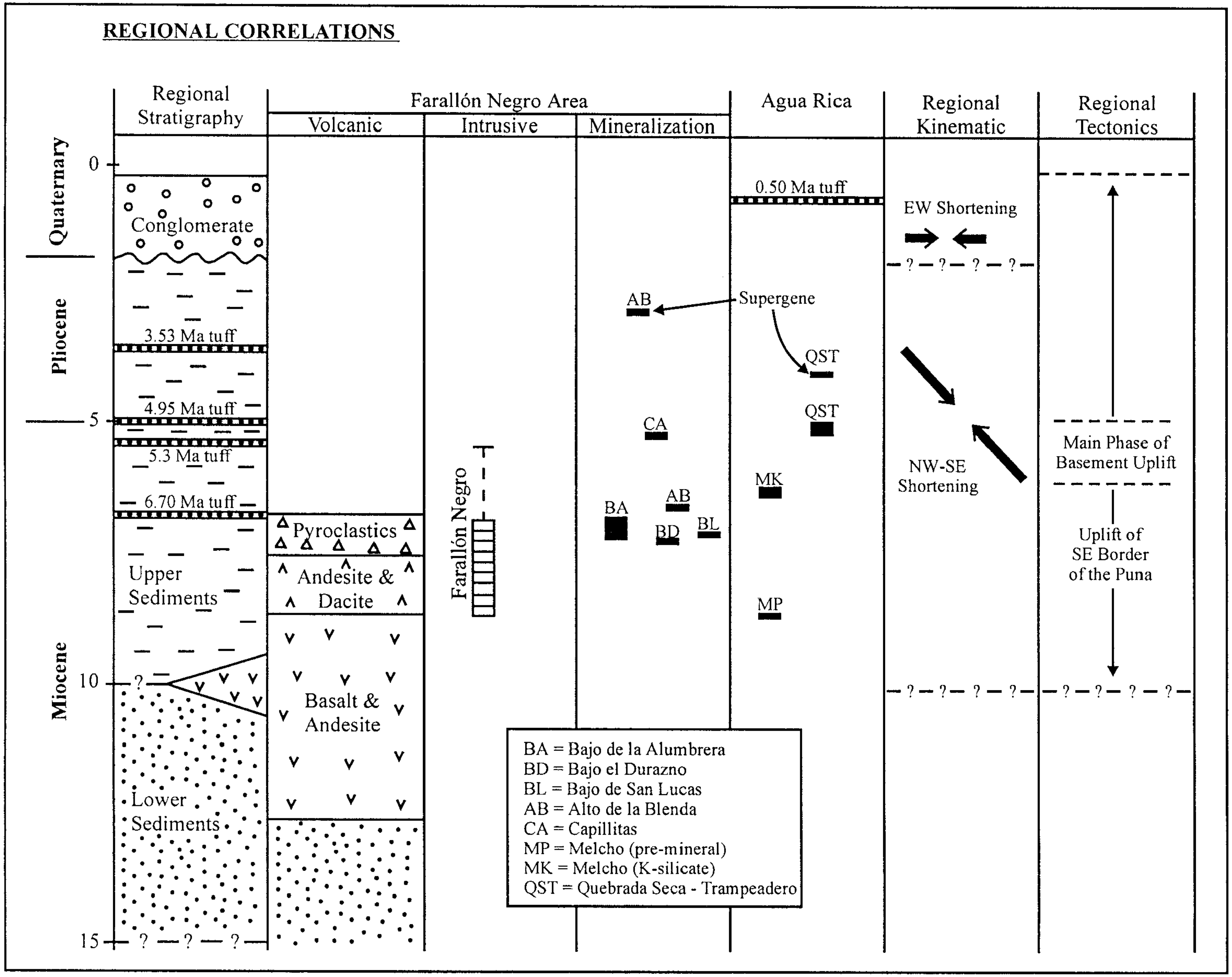

Figure 5. Summary diagram of the tectono-stratigraphic, magmatic, and mineralization history - SE margin of the Puna region. Data from Allmendinger (1996), Caelles et al. (1971), Sasso and Clark (1998), and this study.

Ma). This time span compares well with that determined for the Far Southeast-Lepanto system in the Philippines (Arribas et al., 1995) and suggests that a vertical column of rock of ~ 1.5 km was eroded during this time. Alternatively, the porphyries and associated early, K-silicate alteration were emplaced at shallower levels from the paleosurface and uplift and erosion were less intense.

Telescoping at Agua Rica may be attributed to synhydrothermal degradation of the paleosurface triggered by the intense, regional tectonic uplift of the Sierras Pampeanas. Tectonic uplift of the region was probably diachronous and estimated to have commenced between 5 and 10 Ma (Allmendinger, 1986), with significant shortening, associated with high-angle reverse faults of the thick-skinned, Laramide-style tectonism that formed the up to 6,000 m high Sierras Pampeanas, occurring at ~6 Ma (Jordan et al., 1983; Jordan et al., in press). This rapid uplift is inferred to have contributed much of the sediments that filled neighboring basins with accumulation rates of ~560 m/m.y. (Allmendinger, 1986). Several ash markers interbedded in the dominantly terrigenous sedimentary sequences of the region further document significant sediment accumulation (and therefore erosion) between 6.70 and 3.53 Ma with individual horizons at 6.70, 5.30, and 4.95 Ma (Allmendinger, 1986), which are in remarkable agreement with the ages of the various alteration-mineralization stages recorded at Agua Rica and the Farallón Negro cluster (Sasso and Clark, 1998) (Fig. 5).

Evidence from Agua Rica implies that uplift in the region was a discontinuous process, with stages of intense deformation and shortening alternating with periods of tectonic quiescence. Uplift has continued at intervening stages to the present (Jordan et al., 1983) and caused exhumation of the hydrothermal systems at Agua Rica and development of the immature chalcocite blanket at Quebrada Seca-Trampeadero at approximately 3.9 Ma. Remnants of 0.5 m.y. old ash-fall tuffs and perched paleo-stream conglomerates further support that canyon incision and erosion induced by topographic uplift are still active in the region.

Conclusions and Discussion

Copper-molybdenum-gold mineralization at Agua Rica is associated with a complex array of porphyritic stocks and hydrothermal breccias of late Miocene-early Pliocene age that intruded a basement of ?Precambrian to early Paleozoic metasedimentary rocks and Paleozoic granitoids. The area contains two main porphyry copper centers emplaced at the intersection of NW- and NE-trending faults with a regional EW-trending lineament of hydrothermal deposits.

Hypogene copper-molybdenum-gold mineralization is present in porphyry-style and epithermal assemblages at Quebrada Seca-Trampeadero, whereas low-grade copper-molybdenum mineralization occurs at Melcho. At Quebrada Seca-Trampeadero, main stage copper-molybdenum-gold mineralization is of epithermal, high-sulfidation type and contained in several, pyrite-rich associations of covellite, chalcopyrite, bornite, and enargite with minor amounts of copper sulfosalts and chalcocite. This mineralization is intimately associated with advanced argillic alteration assemblages rich in sericite, pyrophyllite, zunyite, dickite, kaolinite, and alunite and local vuggy silica ledges. Intermediate argillic alteration, characterized by sericite and chlorite, is locally present at depth and, together with the advanced argillic assemblages, crosscut and overprint earlier-formed, magnetite-rich K-silicate alteration.

Supergene copper mineralization, in the form of an immature molybdenum- and gold-bearing chalcocite blanket, is present at Quebrada Seca-Trampeadero, where it constitutes the bulk of the near-surface, open pittable resource of the project. Supergene chalcocite dominates the upper part of the blanket and is underlain by a covellite-rich zone. The leached capping is gold-rich and is dominated by jarositic limonites with abundant copper-bearing relict sulfides.

The hypogene alteration and mineralization events at Agua Rica formed part of a short-lived hydrothermal system of approximately 1.4 m.y. duration, between 6.29 and 4.88 Ma. Synmineralization uplift and erosion caused the juxtaposition of epithermal associations onto higher-temperature, deeper-seated assemblages. Synmineralization erosion was induced by the regional tectonic uplift that formed the Sierras Pampeanas in the late Miocene-early Pliocene. Supergene chalcocite formation was favored by the presence of the acid-generating and low-neutralizing capacities of the pyrite-rich, advanced argillic alteration assemblages associated with hydrothermal telescoping.

The telescoped environment at Quebrada Seca-Trampeadero and its associated chalcocite blanket are features similar to those displayed by the Escondida (Ojeda, 1990) and Chuquicamata (Zentilli et al., 1995) porphyry copper deposits of the late Eocene-early Oligocene belt of northern Chile. The intimate association between porphyry and high-sulfidation epithermal mineralization is well preserved at the La Fortuna prospect (Perelló et al., 1996) of the same belt. Whereas Escondida (Alpers and Brimhall, 1988; Padilla-Garza, 1998), Chuquicamata (Reynolds et al., in press) and La Fortuna (Perelló et al., 1996) seem to have experienced 2 to 3 m.y. hiatuses between K-silicate and advanced argillic alteration stages, the Quebrada Seca-Trampeadero system seems to have undergone a geologically instantaneous overprint, in ~200,000 years.

The Cu-Au mineralization of Agua Rica departs from the typical geometry of gold-rich porphyry copper deposits (Sillitoe, 1979; Perelló and Cabello, 1989), in that much of the gold was preferentially associated with the late, epithermal overprint and little gold was introduced by early K-silicate alteration, despite its magnetite-rich nature. Moreover, this early alteration event seems to constitute a low-grade core at Quebrada Seca-Trampeadero, similar to that observed, for example, at Island Copper, Canada (Perelló et al., 1995) and Taysan, Philippines (JP and NR; personal observations, 1996). At Island Copper, however, the central core is characterized by a quartz-magnetite-amphibole assemblage rich in albite but devoid of K-silicate alteration products.

The Cu-Mo-Au metal signature of the Agua Rica deposit confirms that porphyry deposits cannot be subdivided only into Cu-Au and Cu-Mo categories associated with specific geotectonic settings as proposed by Kesler (1973), but rather they are part of a broader spectrum containing Cu-Mo-Au examples with Cu-, Mo-, and Au-only porphyry deposits as end-members of this spectrum.

The presence of a relatively young (3.9 Ma or younger) chalcocite blanket at Agua Rica suggests that, despite the overall regional climatic desiccation imposed in the middle Miocene (Alpers and Brimhall, 1988; Sillitoe and McKee, 1996; Jordan et al., in press), significant supergene mineralization can take place under the right conditions. In the case of Agua Rica, these conditions included the pyrite-rich, high-grade epithermal copper mineralization hosted by the widespread, non-reactive argillic and sericitic assemblages and the pluvial regime of the up to 5,500 m high Sierra de Aconquija structural block.

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