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A REVIEW OF THE GEOLOGY AND MINERALISATION OF THE ALUMBRERA PORPHYRY COPPER-GOLD DEPOSIT, NORTHWESTERN ARGENTINA.

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Abstract - The Bajo de la Alumbrera porphyry copper-gold deposit is located within the northern Sierras Pampeanas in the eastern Andes Mountains of northwestern Argentina. It formed in a tectonically favourable location within a major arc-oblique wrench fault system, the Tucumán Transfer Zone. Initial andesitic volcanism deposited on crystalline Lower Palaeozoic basement, and subsequently emplaced dacitic subvolcanic stocks are directly related to eastward subduction of the Nazca oceanic plate beneath the western continental margin of South America. Structural preparation and shallowing of the angle of subduction of the Nazca plate - related to the arc-normal Juan Fernández Ridge on that plate - probably aided the ascent of calc-alkaline oceanic arc-related magma into the Tucumán Transfer Zone.

The commencement of volcanism was approximately coincident with the shallowing of the angle of subduction beneath the northern Sierras Pampeanas. Intrusion of the mineralised porphyries was contemporaneous with the development of thick-skinned shortening which produced uplift of the Sierras de Aconquija basement block to the southeast at between 10 and 5 Ma. Structural degradation of the crystalline basement brought about by the development of a broad asthenospheric wedge above the descending Nazca plate, aided the development of block uplift caused by generally east-west shortening at that time.

Ar-Ar dating of the various mineralised intrusive phases indicates intrusive activity lasted for approximately 270 000 years. The upper age of mineralisation is interpreted to be at the onset of feldspar destructive alteration (phyllic-argillic styles) at 6.75 ± 0.09 Ma. The presence of an apparently older, unmineralised phase (the Los Amarillos Porphyry - LAP) adjacent to the mineralised porphyries suggests that the evolution from unmineralised to mineralised magma may have been quite rapid. However, due to the highly altered nature of the LAP, no clear genetic relationships have been established between these porphyries.

Mineralisation was focussed on the intrusive centre and the surrounding andesitic host rocks. Reconstruction of the original geometry of the deposit indicates that the cluster of porphyry stocks and dykes that define the intrusive centre formed a sub-circular body with a diameter of around 500 m, while the overall dimensions of the mineralised system (at greater than 0.15% Cu) was approximately 800 x 800 m. The vertical dimension of the mineralisation is less easily measured, but was probably in the range of 800 to 1000 m. Approximately 3.36 million tonnes of copper and 409 tonnes of gold were deposited within this volume.

Fluid inclusion studies indicate that deposition of mineralisation seems to have been strongly controlled by cooling of the mineralising fluids, with sulphide phases being formed as the fluid cooled below a 400 to 360ºC temperature threshold.

Mineralisation was accompanied by the near simultaneous formation of quartz-magnetite and potassic alteration in the porphyries and potassic alteration of the adjacent andesites. An unmineralised propylitic halo developed in the andesites beyond the limit of potassic alteration. Feldspar destructive (phyllic ± argillic) alteration post-dated the mineralisation and probably formed in response to degradation of the thermal plume and consequent induction of increasingly acidic phreatic water into convection cells adjacent to the intrusives. Feldspar destructive alteration is usually accompanied by decreasing grade, suggesting that at Alumbrera this alteration stage remobilised and removed mineralisation.

Structural rotation of the northern Sierras Pampeanas during the Upper Miocene to Lower Pliocene resulted in the reactivation of earlier structures in a transpressional regime that caused dismemberment of the porphyry mineralisation at Alumbrera. Strong alteration of the earliest of the major faults suggests that structural disruption occurred during the development of feldspar destructive alteration, and may have been responsible for the termination of this alteration event. Subsequent movement resulted in displacement of the ore blocks across both normal and reverse faults.

Active uplift of the Sierras Pampeanas and consequent rapid erosion prevented the development of significant secondary oxide or supergene mineralisation at Alumbrera.

Introduction

The Bajo de la Alumbrera porphyry copper-gold deposit (subsequently shortened to "Alumbrera") is located in Catamarca Province in the northwest of Argentina. It lies 145 km to the northwest and 150 km southwest of the Provincial capitals of Catamarca and Tucumán respectively.

The exploration and mining rights to the deposit are owned by Yacimientos Mineros Aguas de Dionisio (YMAD), a statutory corporation representing the provincial government of Catamarca, the University of Tucumán and the Argentine National Government. YMAD has a joint-venture agreement with Minera Alumbrera Limited (MAA) to mine the deposit. At the time of writing, Minera Alumbrera's shareholders were Xstrata plc (based in Switzerland) 50%, Wheaton River Minerals Ltd. 37.5 % and Northern Orion Resources Inc. 12.5 %. The latter two are both Canadian mining companies. MAA is managed by Xstrata Copper.

Discovery History

Mineralisation was first recognised at the site of the Alumbrera deposit by Mr Abel Peirano, who worked with the Tucumán National University between 1938 and 1945. Additional research was subsequently undertaken by G Gecione of the University of Tucumán during reconnaissance exploration that lasted until 1949. Sporadic investigations continued until the early 1960s. Geochemical sampling by Mazetti and Sisters in 1968 helped classify the deposit as belonging to the porphyry copper style of mineralisation. Geological investigations by various workers continued intermittently during the 1970s and 1980s, with significant contributions being made by researchers from the University of Arizona under the direction of Dr J Guilbert. Chief among these was a study by Stults (1985) who undertook a detailed investigation of the alteration and mineralisation of the deposit, including fluid inclusion microthermometry. Important aspects of this and other studies are captured in Guilbert (1995). Sporadic exploration of the deposit for commercial purposes had been undertaken by YMAD (a state mining entity) since 1967. In early 1993, International Musto Exploration Ltd negotiated access to the deposit with YMAD and commenced a focussed exploration program. In February 1994, a 50/50 Joint venture was negotiated between Musto and MIM Holdings Limited of Australia, and Minera Alumbrera Limited was created to manage the exploration and eventual operation of the deposit. Exploration and preliminary development continued until the commencement of processing operations in September 1997.

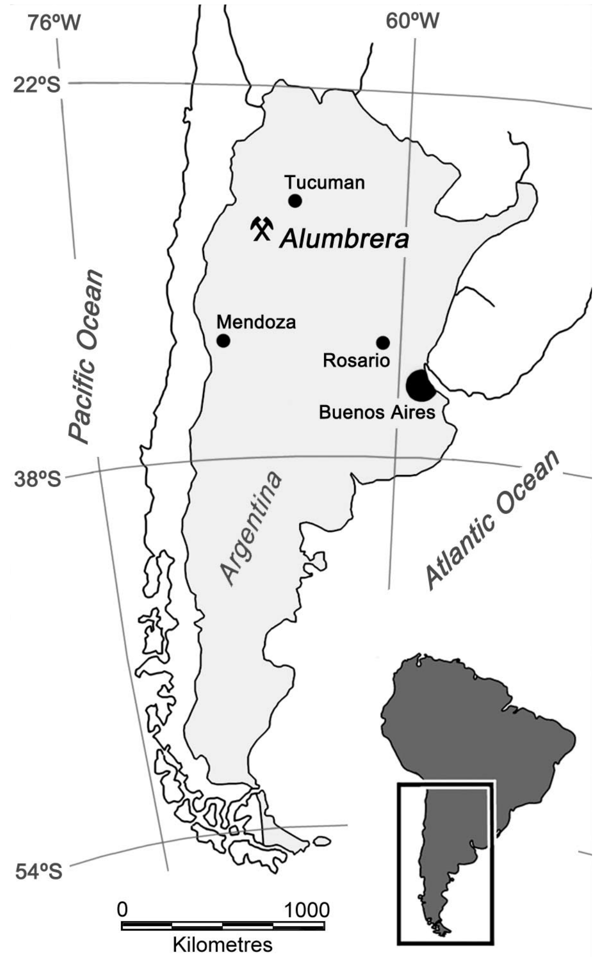

Figure 1: ***Location Map.*** The Alumbrera mine is located in Catamarca Province, northwestern Argentina. Concentrate is transported to Cruz del Norte near Tucumán by a 316 km slurry pipeline and then by rail to port facilities at San Martín on the Rio Paraná near Rosario.

Resources and Production

The porphyry copper-gold deposit at Bajo de la Alumbrera contains economic mineralisation which has produced over 1.46 million tonnes of copper in concentrate and 201.55 tonnes (6.48 Moz) of gold in concentrate and doré since commencement of processing operations in September 1997. This represented 220 million tonnes (Mt) of treated material at an average grade of 0.66% Cu and 0.86g/t Au.

Remaining resources and reserves (including stockpiled material) at the end of 2004 were 404 million tonnes at average grades of 0.47% Cu and 0.51g/t Au. Of this, the reserves at 31 December 2004 were 374 Mt at 0.48% Cu and 0.52 g/t Au. Production under the current mine plan is expected to continue until mid 2015.

The global metal resource of the deposit is therefore in the order of 3.36 million tonnes of copper and 409 tonnes of gold.

In 2004, 111.64 Mt of ore and waste were mined, of which 32.18 Mt was ore at a head grade of 0.56% Cu and 0.72 g/t Au. A total of 35.35 Mt was treated by the mill to produce 176 438 tonnes of fine copper and 19.69 tonnes of gold in concentrate and doré.

Tectonic Framework

The tectonic framework of the Argentine Andes is dominated by compressional tectonics, as it has since the onset of east-directed subduction of the Nazca Plate beneath the South American continental plate in the early Jurassic.

The tectonomorphic development of the Andes has been driven by variations in the angle of subduction of the descending Nazca plate. Beneath the western margin of continental South America, the subducting plate can be divided into five segments based on the angle of subduction.

Beneath two of these segments - between 2°S and 15°S in central Peru, and between approximately 28°S and 33°S in northwestern Argentina - the slab currently descends at angles of 5° to 10°, where-as the adjacent segments of the descending plate dip at angles of between 25° and 30° (Barazangi & Isacks, 1976).

The development of distinctive tectonomorphic terrains in the overlying plate correspond approximately to changes in dip of the Wadati-Benioff zone.

The Sierras Pampeanas terrain developed above the southern segment of flat slab subduction, between latitudes

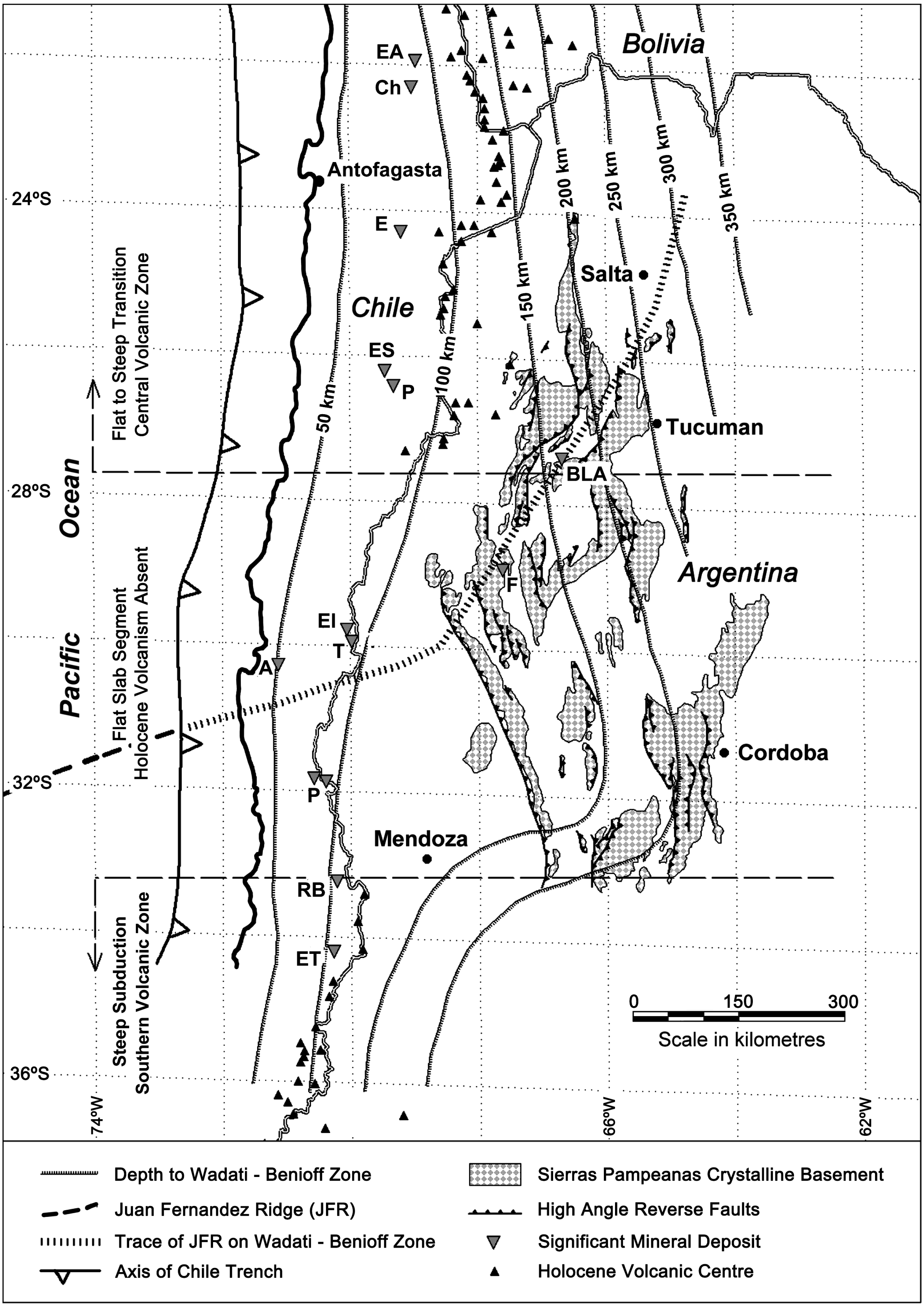

Figure 2: ***Position of Bajo de la Alumbrera in relation to uplifted basement blocks of the Sierras Pampeanas terrain, deformation of the subducted Nazca Plate and the position of the subducted Juan Fernandez Ridge.*** Significant mineralised deposits are as follows : In Argentina BLA = Bajo de la Alumbrera; F = Famatina. In Chile A= Andacollo; Ch = Chuquicamata; E= Escondida; EA = El Abra EI = El Indio; ES = El Salvador; ET = El Teniente; P = Los Pelambres / Pachon; Po = Potrerillos; RB = Rio Blanco; T = Tambo. Adapted from Proffett, (2003); Based on data from Jordan, et. al. (1983), Cahill & Isaacs (1992), Cross & Pilger (1982), and Allmendinger, et. al., (1983). Data on Holocene volcanic centres from Siebert & Simkin (2002).

of 28°S and 33°15'S. South of this segment, the dip of the descending Nazca plate changes abruptly to approximately 30°. North of the Sierras Pampeanas, the subducting slab gradually steepens toward the north, reaching and angle of 30° at approximately 24°S. Deformational character undergoes a corresponding change from thick skinned in the Sierras Pampeanas, through a transition zone of mixed thick and thin skinned deformation in the Santa Barbara System to the Sub Andean belt north of 24°S, which is dominated by thin-skinned shortening (Allmendinger, *et al.,* 1983).

Flattening of the subducted slab beneath the Sierras Pampeanas is thought to have started at approximately 13 Ma and to be related to the subduction of the Juan Fernández Ridge which lies on the Nazca plate. The corresponding thermal buoyancy of this intra-plate chain of arc-perpendicular sea mounts and islands is believed to have led to, or aided, flattening of the subduction angle (Pilger, 1981). The current southern margin of the flat slab segment lies approximately due east of the ridge axis. According to this model, flattening and deformation of the plate boundary began in the north and moved southwards, which should have resulted in a southward decreasing age of deformation within the Sierras Pampeanas.

However, the timing of deformation in the northern Sierras Pampeanas (Strecker, *et al.,* 1989; Sasso, 1997; Coughlin, *et al.,* 1998) at around 7 to 5 Ma, which corresponds closely with timing of uplift and deformation of the Nevados del Famatina in the central part of the Sierras Pampeanas at 5.3 ± 0.9 Ma (Losada-Calderon, *et al.,* 1994) argues against a progressive southerly deformation.

Strecker *et al.,* (1989) propose the presence of a broad asthenospheric wedge above the shallow subducting plate which has caused thermal thinning of the lithosphere below the northern Sierras Pampeanas. Uplift of basement blocks in this area is proposed to be a response to shortening of the consequently mechanically weakened basement.

Regional Structure

The Alumbrera mine is located on the northwestern margin of the Sierras Pampeanas, a basin and range terrain (Jordan & Allmendinger, 1986) which consists of uplifted north trending basement blocks with intervening basins. Basement lithologies exposed on the ranges generally consist of crystalline or metamorphic rocks of late Cambrian to Ordovician age, with Tertiary and Quaternary basin fill. The principal structures are compressional in nature, with uplifted basement blocks usually bounded by high angle reverse faults.

At the latitude of the Alumbrera deposit, the dominant north-south structural grain of the Sierras Pampeanas changes significantly where it is truncated by northeast trending faults and basement blocks. This change in trend was termed the "Tucumán Lineament" by Mon (1976). It separates the Sierras Pampeanas to the south, from the Puna region to the north. The Puna is a high (average 4000 m) plateau which extends south from the Bolivian Altiplano, and is characterised by an abundance of recent volcanism, with many vents still active. Volcanic activity has been absent from the Sierras Pampeanas (above the flat-slab segment discussed above) since approximately 5 Ma, corresponding to the cessation of the Miocene age volcanism which had been associated with the broadening of the Andean volcanic arc (Kay, *et al,* 1988).

Timing of basement uplift in the Sierra de Aconquija and Sierra de Capillitas to the east of Alumbrera (Fig. 3b) has been constrained on the basis of Ar-Ar microprobe analysis by Sasso (1997) to between 5.5 and 5.0 Ma. Similarly, Coughlin *et al.,* (1998) using apatite fission track dating, note that a significant cooling event occurred between approximately 10 and 5 Ma, corresponding to uplift of the Sierras de Aconquija.

The northern Sierras Pampeanas is probably still experiencing basement uplift. Coughlin (*op cit*) also notes evidence of very young cooling (<3 Ma) in two fission track samples, which supports evidence cited in Strecker *et al.,* (1989) for Quaternary tectonism on the western margin of the Sierra de Aconquija. Mapping close to the Alumbrera mine has also identified recent reverse faulting that has placed Miocene volcanic rocks structurally above semi-consolidated colluvial sediments, corroborating Coughlin's proposal that basement uplift migrated westwards from the main Sierra de Aconquija to a position east of the Alumbrera mine at approximately 7 Ma.

The mineralised complex at Alumbrera occurs adjacent to the Tucuman Transfer Zone, a north-east trending structural zone which defines the boundary between the Sierras Pampeanas to the south from the Santa Barbara system to the north and the Puna plateau to the northwest.

The principal structures determining the geometry of basement blocks in the Alumbrera area are shown on Fig. 3a.

Regional Stratigraphy

Basement Lithologies

The oldest rocks in the Alumbrera area are a series of generally well-bedded, low to medium grade metamorphosed shales and sandstones, which have been regionally metamorphosed to lower greenschist facies. These sediments are mapped in the Vis Vis Valley (6 km SE of Alumbrera) and Sierra de Ovejeria (Fig. 3b) to the south of the mine where they typically outcrop as slates, phyllites and quartzites of the Suncho Formation. They are the southernmost expression of a deep marine basin which formed to the west of the Amazon Craton during Neoproterozoic to Lower-Cambrian times (Acenolaza, *et al.,* 1989).

The Suncho Formation has been intruded by elements of the Capillitas Batholith throughout the study area (i.e. Fig. 3). Intrusives of the batholith encompass a variety of compositions from syenogranites to monzogranites. Igneous textures range from medium grained equigranular to strongly porphyritic, with feldspar phenocrysts in excess of 50 mm in many of the granitic phases. McBride *et al.,* (1975) determined an age for the Capillitas Granite of from 471 to 423 Ma (Upper-Ordovician to Lower-Silurian) using a K-Ar technique.

Figure 3 Colour Insert

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Miocene Age Lithologies

El Morterito Formation

Continental red-beds of the El Morterito Formation unconformably overlie the Palaeozoic basement throughout the (Fig. 3), above a planate surface which developed on the basement throughout the Palaeozoic. In the Alumbrera area, the El Morterito Formation occurs in the foothills of Cerro Durazno (Fig. 3b), where it is limited to a thickness of generally less than 100 m. The unit has been assigned a Lower-Miocene age on the basis of vertebrate fossil fauna (Turner, 1962; 1973) and radiometric dating of a basal tuff unit by Bossi *et al.,* (1993) which gave an age of 13 Ma.

The El Morterito stratigraphy at the base of Cerro Durazno and north of the Durazno Fault has a lower unit composed of poorly sorted fine to medium grained sandstones and siltstones. The upper parts of this unit also contain abundant intraformational (mudflake) breccias and chert nodules after sulphates, indicating a depositional environment typical of a playa lake in an arid terrain. Above this sequence, the depositional environment changes rapidly (possibly across a low angle unconformity) to one dominated by fluvial deposition, with moderately sorted medium to coarse sandstones, gravels and pebble to cobble conglomerates. The conglomerates are polymict and generally reflect a broad range of basement lithologies, from granites to subvolcanic porphyries. There is little material derived from volcanic sources, with the exception of a minor component of fine grained basaltic clasts.

The transition from playa lake to active fluvial systems within the El Morterito Formation reflects the rejuvenation of the hinterland of the palaeo-basin and the commencement of basement uplift in the northern Sierras Pampeanas, immediately prior to the onset of andesitic volcanism.

Farallón Negro Volcanics

Throughout the study area (Fig. 3), the El Morterito Formation is immediately overlain by the Mid- to Upper-Miocene age andesitic volcanics of the Farallón Negro Volcanics (FNV). The FNV complex is the easternmost expression of Cenozoic volcanism in northern Argentina. Whole rock geochemistry determined by Sasso (1997) on samples of the FNV indicate that the volcanics have a calc-alkaline composition, and may be sub-classified as Shoshonites on the basis of their high potassium content.

Recent data from Halter *et al.,* (2004) indicate that the main volume of the FNV complex was erupted between 9.7 and 7.35 Ma, with the youngest extrusive event being the eruption of dacites at 7.35 Ma.

The contact between the FNV and the El Morterito Formation is poorly understood. On the eastern margin of Cerro Bola del Atajo (Fig. 3b), beds of FNV are conformable with the narrow interval of El Morterito Formation which lies above granitic basement in this area. Similarly, to the south of Alumbrera, FNV are found interbedded with the El Morterito Formation along the downthrown (northern) block of volcanics adjacent to the trace of the Buenaventura Fault (Fig. 3b). North of this fault, sand dykes from the El Morterito Formation are found within the lowermost units of the FNV, indicating a close temporal depositional relationship between the two units in the area. Further to the north, in the well exposed southern flanks of the Cerro Durazno, the conformable contact between the two units exhibits a well defined bedding and separation of the differing andesitic and basement derived sediments.

In the area between the pronounced arch of El Morterito Formation exposed to the west of Cerro Durazno and Cerro Bola del Atajo (Fig. 3b), the contact between the El Morterito Formation and the overlying FNV is notably different from that seen in other areas. Here, the volcanics lie above an angular erosional unconformity. The degree of angular discordance seems to be variable, but is generally less than 20°. Erosion of the El Morterito Formation prior to the deposition of the volcanic units can involve the removal of up to 30 m of material. In one area, it appears as if El Morterito Formation conglomerates have been deposited above andesites of the FNV.

Recent drilling (2003) beneath the Alumbrera open pit penetrated basement lithologies in several holes for the first time. These drill holes passed directly from fresh andesite to a strongly silicified, bleached quartzite. Although the quartzite does not exhibit the well bedded appearance of the quartzites in the Vis Vis Valley to the south of the mine, the unit intersected in these holes is interpreted as an altered equivalent of the Suncho Formation. This implies that the El Morterito sandstones were either eroded beneath the mine area prior to deposition of the FNV sequence, or the area immediately adjacent to the mine was a relative topographic high during deposition of the El Morterito Formation.

The variable contact relationships noted between these two units suggests that volcanic activity commenced soon after basin inversion began. Rapid uplift of the El Morterito sedimentary basin probably resulted in soft sediment deformation of at least the upper coarse sedimentary package. Continued deformation of the basin, accompanied by rapid deposition of the lower facies of the FNV, resulted in a variably developed erosional unconformity between these two units.

Following a period of deformation of the lower volcanic facies, sedimentation within the palaeo-basin continued, with input from dominantly volcanic sources, but also a minor input from basement rocks (decreasing over time), resulting in the interbedding of the El Morterito Formation and FNV, with resultant soft sediment and dewatering features such as sand dykes.

Throughout the study area (Fig. 3), the FNV are dominated by thick sequences of poorly bedded flows of andesitic detritus. These flows generally comprise interbeds of up to 2 m in thickness of extremely poorly sorted, matrix supported sediment. Rounded to subangular polymict clasts of almost universal andesitic composition are present throughout the flows. Clast sizes vary from several cm to 2 m in diameter and occasionally exhibit reverse grading within individual beds. The flows are therefore classified as debris flows according to the terminology proposed by Smith (1986). The presence of occasional clasts which appear to have been plastic prior to incorporation into the flow, plus the presence of dark fine grained reaction rims around many clasts lends weight to the probability that the flows were hot during the process of deposition.

In the area of the Alumbrera tailings dam, bedding within the flows is notably more uniform, and individual beds can be traced over larger lateral distances. The quantity of andesite dykes cutting the debris flows also diminishes significantly in this area. Sasso (1997) attributed this change to lateral facies changes away from a central volcanic vent or cone, with the more bedded facies close to the tailings dam representing distal flows into a basin surrounding the vent. However, during drilling of geotechnical foundation holes prior to construction of the dam wall, several holes intersected fine grained andesitic or basaltic dykes that are not present at surface. Similar anomalies were noted during later drilling of hydrological test wells downstream of the tailings dam site. In addition, this drilling proved the existence of large faults beneath what at surface appear to be only minor fractures.

Analyses and interpretation of the data leads to the conclusion that rather than lateral change, the change in the debris flow material in the area of the tailings dam is the result of vertical facies change above what appears to be a low angle erosional unconformity. This unconformity apparently separates a lower facies of debris flow material with poorly defined bedding and containing abundant andesite and trachyandesite dykes from an upper facies in which individual debris flows are more easily discernible and post depositional dykes are generally absent. According to this interpretation, the upper volcanic facies would be equivalent to the “Medial Volcaniclastic Facies” of Sasso (1997).

The unconformity between Upper and Lower facies of the FNV is also reflected in gross compositional changes within the andesite pile, with hornblende and pyroxene units dominating below the unconformity and pyroxene + plagioclase above. A similar compositional change across a 30° angular unconformity has been noted in the FNV to the north of Cerro Bola del Atajo, north of the Escaleras Fault. To date insufficient work has been done to correlate the two unconformities. However, the presence of the previously noted unconformity north of the Escaleras Fault allows the possibility of interpreting the well bedded facies evident in the steep cliffs of the southern face of Cerro Durazno as belonging to the upper facies.

The case for distinct facies within the FNV is also supported by the complex contact relationships with the El Morterito Formation noted at the beginning of this section.

Within the study area (Fig. 3), the only sedimentary unit found above the FNV is a thin unit of boulder conglomerate which overlies a low angle unconformity and is only very sporadically encountered. This unit consists almost exclusively of rounded fluvial pebble to cobble conglomerates derived exclusively from the FNV, and when found is generally in the order of 2 to 4 m in thickness. This unit is tentatively correlated with the Punaschotter Formation as described by Sasso (1997), although the significantly reduced thickness makes correlation imprecise.

Intrusive Lithologies

Regionally, the porphyry intrusives which host the Alumbrera deposit form part of a calc-alkaline suite of dacitic porphyries which intruded the Sierras Pampeanas during the Miocene.

Within the area of outcrop of the FNV, there are several other partially explored mineralised dacite porphyries with lithologic, mineralogic and/or alteration characteristics similar to those at Alumbrera (see Fig. 3b). However, none seem to have developed the tenor of mineralisation that is apparent at Alumbrera and all are sub-economic at the current level of exploration. Ar-Ar dating of the intrusive phases at these prospects by Sasso (1997) indicated similar ages to the porphyries at Alumbrera, suggesting partitioning from a similar magmatic source. Comparative ages are given in Table 1.

Recent Ar-Ar dating of the mineralised dacite porphyry complex at Alumbrera by Halter, *et al.,* (2004) has confirmed an intrusion age of 6.8 Ma.

In addition to these mineralised systems, there are a series of northwest trending dykes passing to the east of the Alumbrera porphyry stock cluster. These are mineralogically and texturally distinct from the Alumbrera porphyries. They typically contain 5% to 10% euhedral hornblende crystals up to 10 mm across, rare blocky pyroxenes to 2 mm, and fine crystals of plagioclase to 1 mm, all set in a very fine-grained matrix. They form continuous dykes of between 5 and 20 m in width that can be traced for several kilometres from stock-like bodies north of the Buenaventura Fault. The timing of these dykes is difficult to determine, as contact relationships with other porphyries have not been observed in the field. One of these dykes has been mapped as being strongly deflected from sub-vertical and northwest-trending, to shallowly dipping north-trending as it approaches the Alumbrera porphyry stock cluster, suggesting that it is younger than the Alumbrera porphyries.

Deposit Name	Sample Number	Lithology	Determined Age
Durazno	FAR 65, 229, 224	Andesite porphyry	8.26 ± 0.13
Alto de la Blenda	FAR 216	Monzonite	7.50 ± 0.20
Agua Tapada	FAR 238	Dacite porphyry	7.39 ± 0.17
Alumbrera		P2 Porphyry	7.10 ± 0.13

Table 1: ***Comparative ages of mineralised porphyries intruding Farallón Negro Volcanics in the Sierras Pampeanas near Alumbrera.*** Ar-Ar dating by Sasso (1997).

Beyond the area of outcrop of the FNV Complex, there are several other mineralised porphyry systems in the northern Sierras Pampeanas. Comparative ages for a selection these are listed in Table 2. The most important is the ***Agua Rica*** porphyry copper-gold-molybdenum deposit (Fig. 3b), with quoted resources of 750 Mt @ 0.66% Cu, 0.037% Mo, 0.32g/t Au and 3.2g/t Ag at 0.4% Cu cutoff (Northern Orion Website, March 2004), which is currently at pre-feasibility stage of development.

The ***Capillitas*** deposit (Fig. 3b) is a rhyodacitic diatreme intruding the upthrust basement block of Capillitas Granite between Alumbrera and the Sierra de Aconquija. Mineralisation consists of a series of polymetallic hydrothermal veins that were exploited for copper, gold, zinc, lead and silver over a number of years. Currently, the mine produces gem quality rhodochrosite which formed as a final vein fill episode. The sulphide veins are cut by a late stage dacite dyke, dated at 5.16 ± 0.05 Ma, defining an upper age limit for mineralisation.

Deposit Geology

The Bajo de la Alumbrera deposit lies within a naturally occurring topographic "bowl" or "bajo" formed by the preferential erosion of the alteration halo surrounding the deposit. The Bajo covers an area of 3200 x 2200 m and has a central elevation of 2550 m ASL. The hills surrounding the Bajo reach a maximum height of 2880 m ASL in the southwest quadrant.

Mineralisation at Alumbrera is associated with the intrusion of a cluster of dacite (field term) stocks into the lower facies of the Farallón Negro Volcanics (FNV). Detailed mapping (Proffett 1997; 2003) has defined a total of 7 separate intrusions including pre-, syn- and post-mineralisation phases.

Pre-mineralisation porphyries are only of minor volumetric importance within the area of the mineralisation. A 5 to 20 m wide porphyry dyke known as the *Northeast Porphyry* occurs in the northeastern quadrant of the "Bajo". Although there are no directly observable contact relationships between this and other porphyries within the Bajo, mapping by Proffett indicates that the dyke is cut by mineralised quartz veins and is altered to a similar degree to the surrounding country rock, suggesting that it is a pre-mineral intrusive.

A second intrusive which may also be pre-mineral surrounds the main mineralised porphyry stocks on the south and western sides. This body - referred to as the *Los Amarillos Porphyry* (LAP) - is strongly altered by phyllic alteration, rendering it's original mineralogy and texture difficult to determine. However, in comparison to the other porphyries in the deposit it has an anomalous content of pink quartz phenocrysts to 5 mm in size, many of which are fractured. Proffett (2003) includes a body of *igneous breccia* within the LAP. The igneous breccia is described as having angular to rounded quartz vein fragments of various sizes, together with fragments of what appears to be quartz-magnetite altered P2 porphyry (see below) and andesite fragments to several tens of centimetres in size in a strongly altered quartz-feldspar matrix.

Both the Igneous Breccia and LAP are truncated by the earliest phase of the P3 porphyry. However no contact relationships exist between these bodies and the earliest mineralised porphyry phase, other than the presence of possible P2 blocks within the breccia. The LAP is atypical of the Alumbrera porphyries in general because the volume of the porphyry body decreases with depth, so that in cross section it resembles a "rootless stock". It is also apparently atypical of the remaining Alumbrera porphyry bodies in that the majority of mineralisation is vein-controlled with disseminated sulphides being virtually absent.

There are no well defined contact relationships between the Igneous Breccia and the LAP, so that the apparent age of the breccia (i.e. younger than P2) cannot be definitively extended to the LAP. Therefore, the LAP is regarded as being older than the mineralised porphyries within the Bajo, although it seems probable that the younger stocks may have exploited the same ascent route, suggesting that the age differences are relatively small.

Proffett (*op cit*) notes the presence of four distinct phases of intrusion of mineralised porphyry stocks, with an intrusive paragenesis based on observed contact relationships.

The *Colorado Norte or "P2" porphyry* is the oldest of the mineralised porphyries. The main residual mass of this porphyry occurs on the eastern side of the deposit, where it forms an oblate body which probably had original dimensions of approximately 350 m north-south by 200 m east-west and a depth extent close to the eastern porphyry margin of more than 500 m. The P2 body is extensively intruded by later porphyries, and as a consequence has an irregular outcrop pattern and unpredictable shape in cross section. Isolated occurrences of P2 are found elsewhere in the deposit, although these appear to be disconnected remnants and do not form interpretable bodies of significant size.

Of all the porphyries at Alumbrera, the P2 is generally the most strongly affected by quartz-magnetite alteration. Where the primary texture is still discernible, it is more

Deposit Name	Sample Number	Lithology	Determined Age
Agua Rica	FAR 169	Monzonite	8.56 ± 0.48
Cerro Atajo	FAR 307	Basaltic Andesite	8.15 ± 0.10
San Lucas	FAR 147	Dacite porphyry	7.35 ± 0.06
Capillatas	FAR 318	Dacite	5.16 ± (0.05

Table 2: ***Comparative ages of mineralised porphyries outside of the Farallón Negro Volcanics in the Sierras Pampeanas near Alumbrera.*** Ar-Ar dating by Sasso (1997).

finely crystalline than later porphyries, with plagioclase phenocrysts from 3 to 4 mm across within a mosaic textured quartz and potassic feldspar groundmass. Primary quartz crystals are extremely rare.

The *P3 suite* of porphyries is the major intrusive phase at Alumbrera. It represents the largest volume of porphyry within the deposit, and comprises several (three to five) separate mineralised intrusive pulses. These pulses are almost impossible to distinguish during pit mapping, because of their textural and mineralogical similarities. In drill core, contacts are usually identifiable by subtle changes in the intensity of potassic alteration or tenor of mineralisation. In some cases, flow alignment of phenocrysts indicates changes in the intrusive phases. The absence of well defined contacts cutting pre-existing veining and the highly irregular nature of contacts suggests that the separate intrusives formed as distinct pulses of magma intruding in rapid succession, before the previous pulse had time to solidify and form distinctive veins.

What is apparent, is that each successive pulse carried less potassic alteration, less magnetite and also less copper and gold.

Proffett (2003) records the presence of a porphyry of indeterminate age in the southeast of the deposit, the *Quartz Eye Porphyry* (QEP). The QEP has a definite cross cutting relationship with the P2 porphyry. P2 xenoliths occur within the QEP close to the contact between the two. Surface outcrops also contained numerous fragments of pink, partially resorbed quartz veins to 15 mm in diameter. The relationship between the QEP and the P3 porphyries however, is not well defined. Proffett (*op cit*) notes that quartz veins within the QEP are truncated by the late phase of the P3 porphyry, but that contact relationships between the QEP and the early phase of P3 are poorly defined. He also indicates that the QEP may in fact be a quartz-rich phase associated with the initial intrusion of the P3 stocks. Within the mine, the paucity of definitive contact relationships between the two porphyries leads to the interpretation that the QEP is part of the P3 stock.

Late northwest trending porphyry dykes cross the Bajo and extend for several kilometres in either direction away from the mine. These dykes cut all alteration features, except the youngest phyllic phase. Where the dykes cut strong phyllic alteration in both earlier porphyries and andesites, they are only weakly affected, usually with sericitisation of the plagioclase phenocrysts and partial chloritisation of mafics.

These late dykes are unmineralised, with the exception of rare, late pyrite veinlets that formed during phyllic alteration. Compositionally and texturally they are similar to the late phases of the P3 intrusive suite, with the notable exception that they are quartz phyric, with up to 5% quartz present as 5 to 8 mm subhedral crystals.

The origin of these porphyry dykes is unclear. However, the discovery of a small xenolith of mineralised, quartz-magnetite altered porphyry in a dyke some two kilometres southeast of the mine suggests that they may be late phases of the same parent magma as the mineralised porphyries.

Alteration and Mineralisation

Mineralisation

The global metal resource of the Bajo de la Alumbrera deposit (production + remaining resource and reserves as known at the end of 2004) is in the order of 3.36 million tonnes of copper and 409 tonnes (13.15 Moz) of gold.

The ore mineralogy of the Alumbrera orebody is relatively simple. Hypogene sulphide phases are dominated by chalcopyrite and pyrite. Minor chalcocite and covellite are confined to a thin enrichment zone which was developed sporadically in the upper 50 m of the deposit, and as coatings on pyrite crystals below the more heavily leached zones adjacent to the major faults. Gold occurs as inclusions and attachments to chalcopyrite, as rare free grains and less commonly as attachments to pyrite, although this latter association is not a significant contributor to overall gold production.

Active erosion within the Bajo prevented the development of more significant leaching or secondary enrichment zones at Alumbrera. Prior to mining, copper and iron sulphides existed at surface in the ore zones and surrounding areas of highly pyritic phyllic alteration of both the andesites and the dacite porphyries. Minor (generally less than 5% of total sulphides) chalcocite exists to depths of up to 250 m below the original surface in some parts of the deposit, almost exclusively as atoll textures around chalcopyrite grains. These occurrences are generally unrelated to other processes (such as leaching or oxidation) indicative of metal mobilisation, and so are not easily explained in terms of secondary enrichment processes. Qualitative analysis suggests that these occurrences may be related to mobilisation of iron or copper during phyllic alteration, although empirical evidence for such movement is lacking at this stage.

According to fluid inclusion studies undertaken by Ulrich, *et al.,* (2002) the primary driver for hypogene metal precipitation at Alumbrera was cooling of the metal rich brines following emplacement of the porphyry stocks. Their study documented the precipitation of around 85% of copper and gold from the ore fluid after cooling of the fluid from around 400ºC to 305ºC.

Economic mineralisation is present as both disseminated sulphide grains and sulphide veins and veinlets. In general, disseminated sulphides are most apparent in the earlier porphyry phases and tend to be less important in later porphyries, where mineralisation can often be controlled solely by veins and fractures. This probably reflects the relative cooling times of the porphyries, with rapid cooling of the earliest stocks “freezing” a relatively larger proportion of the ore fluid in the groundmass, and slower cooling of the later stocks facilitating migration of the fluid into fractures generated by the cooling magma.

Barren Core

A feature of the Alumbrera mineralisation in common with many other porphyry copper systems is the presence of a “Barren Core”. At Alumbrera, the barren core is an economic rather than a geological feature, defined by an

Colour plates 1 to 4

Double sided colour insert

Figure 4a & 4b

Colour plate with views of Geology and Mineralisation

Double sided colour insert

inner 0.15% Cu boundary in the central part of the porphyry complex. This boundary encompasses not only the late, barren or low grade intrusives of the P3 porphyry suite and late dykes, but also elements of the potassic or quartz-magnetite altered Early P3 and P2 porphyries. The barren core seems to have developed as a result of remobilisation of sulphides and gold during progressive heating of the central parts of the deposit by successive pulses of magma. In this model, the earliest mineralised intrusives were emplaced in a relatively cool rock mass. Metal rich fluids would have cooled quickly, depositing metal sulphides within the porphyry and immediately adjacent country rock. With successive pulses of magma injection, temperatures in the core of the deposit would have risen rapidly, to the degree that late fluids would have been under-saturated and able to remobilise the earlier sulphides. Fluid inclusion evidence (Ullrich *et al.,* 2002) supports this theory, with homogenisation temperatures of inclusions from the barren core often exceeding 700°C.

Late Sulphide Veins

Another feature of mineralisation at Alumbrera is the presence of late high grade massive sulphide veins which flank the Barren Core on the eastern and western sides of the deposit. These veins contain massive chalcopyrite and pyrite with rare selvedge alteration, which, if present, is usually biotite ± potassic feldspar. They typically cross cut other mineralised veins associated with earlier potassic alteration episodes. Sulphides and oxides usually comprise 90% of the vein volume. Gangue mineralogy is commonly quartz + biotite, although anhydrite is also represented. In the latter case, sulphides usually occupy the central part of the vein, allowing the possibility that the sulphides are occupying space caused by dilation of earlier anhydrite veins.

A feature of these veins which contrasts with the majority of mineralised veins in the deposit is the presence of specular haematite rather than magnetite as the dominant iron oxide. The hematite forms bladed crystals up to 10 mm in length, and usually comprises less than 10% of the metallic component of the vein.

The formation of these late veins is thought to be related to remobilisation of metals during development of the barren core. Where mining has exposed these veins on the eastern side of the deposit, they form a steeply dipping vein set trending approximately north-south, with individual veins able to be traced for up to 10 m, both along strike and down dip.

Alteration

Potassic Alteration

Mineralisation accompanied the intrusion of the various dacite porphyry stocks and was in turn accompanied by variable degrees of potassic alteration of the dacites and surrounding mineralised country rock. At Alumbrera, there is no direct relationship between degree of potassic alteration and mineralisation. Highly altered rock can sometimes only carry low copper and gold grades, while weakly mineralised material may at times contain high grades. In general however, increasing copper and gold grades reflect an increasing tenor of potassic alteration of the host lithology.

Throughout the deposit, and regardless of lithology, mineralised veins consist of chalcopyrite + pyrite + magnetite with accessory bornite and molybdenite in a gangue of either anhydrite ± gypsum or quartz + potassic feldspar ± biotite.

Potassic alteration within the porphyries is generally manifested by the progressive replacement of matrix minerals by a fine mosaic of quartz + potassic feldspar, and secondary biotite replacing authigenic hornblende and biotite with increasing intensity of alteration. At its most intense, potassic alteration results in complete recrystallisation of the groundmass, pseudomorphing of authigenic mafic minerals by secondary biotite and pseudomorphing of calcic plagioclase phenocrysts by potassic feldspar.

Within the andesites, potassic alteration is characterised by the development of secondary biotite in the matrix. Incipient biotitisation on the fringes of the alteration system produced sub-spherical clumps of secondary biotite that can initially be misidentified as extraneous rock fragments. With increasing intensity of alteration, secondary biotite becomes ubiquitous throughout the matrix, although the primary rock texture is still preserved. However, the most intense potassic alteration of andesite hosts results in almost total obliteration of the original rock fabric and its replacement by secondary biotite. In these zones of intense biotite alteration, mineralised veins often have halos of quartz and potassic feldspar, overprinting earlier formed secondary biotite.

Quartz-Magnetite Alteration

Magnetite is one of the principal components of the alteration and mineralisation system at Alumbrera. As already noted, magnetite is a consistent, if variable, component of mineralised veins. In addition, quartz-magnetite alteration is commonly associated with the earliest intrusive phases. This is particularly true of the P2 porphyry, a large proportion of which is overprinted by this style of alteration to such an extent that the original porphyry texture is obliterated. Similarly, large sections of the early stages of the P3 porphyry are affected by quartz-magnetite alteration which diminishes progressively in each of the successive intrusive pulses.

At a drill hole scale, it is tempting to consider that there was an initial stage of massive magnetite alteration that preceded copper-gold mineralisation of the P2 intrusive. Copper and gold grades correlate poorly with magnetite concentrations in many parts of this phase of the porphyry. Inspection of these areas reveals intervals of intense magnetite alteration which contain only sparse chalcopyrite. Where such mineralisation is present, it is always associated with quartz veining, and sulphides always have one common boundary with a silicate mineral. These intervals give the appearance of a phase of intense magnetite alteration which overprinted the porphyry soon after its intrusion and preceded the main sulphide mineralisation.

Propylitic Alteration

Propylitic alteration at Alumbrera is defined by the presence of epidote and chlorite together with the sporadic development of calcite veins and breccias. It forms a nearly circular halo around the Alumbrera deposit, and fits neatly within the confines of the Bajo. At the outermost limit of the propylitic zone, chlorite was sporadically formed in the matrix of andesite debris flow material, while epidote tends to pseudomorph fine plagioclase. Chlorite dominates the alteration system in these areas, particularly in the hills on the eastern side of the Bajo. In the more competent andesite dykes, alteration tends to be confined to millimetre scale chloritic alteration halos fringing fractures and by occasional epidote + chlorite + carbonate veins.

Closer to the intrusive centre, the texture of the alteration changes to knots and masses of chlorite and epidote, with epidote being relatively more abundant than in the outermost parts of the alteration halo.

At Alumbrera, the propylitic alteration zone is unmineralised, with the exception of some pyritic veining on its inner margin where it has been overprinted by later phyllic/argillic assemblages. The temporal relationship between the potassic and propylitic alteration is deduced to be approximately coeval, as late dykes in the northwest of the deposit cut both potassic and propylitic alteration styles, but are affected by later phyllic alteration. The absence of significant sulphur as either sulphides or sulphates implies that the alteration is not directly influenced by magmatic fluids.

In addition, the absence of quartz veining associated with this alteration style indicates that the fluids producing the alteration never reached significant temperatures, or that insufficient quantities of fluids passed through the rock. Limited geochemical data indicate there has not been significant chemical addition or removal affecting the bulk composition of the parent andesites. These field observations, together with the geochemical data, support the suggestion by Proffett (2003) that the propylitic alteration at Alumbrera is a product of isochemical modification of the rock mass by meteoric water drawn to the intrusive centre as part of a convective cell or during cooling of the porphyry mass.

Feldspar Destructive Alteration

The term “feldspar destructive alteration” (FDA) is used at Alumbrera to encompass an alteration style which includes processes generally recognised as phyllic and/or argillic styles. The application of these terms has been avoided at Alumbrera due to the ambiguity of their use in the literature.

At Alumbrera, FDA developed relatively late in the thermal evolution of the deposit. It overprints both the potassic and propylitic alteration assemblages, and can be found in all porphyry phases. It tends to be most intense in the andesites beyond the boundaries of the central porphyry stocks, although as noted previously, the Los Amarillos Porphyry has been strongly modified by this alteration style. Sericite from the FDA zone has been dated at 6.75 ± 0.09 Ma by Ar-Ar methods (Sasso & Clark, 1998).

Within the central porphyry mass, FDA generally only weakly overprints the preceding potassic alteration styles, to the extent that remaining plagioclase phenocrysts are altered to sericite, and mafics are generally replaced by chlorite of brown sericite. Magnetite is altered to chlorite in some areas, and destroyed with increasing intensity of FDA.

Alteration seems to stop with the formation of what would be termed “argillic” alteration in other hydrothermal systems. A poorly constrained survey of the alteration at Alumbrera by Hauff (1995) using a PIMA infra-red spectrometer indicates that illite is the dominant clay mineral developed during FDA, accompanied by an irregular and subordinate distribution of kaolinite. Advanced argillic alteration, with the accompanying formation of kaolinitic clays, is generally restricted to fault zones where percolation of meteoric water and the oxidation of sulphides produce low pH zones for several metres adjacent to the principal faults.

Weak FDA within the porphyries initially results in sericitisation of plagioclase and chloritisation of the mafic minerals. With greater intensity, chloritised mafics change progressively to brown and then to white sericite, with concurrent sericitisation and chloritisation of matrix material. With increased alteration, formation of expanding clays becomes evident, particularly at sites of former plagioclase phenocrysts.

Within the andesites, weak FDA manifests itself as alteration of primary or secondary mafic minerals to chlorite or brown sericite. With increasing intensity of alteration, iron is progressively lost from the silicate minerals and chlorite and brown sericite are converted into white or clear sericite and clay minerals. At its most intense, the original texture of the rock is obliterated and recognition of primary lithology becomes impossible.

In all lithologies, FDA is accompanied by the development of a pyritic stockwork incorporating sub-millimetric up to 10 mm thick massive veins. The selvedges of these veins are almost invariably altered to the assemblages noted above (“D” veins of Proffett, 2003). The density of pyrite veining therefore tends to control the intensity of FDA, although the susceptibility of the host lithology to alteration also plays a significant role.

Sulphate

Sulphate veins are present to a greater or lesser degree throughout the deposit. In the upper parts of the orebody and surrounding rocks, the dominant sulphate is gypsum, which forms intense network vein systems in the andesites adjacent to the porphyry stocks, and also within the porphyries themselves. Intense gypsum veining is often associated with FDA, which is most commonly found in the upper parts of the deposit.

With increasing depth within the alteration system, anhydrite becomes the dominant sulphate, forming mosaic textured finely crystalline pink and purple veins up to 10 mm thick in both the porphyries and andesites.

Mineralised primary sulphate veins are associated with the intrusion of the porphyries, and include both gypsum and anhydrite as the gangue mineral, either in distinct veins or coexisting with sulphides in the same vein. Sulphides (pyrite and chalcopyrite, with occasional molybdenite) are disseminated within the veins, or may form a distinct centreline. When found in potassic altered andesites, primary sulphate veins have sharp, well defined boundaries with the surrounding rock, or are rarely flanked by selvedge zones of potassium feldspar, suggesting that they were in chemical equilibrium with the wallrock. At the deepest levels of sulphide mineralisation, anhydrite veins contain disseminated fine grains of primary bornite.

Weakly mineralised or barren sulphate veins were also produced during FDA, due to the alteration of primary lithologies, particularly calcic plagioclase, which probably liberated abundant Ca. These veins occupy secondary sites such as joints and faults. The processes involved in their formation may also have resulted in the redistribution of minor amounts of sulphides, to produce weak mineralisation in the vein set.

A second, unmineralised family of fibrous gypsum veins up to 30 mm thick is also found at Alumbrera, although it is volumetrically less significant than the mineralised sulphate veins. Where the two styles can be seen together, fibrous veins truncate the mineralised variety. These fibrous veins generally lack sulphides, although disseminated pyrite occasionally occurs within them. They are distributed sporadically around the fringes of the deposit, notably on the eastern side of the Bajo, close to the outer limit of FDA.

One possible explanation for the distribution of veining as noted above is that anhydrite veins accompanied the main intrusive and mineralisation phases, and were sites of sulphate deposition as the fluids cooled. In the upper parts of the orebody, hydration during the FDA event converted anhydrite to gypsum, and resulted in the formation of mineralised gypsum veins.

Volume changes resulting from the hydration of anhydrite and development of FDA may then have caused slow dilation in the surrounding rock mass, allowing the development of the late unmineralised fibrous gypsum veins.

Structure

The principal faults mapped within the Bajo, which reflect the transtensional northwest trending structural trend discussed previously, are post-mineral. Their relationship to FDA and to late northwest trending dykes suggest that structural disruption of the mineralisation occurred during the waning stages of the FDA event. There is no evidence of significant pre-mineral structures within in the Bajo which may have acted as a focussing mechanism for the intrusion of the mineralised porphyries.

The main structures which transect the orebody are normal faults with movements of up to 200 m throw and a variable sense of strike-slip movement. The recent interpretation of quartzite basement beneath the FNV has allowed a refinement of movement vectors.

There are three principal faults which displace ore blocks. On the east side of the Bajo, the moderately southwest dipping (60 to 70°) Ron Fault has displaced the quartzite basement by more than 150 m. To the west of the deposit, Steve's fault is a moderately east dipping (50 to 65°) normal fault which has displaced the western porphyry boundary by up to 200 m. The third major structure is the Gypsum Fault, a steeply west dipping (60 to 75°) structure with interpreted left lateral movement of up to 70 m (based on displacement of ore boundaries), and a vertical component of 20 to 50 m in the normal sense. The latter fault is characterised by extensive development of platy gypsum and clay, indicating that the fault may have been active during the development of FDA.

Prior to the discovery of the quartzite basement blocks beneath the deposit and the recent discovery of an unconformity within the FNV, Proffett (1997; 2003) had interpreted vertical movement on the Gypsum Fault to be in the order of 200 m, based on the offset of volcanic stratigraphy in the eastern and western slopes of the Bajo.

Mine development during 2004 revealed the presence of a previously unmapped fault crossing the northern pit margin. The Rampa Norte fault appears to have formed relatively late in the structural development of the deposit. Initial mapping indicates this structure displaces the Gypsum Fault, and probably the Ron and Steve's Faults as well. Relative displacement of the Gypsum Fault shows high angle reverse movement, making Rampa Norte fault unique within the pit area. At currently exposed levels, the fault juxtaposition of weakly mineralised blocks, and a paucity of correlatable features prevents an accurate estimation of ore displacement. It remains an interesting target for future drilling programs.

In summary, faulting within the mine area appears to be the result of transpressional forces generated by clockwise rotation of up to 29° in the northern Sierras Pampeanas during the late Miocene or early Pliocene (Aubrey, e*t al.,* 1996). A structural paragenesis would have the Gypsum Fault as the earliest interpretable structure within the mine area, followed by the development of the Ron and Steve's faults. Current information suggests that the Rampa Norte fault is the youngest significant structure.

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