

MARCONA AND PAMPA DE PONGO: GIANT MESOZOIC Fe-(Cu, Au) DEPOSITS IN THE PERUVIAN COASTAL BELT

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Abstract – Located approximately 400 km south of Lima, Peru, the Marcona and Pampa de Pongo deposits are the largest iron accumulations with associated copper and gold along the western coast of South America. Approximate resources include more than 1400 Mt of iron ore at Marcona and 1000 Mt of magnetite mineralisation at Pampa de Pongo. Both deposits contain some copper and gold and exhibit numerous features that allow their inclusion in the “Iron Oxide-Copper-Gold” clan of deposits, alongside such examples as Candelaria and Mantos Blancos in Chile. The two deposits form part of a cluster of similar occurrences that together define the “Marcona Fe-Cu District”.

The Marcona iron deposits were first identified in 1915 and mining commenced in 1953, while artesanal copper mining had been carried out in the district from the late 19th century. The larger iron bodies are hosted by the Lower Paleozoic Marcona and Middle to Upper Jurassic Río Grande Formations. The Marcona Formation is dominated by arenites and both calcitic and dolomitic carbonates, whereas the Río Grande Formation comprises a thick sequence of basaltic andesites and andesites (sills and flows), volcanoclastics and minor limestones. Although including major carbonate replacement facies, the iron deposits widely exhibit previously undocumented, intra-mineralisation hydrothermal breccia textures and multistage iron oxide \pm sulphide/copper mineralisation. Copper mineralisation is mainly associated with magnetite and lesser specularite. The iron oxide bodies strike northeast and north-northwest and show both fault and lithological controls on ore geometry. Intra- and post-iron mineralisation igneous activity in the Marcona Mine area included dacitic/granodioritic dykes and andesitic “ocöite” dykes.

The hitherto undocumented Pampa de Pongo Fe (-Cu-Au) deposit, covered by at least 20 m of sand, was discovered in 1994 by drilling a large magnetic anomaly 30 km southeast of Marcona. Host rocks to the mineralisation are dolostones and andesitic volcanics of the Oxfordian-Tithonian Jahuay Formation, which are higher in the sequence than the Marcona iron deposits. The iron mineralisation exhibits both replacement and breccia-fill facies within a steeply northwest-dipping fault corridor. Magnetite mineralisation in the andesites is associated with Fe-chlorite, talc and clinochrysotile, whereas replacement of the underlying dolostone includes magnetite-amphibole-serpentine associations.

The age of the Pampa de Pongo deposit is uncertain, although the preferred genetic model for the district involves a large metal flux coeval with deep-seated Jurassic, and probably Cretaceous igneous intrusive activity. This was triggered by the introduction of mantle-derived melt along the root zone of the extensional faults within an active continental arc. At a local scale, iron oxide-associated mineralisation at Marcona, Pampa de Pongo and the surrounding district probably formed in an environment characterised by repeated crustal extension over a +20-60 my period. The anomalous concentration of thick andesitic volcanics or sills and dykes at Marcona, and evidence for district-scale thermal anomalies preceding and during the main introduction of iron oxide mineralisation, indicate that the area was also an important volcanic centre and the site of a long-lived thermal anomaly.

Introduction

The Marcona Fe (-Cu, Au, Zn, Co) deposit and Pampa de Pongo Fe (-Cu-Au) prospect represent two large Fe-oxide-rich Mesozoic hydrothermal centres situated approximately 400 km south of Lima, Peru. (Figure 1). Together with the granitoid-hosted magnetite-apatite system

at Hierro Acarí (Injoque, 1985, and Vidal, *et al.*, 1990) and Cu-Fe-Au vein system at Cobrepampa, the two deposits make up a strongly mineralised segment of the littoral zone, herein termed the Marcona Fe-Cu District, which constitutes the apparent apogee of this mineralisation style in the Central Andes.

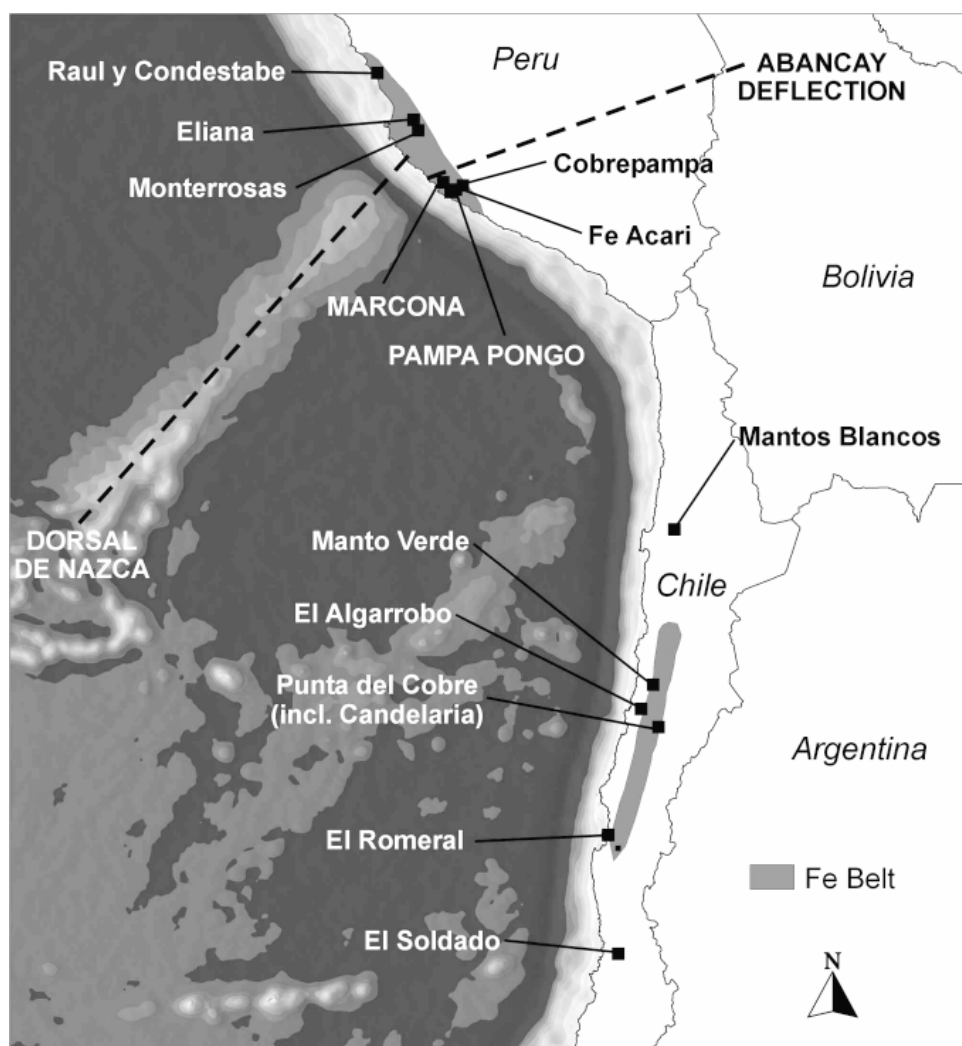


Figure 1: Map of South America showing the location of major FeOx-Cu-Au deposits.

Total resources at the Marcona mine include approximately 1440 Mt @ 54.1% Fe and 0.11% Cu, dispersed in eight major and at least 47 minor orebodies. Preliminary drilling at Pampa de Pongo infers a resource of more than 1000 Mt @ 75% magnetite. Each of these centres incorporates more ore-grade magnetite than the entire Chilean Cretaceous iron belt, and together they represent the most important metallogenic episode of Mesozoic age in the Central Andes. Although Cu has been only modestly produced at Marcona and economic grade Cu and Au has not yet been identified at Pampa de Pongo, these deposits clearly correspond in all salient aspects to the iron oxide-rich copper-gold-polymetallic clan. Megascopic and microscopic petrographic relationships at Marcona and Pampa de Pongo indicate many points of comparison with the Chilean deposits, particularly Candelaria (Ryan, *et al.*, 1995; Ullrich & Clark, 1997; 1999; Ullrich, *et al.*, 2001).

The Marcona deposit has been widely described since its original development, having been the subject of a dedicated PhD thesis (Atchley, 1956) and included in comprehensive overviews of the “Cu-Fe-amphibole [skarn] deposits” of the coastal area of central Peru (Injoque, 1985; Atkin, *et al.*, 1985; Vidal, *et al.*, 1990). However, there is little detailed information on *mesoscopic* textural relationships. Hence, key aspects of ore genesis remain

obscure. Information on the early history of mining and exploration at Marcona is summarised from Adrian (1858) and Bourret and Hayes (1957). Pampa de Pongo has not been previously described.

Geological Setting

A belt approximately 70 km wide and stretching 400 km along the Peruvian coast from Lima to south of Chala (*ca.* 16° S) hosts numerous mineral occurrences grouped together under the general heading of iron oxide-copper-gold deposits (*eg.* Clark, *et al.*, 1990; Figure 1). The belt consists locally of a series of Precambrian gneisses and schists overlain by subordinate Palaeozoic sediments and volcanics and by more extensive volcano-sedimentary rocks of Triassic-Jurassic age. Numerous dykes and stocks ranging from acidic to basic composition intrude the belt. Tertiary ignimbrites and Quaternary aeolian deposits cover a large part of the area. The geological relationships at Marcona (Figure 2) have been well documented by, *inter alios*, Atchley (1956), Caldas (1978) and Injoque (1985), and the regional setting is clearly described by Shackleton, *et al.* (1979) and Pitcher, *et al.* (1985).

The Marcona Fe-Cu District lies athwart the intersection of the aseismic, NE-trending Nazca Ridge (*Dorsal de*

Nazca) and the continental margin, delimiting the southern limit of the major Peruvian flat-slab domain and the northern limit of the Central Volcanic Zone. It also lies in the region of the Abancay Deflection. The latter forms a continental-scale NE-SW sinistral shear zone centred in the *Cordillera Oriental*.

Stratigraphy in the Marcona Fe-Cu District includes a Mesoproterozoic (Wasteneys, *et al.*, 1995) basement gneiss complex, overlain by Paleozoic dolomites, limestones and sediments and a thick sequence of Jurassic volcanics and sediments. Caldas (1978) subdivides the Palaeozoic sequence into the San Juan Formation and Marcona Formation, with the upper distinguished from the lower unit by the presence of a quartzite layer and thin chert laminations within the carbonates. The Jurassic sequence has also been subdivided by Caldas (1978) into the Río Grande, Jahuay and Yauca Formations. The Río Grande Formation and overlying Jahuay Formation include mostly andesitic volcanics, sediments and limestones. The Yauca Formation includes mostly fine-grained sediments and lesser sandstone. The iron bodies at Marcona are sufficiently extensive to be distinguished as a distinct unit ("*fierro*") on the 1:100 000 scale geological map of the San Juan quadrangle (Caldas, 1978). Figure 3 is a summarised stratigraphic column illustrating both the older classification of Atchley (1956) which is still used by the mine geologists at Marcona, and the more comprehensive work of Caldas (1978) together with published dates for mineralisation and host formations from Vidal, *et al.* (1990) and Wasteneys *et al.* (1995).

A wide-range of intrusive rocks are recognised in the Marcona area. The San Nicolás Batholith intrudes the basement metamorphic complex and the Palaeozoic

sediments, but predates the Jurassic sequence. Compositional variations within the batholith include monzogranite in the centre passing outwards to granodiorite and gabbro-diorite. U-Pb zircon ages for the batholith include 390 ± 23 –46 Ma and, more reliably, 425 ± 4 Ma (Mukasa and Henry, 1990). It is inferred that upper greenschist-amphibolite facies metamorphism in the basement rocks predates intrusion of the San Nicolás Batholith (*eg.* Atchley, 1956). Units of the more extensive Coastal Batholith occur east of Pampa de Pongo but are not found in the Marcona mine area. Several intra- and post-mineral hypabyssal intrusives and dykes occur in close proximity to the iron mineralisation. Andesitic "ocöite" dykes cut the iron mineralisation in the Marcona mine area while rocks of similar composition are also present at Pampa de Pongo.

Marcona

Location and General Geology

The Marcona iron deposits are centred at Latitude $15^{\circ}12'30''\text{S}$, Longitude $75^{\circ}7'30''\text{W}$. Small-scale copper mining probably commenced in the district during the late 19th century and continued episodically up to the mid-1980s. Discovery of the Marcona iron deposits was announced in 1915 and mining has been in progress since 1953. In the mine area, the iron deposits are mainly hosted by the Marcona Formation, but also occur in the Río Grande Formation and locally cut the basement. The San Nicolás Batholith crops out to the east of the mines and shows only restricted alteration, suggesting it played no significant role in the genesis of the Marcona iron deposits.

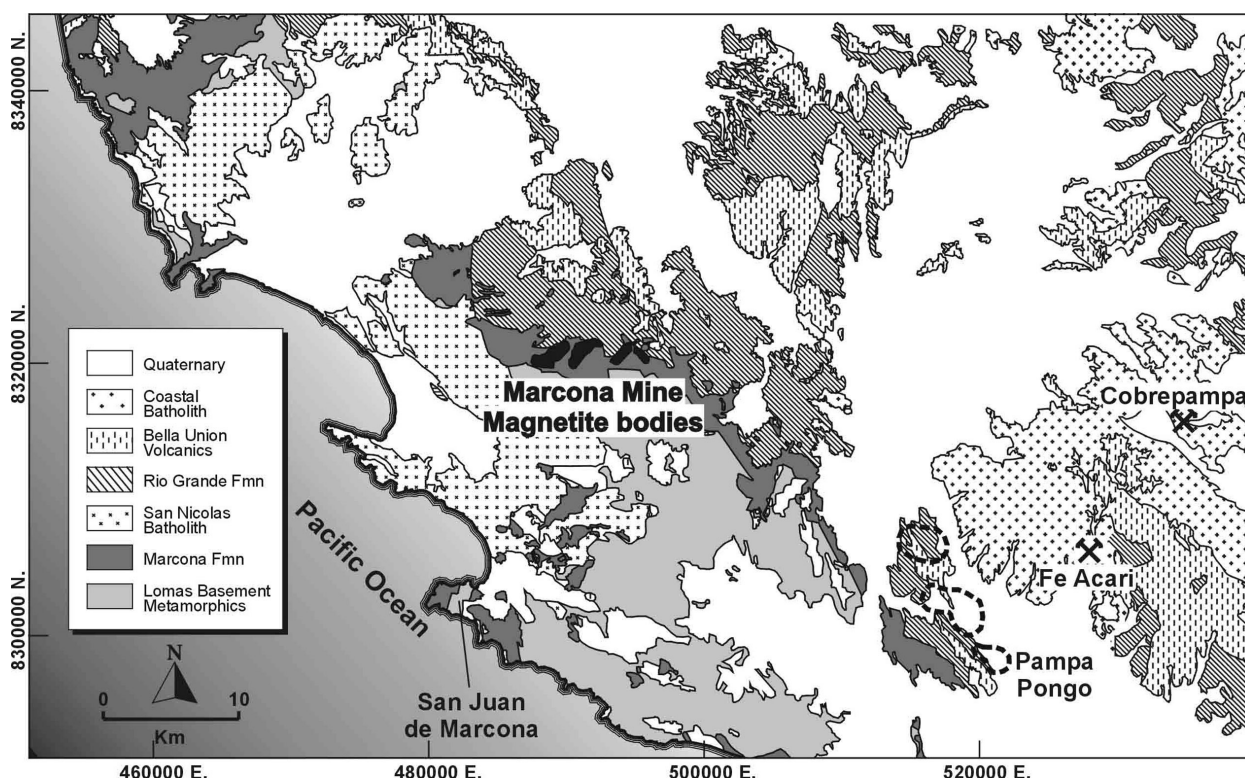


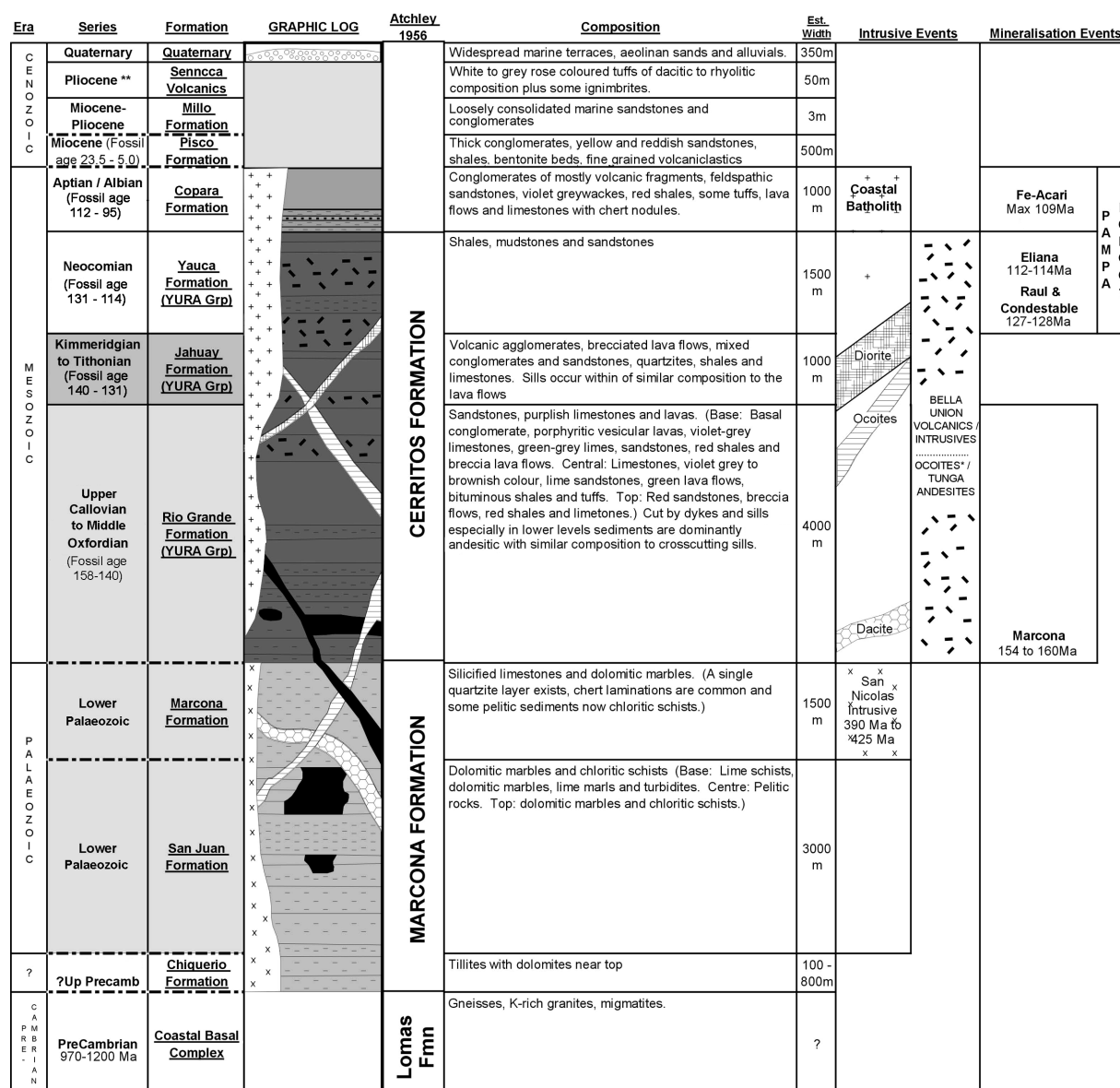
Figure 2: Marcona District Geology

In the mine area, the Marcona Formation is dominated by calcareous rocks, pelites and minor quartzites.

The overlying Río Grande Formation is dominated by porphyritic basaltic-andesitic and andesitic volcanics/sills, volcaniclastics and restricted intercalated shallow-marine limestones containing Toarcian to Oxfordian fauna (*ie.*, *ca.* 143-156 Ma, Caldas, 1978). Dacite and “granodiorite” dykes are observed to exhibit a close relationship to mineralisation. The significance of these dykes has not been studied.

Injoque (1985) and others describe the majority of the volcanic rocks in the Marcona area as shoshonites or latitic andesites, on the basis of K_2O contents of 2.79-3.76 wt.% at SiO_2 contents of *ca.* 52-53 wt.% SiO_2 (*cf.* Peccerillo and Taylor, 1976). However, there is no petrographic evidence for primary magmatic K-enrichment and even the least altered flows and dykes exhibit strong sericitisation of

plagioclase phenocrysts. In a study of burial metamorphism in the Río Grande volcanic succession, Aguirre and Ottley (1985) document such sericite as a component of prehnite-pumpellyite assemblages, but its abundance strongly implies a hydrothermal origin (A.H.C., unpubl.). Hence, on the basis of petrographic observations and alteration characteristics, the volcanics are more-correctly termed high-K calc-alkaline augite andesites. The numerous volcanic and hypabyssal units in the Río Grande Formation near Marcona are frequently characterised by closely spaced, large (# 1.5 cm diameter), glomerophyric aggregates of plagioclase phenocrysts recording multiple magmatic dissolution/overgrowth events, but do not appear to be otherwise unusual. The Chilean term “ocóite” is used locally to describe the dykes due to their characteristic porphyritic appearance in hand specimen. A low-grade metamorphic overprint assemblage is also recognised in the volcanics comprising albite-actinolite-chlorite-titanite \pm epidote/clinozoisite (Reynolds, 2002).



**Early Miocene radiometric date reported by Noble, 79

Principal host for PAMPA PONGO MINERALISATION
Principal host for MARCONA MINERALISATION
Unconformity

Compiled from work by Atchley, 1956 and Caldas, 1978. Mineralisation event dates from Vidal, *et al.* 1990. Age for the Precambrian basement from Wasteneys, *et al.* 1995.

Figure 3: Summarised Stratigraphic Column

The Marcona deposits have received only scant attention from the standpoint of modern geochemical techniques. Thus, only two sulphur isotopic analyses are reported by Injoque (1985): values of -1.76 ‰ and +4.72 ‰ for pyrite are in permissive agreement with a magmatic-hydrothermal origin, but no explanation is given for the compositional difference. Vidal, *et al.* (1990) provide a single Pb isotopic analysis for pyrite. The data, viz. $^{206}\text{Pb}/^{204}\text{Pb} = 18.208$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.567$ and $^{208}\text{Pb}/^{204}\text{Pb} = 38.381$ fall in the range for the wider Arequipa segment of the Mesozoic Coastal Batholith. The very low $^{206}\text{Pb}/^{204}\text{Pb}$ ratio reveals extensive “contamination” by the U-depleted Mesoproterozoic granulitic basement, presumably through assimilation-fractional crystallisation processes. The other comparable deposits analysed by Vidal, *et al.*, Raúl, Eliana, Monterrosas and Leonila, are not demonstrably underlain by the Arequipa Massif, and exhibit more radiogenic $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios.

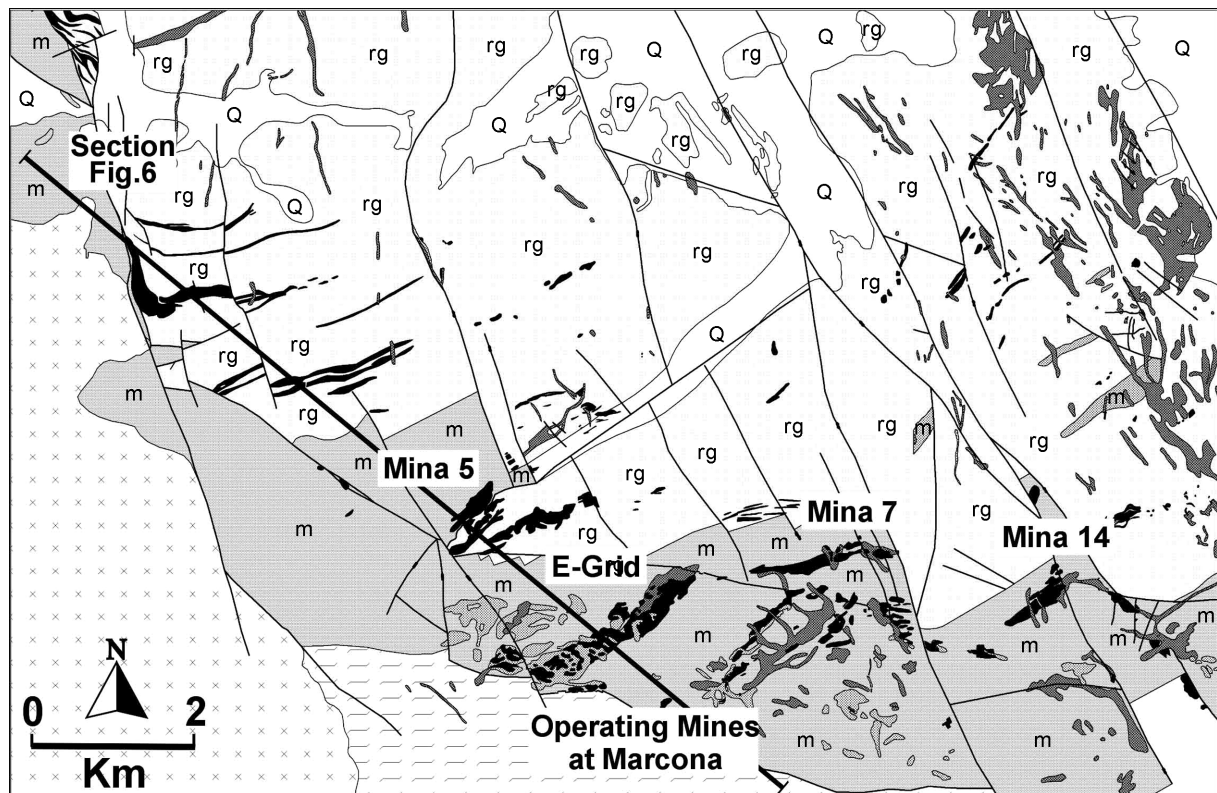
Structure

Three principal structural systems are recognised in the mine area (Atchley, 1956). The Pista Faults, probably the

oldest, strike 295° and dip at 60° to the north. These normal faults were active before and after mineralisation. The Repiticion fault system comprises a series of reverse faults paralleling stratigraphy and with a strike direction of 045° and a 65° northerly dip. Finally the major Huaca fault system which parallels the Cordillera also comprises normal faults with a strike of 335° and dip of 60° to the east. The late stage ocoite dykes are generally aligned parallel to this trend. The Huaca faults have probably been sites of repeated reactivation since at least the early Mesozoic and have a strong influence on present-day topography which would have formed during Miocene to Pliocene uplift and erosion.

Ore Deposit Geology

The gross form and setting of the numerous magnetite orebodies have been well described by Atchley (1956) and subsequent workers. Although iron and copper mineralisation occurs in both the Marcona Formation and in the stratigraphically overlying Río Grande Formation, the iron bodies in the former tend to be larger and higher grade. The main iron bodies are massive, lensoid to tabular



LEGEND

Q	Quaternary	rg	Río Grande Formation
	Ocoite Dykes		San Nicolas Granodiorites
	Magnetite	m	Marcona Formation
	Dacite Intrusives		Basement Complex

Figure 4: Marcona Mine area geology, adapted from Shougang Heirro Peru.

and broadly concordant with the stratification. These occur as crudely *en echelon* arrays of thick, NE-elongated bodies which dip at *ca.* 35°-65°NW, sub-parallel to lithological contacts, and are concentrated in two horizons, termed “E-grid” and 600 m lower stratigraphically, “Mina 7” (Figures 5 & 6). Stockwork-style and disseminated iron mineralisation is also present. Magnetite and specular hematite iron mineralisation occurs in the Río Grande Formation and shows a similar geometry to that in the

Marcona Formation. Both the more massive and stockwork iron mineralisation carry some copper.

Ore-waste contacts are irregular in detail and dyke-like bodies of magnetite widely crosscut all host-rock fabrics. Igneous intrusions, broadly coeval with magnetite emplacement, and including strictly intra-mineralisation bodies, comprise dyke swarms of dacitic “granodioritic” and andesitic composition.

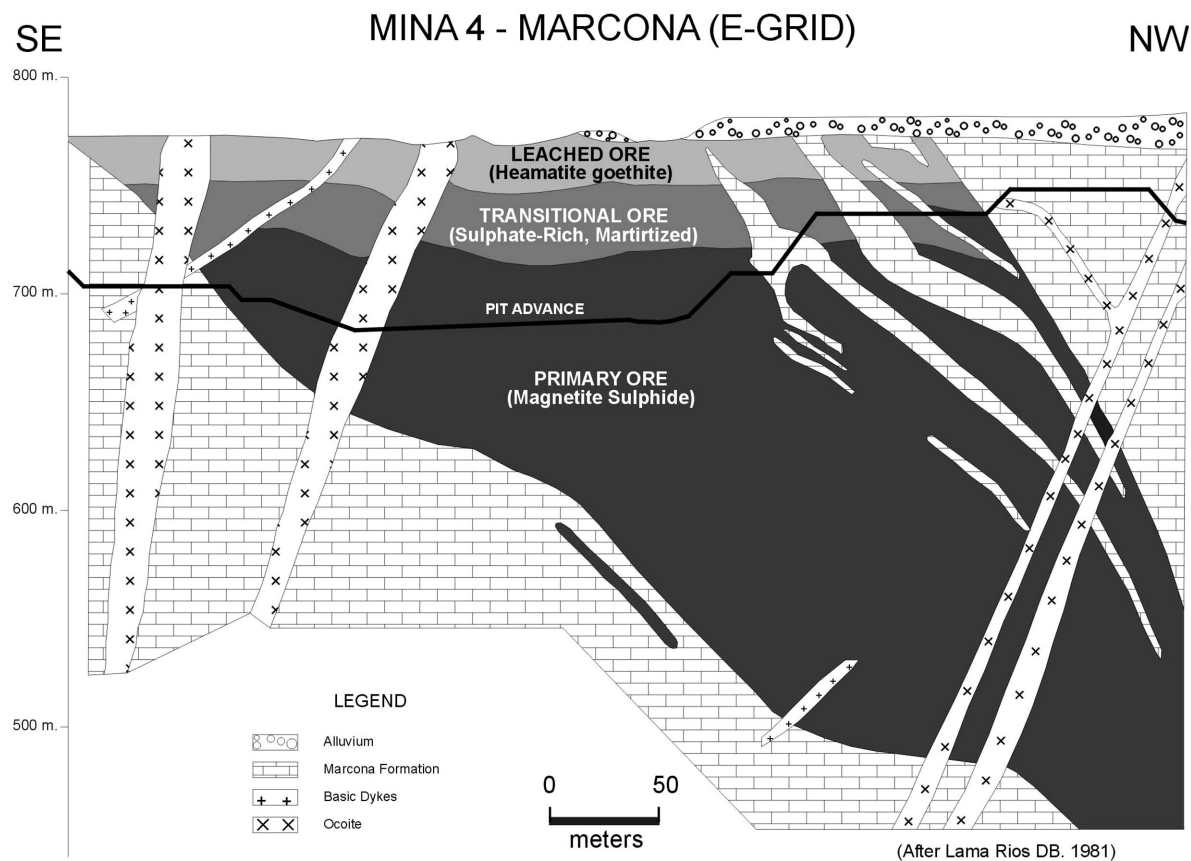


Figure 5: Marcona Section E-Grid (Mine 4) area.

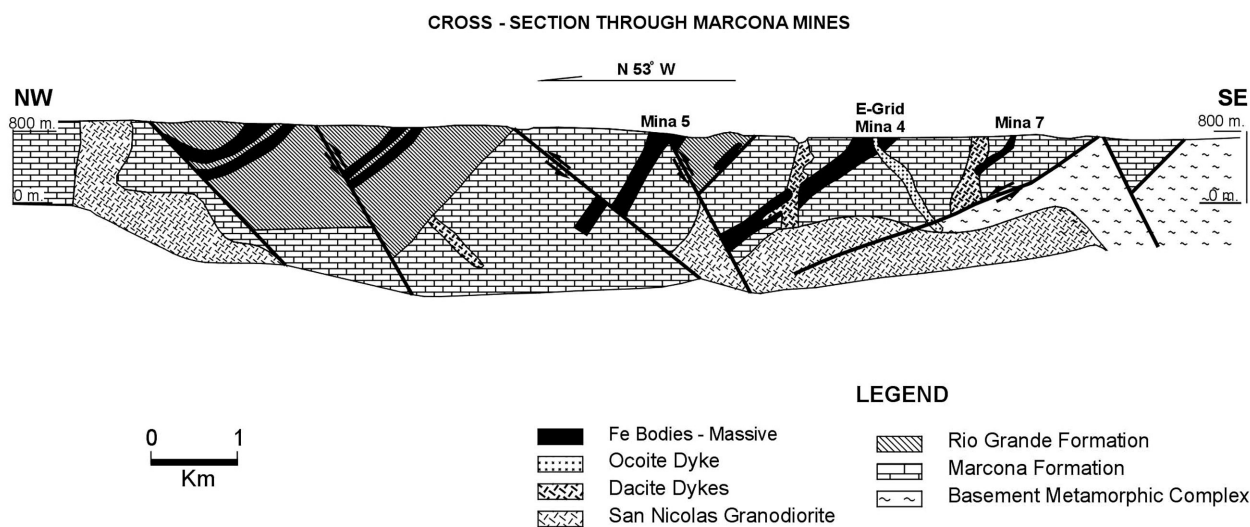


Figure 6: Marcona Section Regional Interpretation

Conventional K-Ar dates of 160 ± 4 and 154 Ma from hydrothermal phlogopite and sericite (Injoque, *et al.*, 1988) would assign the mineralisation to the late stages of arc development. This is supported by the pre-, intra- and post-mineralisation context of swarms of andesitic dykes that probably constitute feeders for the younger Río Grande Formation flows. Vidal, *et al.* (1990) reported whole rock K-Ar dates of 118 ± 3.0 to 137 ± 3.0 Ma for three intermediate post-ore dykes: these ages are unremarkable, but whole-rock dates for such lithologies are notoriously unreliable.

Inferred orebody protoliths include both calcareous and quartzo-feldspathic clastic and pyroclastic horizons intercalated in the andesitic succession (Injoque, *et al.*, 1988). These authors also suggest that extensional fracture zones controlled both fluid circulation, and the emplacement of sill and dyke complexes. In such zones, it is implicit that permeable andesitic rocks have suffered intense Fe-metasomatism, a process more clearly shown by the Pampa de Pongo mineralisation. Moreover, it seems likely that the Fe orebodies hosted by the Palaeozoic and Jurassic strata represent a single, large-scale hydrothermal system.

Finely laminated fabrics are widely exhibited by magnetite- and/or sulphide-rich ores at Marcona and are interpreted as relict bedding (*eg.* Atchley, 1956; Injoque, 1986). Certainly, such textures are commonly observed on the margins of the Marcona orebodies and at Pampa de Pongo, and in such cases selective replacement of carbonate-rich laminae may reasonably be inferred. However, some cases of non-sedimentary fabrics are apparent, such as crudely cylindrical alternating layers of magnetite and/or sulphide and amphibole or chlorite. We interpret such textures as “wrigglic” (*cf.* Kwak and Askin, 1981), reflecting the progress of a metasomatic front through a relatively homogeneous protolith. Such textures are widespread in true skarn deposits, but are not restricted to carbonate hosts.

A further important textural question concerns the role of breccias, which, to our knowledge, have not been recorded by previous workers. Preliminary field studies of the largest mineralised zone, comprising Minas 2, 3 and 4 in the Marcona Formation, as well as examination of drill-core from Mina 11 and Mancha 13, indicate that hydrothermal breccias dominate large proportions of the high-grade (>50% Fe) mineralisation. The breccias exhibit matrices with varying proportions of magnetite, amphibole, phlogopite-biotite-chlorite and sulphides. Two or more superimposed brecciation events are evident in some of the pits and segments of drill core. The breccias range from “jigsaw” fabrics, in which little relative displacement of clasts has occurred, through angular, matrix-supported to “amoeboid” or “ductile” fabrics. A similar spectrum of breccia-types occurs at the Candelaria Cu-Au deposit, Chile (Ullrich and Clark, 1996, 1997). In some outcrops, the clasts exhibit strong variations in lithology or, more typically, alteration type and intensity, and in such cases significant transport of clasts may be inferred.

Our observations, although not comprehensive, suggest that intense hydrothermal fragmentation played a major role in

ore formation. Injoque (1985) favoured a more passive replacement process. It should be emphasised that the breccias, well exposed in for example, Minas 2 and 3, are strictly *intra-mineralisation*, and thus reveal the conditions of emplacement of magnetite and sulphides (mostly pyrite and/or chalcopyrite), rather than recording merely post-ore disturbance. The irregular hanging-wall contact of orebody 3 clearly shows apophyses of magnetite+sulphide-cemented breccia that are re-brecciated and cemented by magnetite-amphibole assemblages.

Weathering and supergene leaching has resulted in a vertical zonation through the iron ore bodies. The upper parts are characterised by massive hematite with actinolite together with minor malachite, atacamite, brochantite and chrysocolla grading down through a transitional zone containing hematite, jarosite and gypsum that overlies the primary zone dominated by magnetite-actinolite-pyrite+chalcopyrite. The main period of weathering related oxidation occurred prior to deposition of the uppermost Pliocene to Pleistocene shallow marine sediments (*eg.* Atchley, *op cit.*; Ortlieb and Macharé, 1990).

Alteration-Mineralisation Relationships

There are few detailed descriptions of the paragenetic relationships of the Marcona orebodies and systematic studies have not been carried out. Previous studies have tended to oversimplify the sequence of events, conforming to traditional skarn models in which “prograde” (anhydrous) silicate minerals precede “retrograde” (hydrous) and magnetite precedes sulphides (*eg.* Injoque, 1985). Preliminary logging of core from Mina 11, Mancha 13 and bench faces in Minas 2, 3 and 4, all in sulphide-rich ore facies, indicate that no such simple transitions occurred. Observations on alteration relationships described here are mostly anecdotal, but the increasing development of several minerals in the vicinity of mineralisation is a guide to the major processes. The main iron minerals are magnetite and haematite. Sulphides include pyrite, pyrrhotite, chalcopyrite, lesser bornite, chalcocite, sphalerite, galena and minor carrollite. Molybdenite, pentlandite, mackinawite and gold have also been reported (*eg.* Injoque, 1988). The paragenesis of the principal iron oxide and sulphide minerals is summarised in Table 1 based on the authors’ observations and preliminary studies of areas immediately adjacent to the Marcona Mines.

District-scale Alteration

A salient characteristic of the clan of ore deposits under discussion is the development of quasi-pervasive district to regional-scale alteration, far more extensive than for example propylitisation surrounding porphyry Cu centres. Because the alteration minerals, such as albitic plagioclase and calcic amphiboles, are commonly developed in low-grade regional metamorphism, distinction between metamorphism and hydrothermal alteration may be difficult. The nature, extent and age of strictly metamorphic effects in the Marcona Formation remain uncertain, although the lack of convincingly metamorphic foliation favours thermal rather than regional processes. Injoque

(1985) records the occurrence of cordierite, and we tentatively ascribe this to the intrusion of the San Nicolás Batholith.

The areal extent of the district-scale alteration assemblages is poorly documented. Chlorite and sericite are widespread in andesites of the Río Grande Formation north of the iron mines. Late epidote and calcite commonly occur as patches or veinlets in many outcrops. Different timings for the district-scale alteration assemblage is suggestive of multiple events.

Pervasive Albitisation

Pervasive albitisation ($An_{\leq 2}$) widely replaces plagioclase phenocrysts in the Río Grande Formation, yielding a pink to cream cast in outcrop, and, closer to magnetite bodies, develops in the rock matrix. Complete albitisation of the andesitic host-rocks, as occurred in the Candelaria deposit, Chile (Ullrich and Clark, 1997) was not attained in the Marcona district despite the greater overall scale of hydrothermal activity. Albite is also developed in oöitic andesite dykes cutting the magnetite bodies (*eg.*, the south contact of the Mina 1 orebody). Here, pink albitic selvages form on the margin of actinolite-chalcopryrite-pyrite veinlets and provide evidence for a resumption of Na metasomatism late in the hydrothermal history.

Potassic Alteration

Post-albite, low temperature red-pink potassic alteration is recognised within the volcanics of the Río Grande Formation associated with fracturing and brecciation together with late stage hematite and sulphides.

Main Iron Oxide Stages

Up to four episodes of magnetite+Ca-amphibole mineralisation are recognised, each forming the matrix of hydrothermal breccias. Of these sub-stages, only the first was apparently sulphide-free. The earliest sulphide assemblage is pyrrhotite-dominant with minor chalcopryrite, pyrite and cubanite. Thereafter, chalcopryrite and pyrite and eventually chalcopryrite are increasingly abundant. Successive overgrowth and replacement of chalcopryrite by bornite and chalcocite has also been recognised in the area. Concentrations of chalcopryrite are associated with pink albite and buff orthoclase as well as with amphibole (locally hornblende rather than tremolite-actinolite). As in many FeOx-Cu-Au deposits, *eg.*, Candelaria, magnetite and specular hematite exhibit mutual, probably multistage pseudomorphous replacement (“martite” and “mushketovite”), demonstrating that the hydrothermal fluids remained close to the magnetite/hematite phase boundary in aO_2 vs. aS_2 space. Specularite has at least locally been an important phase in the early to intermediate stages of iron oxide mineralisation. Specularite occurs most commonly as an open-space filling, associated with episodic fracturing during ore formation.

Late Stage Sulphide + Anhydrite

The polyphase hydrothermal brecciation that dominates the Marcona paragenesis was followed successively by magnetite-actinolite±chalcopryrite veins with pink

K-feldspar selvages, minor, local, chalcopryrite-pyrite, chalcopryrite-anhydrite and mauve anhydrite vein types. The latest phases of hydrothermal activity at Marcona overlapped the emplacement of oöitic dykes which, although locally sericitised, chloritised and epidotised contain negligible magnetite or sulphides.

These associations are very similar to those at Candelaria (*eg.*, Ullrich and Clark, 1999), with the exception of biotite, which is pre-magnetite when present at Marcona. In contrast, K-feldspar antedates the highest-grade Cu sulphide associations at least locally in the area.

Pampa de Pongo

Location and General Geology

The Pampa de Pongo Fe (\pm Cu-Au) deposit is centred at Latitude 15°22'30"S, Longitude 74°49'30"W and was discovered by Río Tinto Mining and Exploration in 1995 while testing a large NNW-SSE trending magnetic anomaly for Fe-Cu-Au mineralisation. Wide-spaced drilling suggests a potential resource of 1000 Mt comprising approximately 75% magnetite (approx. 40% Fe). Hole 1 cut 168.7 m of magnetite grading 52.9% Fe with anomalous Cu and Au.

The Oxfordian-to-Tithonian (Jurassic) Jahuay Formation (Caldas, 1978) hosts the Pampa de Pongo deposit. Lithologies observed in drill-core include thick sequences of coarse volcanoclastics, and conglomerates, banded siltstones, shales, sandstones and carbonate-rich sediments. Clastic and carbonate sediments with plagioclase-phyric andesites are exposed to the northwest and southeast of the mineralised zone, the latter considered to represent both sills and dykes. Drill holes suggest the upper 400–450 m are mostly andesitic dyke/sills, bedded flows and tuffaceous units. These are underlain by more than 600 m of white, predominantly dolomitic marbles, which, outside of the mineralised zone exhibit sparse tremolite porphyroblasts and networks of talc veinlets. To the authors' knowledge, no direct evidence exists for the age of these units. Several holes also cut basement gneiss, implying that a steep angular unconformity cuts out the entire Marcona Formation and possibly the Río Grande Formation.

The dioritic Acari pluton is exposed 800 m to the east of the prospect. This intrusion is considered part of the Arequipa segment (Caldas, 1978) of the Coastal Batholith and, therefore is assigned ages of 96 and 80 Ma by Cobbing (1977, 1998). To our knowledge, the Acari and the more easterly Cobre Pampa plutons have not been dated. However, these dioritic to granodioritic bodies intrude (Caldas, 1978) strata assigned to the Neocomian-Aptian Copara Formation and the Bella Unión hypabyssal complex. These intrusive relationships and the 109 ± 4 Ma whole-rock date for a pre-ore dacitic dyke at Hierro Acari (Vidal, *et al.*, 1990) strongly suggest the Acari pluton post-dates hydrothermal activity at Marcona. Despite the faulted contact with the Acari porphyry, proximity of this intrusion to the Pampa de Pongo deposit may also imply a Cretaceous age for the mineralisation.

Structure

Bedding across the property dips consistently at 15 to 20° and tectonic breccias are recognised in several sections of drill-core. The magnetite has been emplaced along a steep NW-trending fault corridor. This structural zone parallels the Huaca fault system at Marcona and the main ocoite dyke orientation. There are sharp cutoffs to the iron body to the east and west. Copper shows higher grades in the hanging wall and SW footwall (up to 0.42% Cu) and 0.68 g/t Au). Copper and gold content is significantly lower in the majority of the iron mineralisation.

Alteration-Mineralisation Relationships

Preliminary documentation by Carbonell (1996) and Taylor (1996) established the salient features of the mineralisation. These authors emphasised the importance of widespread albitisation, serpentinisation and replacement of all rock-types, in particular dolomitic units, by magnetite. In cross-section a massive magnetite zone up to 1 km in width is haloed by stockwork iron mineralisation. The importance of both fractures and hydrothermal breccias as hosts for magnetite (-pyrrhotite) mineralisation is consistent with the present authors' observations. Taylor (1996) interpreted

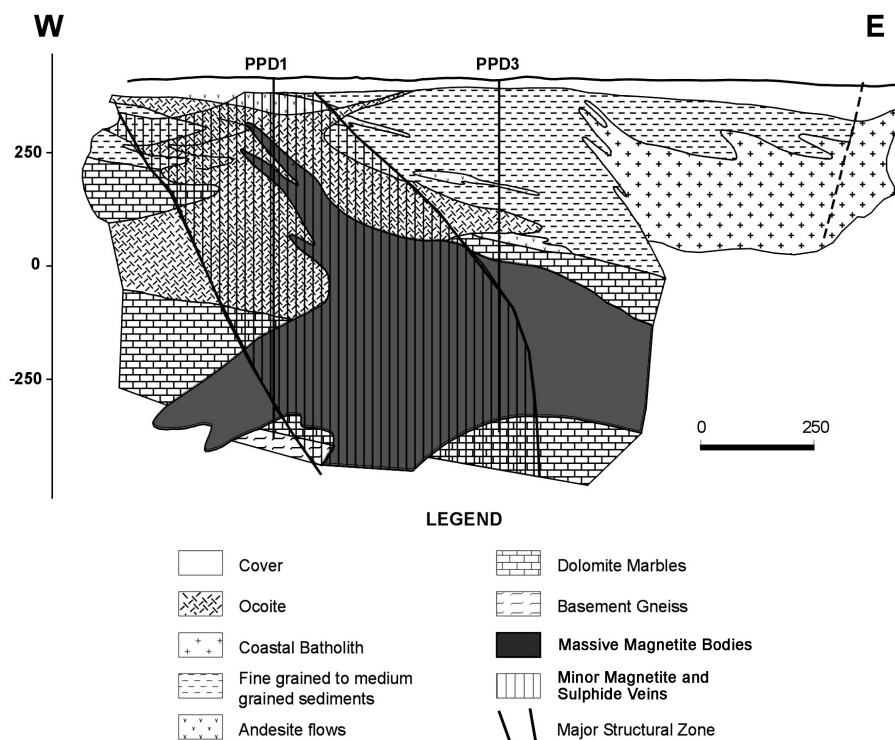


Figure 8: Pampa de Pongo E-W Cross Section (Adapted from drawings by J. Carbonell).

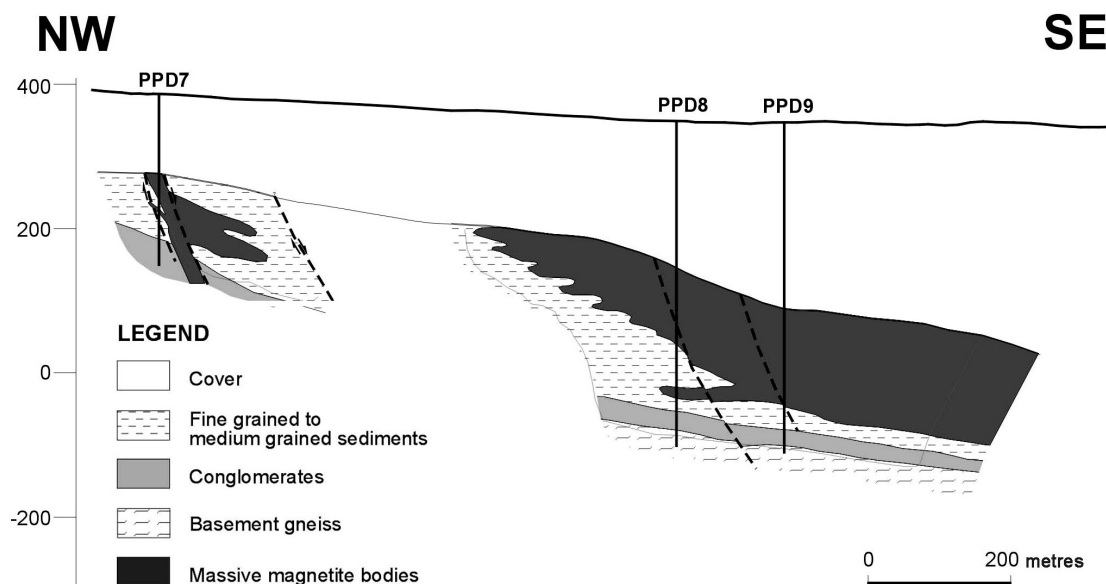


Figure 9: Pampa de Pongo SE-NW Cross Section (Adapted from drawings by J. Carbonell).

the range of fabrics as the product of a spectrum of brecciation conditions, ranging from “crackle” through “mosaic” to “hydraulic” with increasing intensity related to increasing micro-fracture-controlled Fe metasomatism of host-rocks.

Present observations focus on the ore-types and alteration facies developed in the largely ocöitic/andesitic rocks intersected in the upper 400 m of diamond drill-holes PPD-001 (centre-west) and PPD-002 (northeast), *ie.*, in the hanging-wall of the major concentration of magnetite. These drill-holes exhibit striking textural relationships that reveal the processes involved in the emplacement of this exceptionally large magnetite body. Over this interval ore is hosted entirely by andesitic rocks, the majority of which are crowded plagioclase porphyries with complex phenocrysts of ocöite type, and with augite as the dominant magmatic ferromagnesian mineral. The andesites have been extensively altered, although replacement of igneous minerals is rarely complete, even within 10 cm of magnetite bodies. Almost all the observed iron mineralisation occurs as veins, commonly sinuous, and as cements to hydrothermal breccias.

The alteration-mineralisation relationships at Pampa de Pongo are described briefly in sequence from host-rock to magnetite bodies, based on hand-specimen study, and limited petrographic, X-ray powder diffraction, cathode luminescence and electron microprobe investigation.

Peripheral Alteration

Although sericitisation of plagioclase appears to represent an outer alteration facies, the initial process unambiguously related to mineralisation is the development of white rims of albite ($An_{<1}$) on plagioclase phenocrysts. With increasing alteration the rims expand into the phenocrysts and fine-grained, buff, decussate grains of albite form in the matrix, together with local 0.5–1.5 cm rounded patches of epidote + actinolite. These associations are similar to “sodic-calcic” alteration resulting from prograding incursion of non-magmatic fluids in, for example the Yerington district, Nevada porphyry Cu deposits (Dilles and Einaudi, 1992) but here record *Na Metasomatism*. Albite development increases in relatively restricted zones accompanying progressive destruction of igneous plagioclase. The phenocrysts lose definition and the rock is converted to a blotchy association of white and buff albite and ultimately to an extremely fine-grained, porcelainous “albitite”. Although some albite development occurs as envelopes to individual magnetite bodies, Na metasomatism appears to have been a more widespread “precursor” event controlled by sheeted-structures in the andesites with the appearance of a spaced cleavage, as at Marcona.

“Skarn” Development

Several intersections in drill-hole 001 exhibit coarse-to-fine grained assemblages of andraditic garnet ($Grossular_{4-7} Andradite_{93-96}$) intergrown with diopsidic clinopyroxene ($Hed_{<9}$). Such associations would normally be interpreted as evidence for high-temperature “skarnification” of carbonate units. However, some

intervals (*eg.* 115–118 m) show relict albitised plagioclase phenocrysts. The calc-silicate alteration assemblages indicate *Ca metasomatism* of igneous protoliths and could be considered as endoskarn or, more appropriately, “anti-skarn”. Similar relationships are widespread in the hanging wall of the main orebody at Candelaria (Ullrich and Clark, 1997, 1999), where “skarn” development is routinely, and erroneously, interpreted as evidence for the former presence of carbonate sediments (*eg.*, Marschik and Fontboté, 2002). The calc-silicate zones at Pampa de Pongo appear to represent a restricted Ca-metasomatism that post-dated the albitisation, as at Candelaria. However, the andradite-diopside rocks also incorporate large (# 3 cm), crudely-spheroidal white patches dominated by K-feldspar with orthoclase Si-Al ordering, providing strong evidence for *K-metasomatism*, presumably occurring at approximately the same time as the Ca-metasomatism.

Main Magnetite (-Pyrrhotite) Stage

In the upper part of the deposit, magnetite occurs both as exceptionally coarse (to 3 cm) euhedral (octahedral) and subhedral crystals and, probably less commonly, as extremely fine-grained massive grain-aggregates. The former constituted the first stage in the development of veins cutting altered andesite or in the cementation of hydrothermal breccias. The veins range from sinuous (“A-type” in appearance, but continuous for 10’s of cms.) to planar. These may be regarded as the initial stage or peripheral facies of the breccias. Fine magnetite invades the andesite as networks of thin veins, coalescing as irregular patches that in part may be metasomatic. Coarse magnetite is almost everywhere intergrown with Fe sulphides. X-ray studies confirm the presence of both hexagonal and monoclinic pyrrhotite, pyrite and, locally, marcasite. Although pyrite occurs sparsely as coarse (1 cm) cubes and pyritohedra, as well as a fine-grained cement, the characteristic mode of occurrence of the Fe sulphides is as blades up to 15 cm, but averaging 5–7 cm in length and 1–3 mm in width. The coarse pyrrhotite plates, with long axes paralleling the {0001} planes, are extensively pseudomorphed by pyrite (Plate 2) and marcasite (*ie.* Fe loss). The porous pseudomorphs are commonly in-filled by white calcite and some laths are entirely of calcite. In numerous core-sections, pyrrhotite has been pseudomorphed by magnetite. Petrographic relations also reveal the replacement sequence pyrrhotite-pyrite-magnetite. It is implicit that, although these relationships record an overall transition from magnetite-pyrrhotite equilibrium to that of pyrite-calcite, fluctuations in $f S_2$ clearly took place. Only rarely do coarse intergrowths of chalcopyrite and calcite infill the lath-forms. Textures of this type occur in a wide range of ore deposits, but appear to be most characteristic of carbonate-replacement mineralisation of Leadville-type (*eg.*, the “eutectic texture” of Emmons, *et al.*, 1927; the “rod texture” of Thompson and Arehart, 1990), although growth in pre-existing open-space or an abruptly dilating environment is probably a prerequisite.

Minor minerals associated with the magnetite-pyrrhotite assemblage include mackinawite with 0.5–0.7 wt.% Ni and

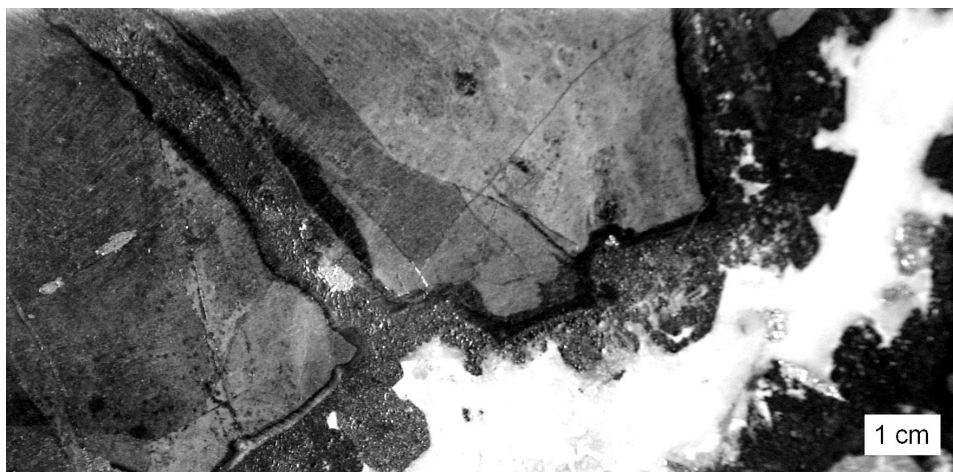


Plate 1: Strongly albitised and chloritised andesite (phenocryst outlines obliterated) with thin, black chlorite – talc selvages, cut by sinuous veins in which early magnetite has been almost entirely engulfed and overgrown by coarse white calcite. DDH 001 - 145.3 m.

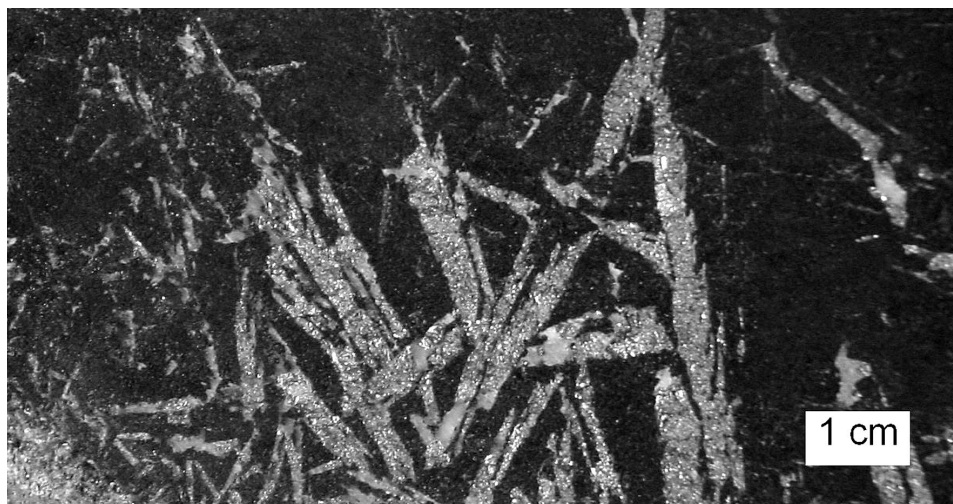


Plate 2: Characteristic texture of main magnetite –Fe sulphide ore in the upper section of the Pampa de Pongo deposit. Coarse-grained massive magnetite is intergrown with plates, originally single crystals of pyrrhotite, now pseudomorphed by fine grained pyrite. DDH 001-81.9 m.

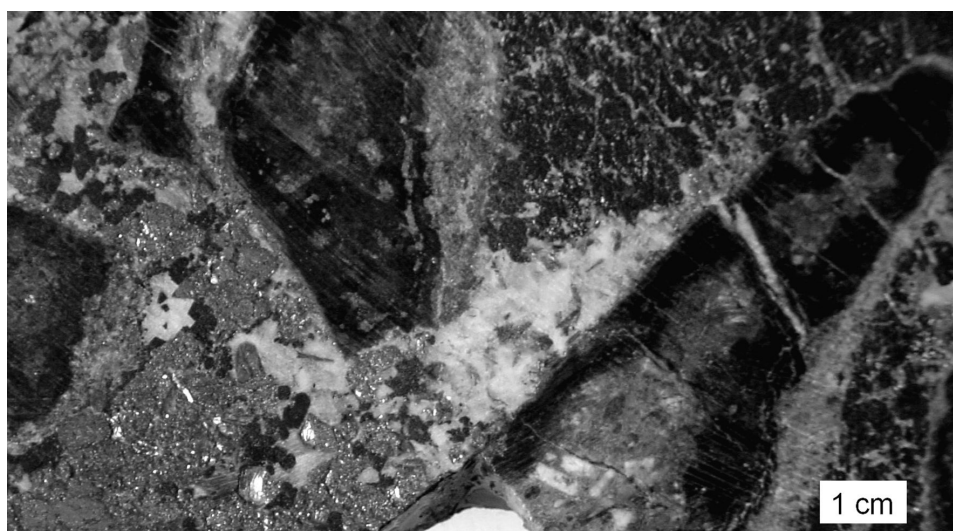


Plate 3: Hydrothermal breccia, with matrix of magnetite, coarse grained pyrite and calcite. Clasts are of moderately altered “ocoite”. Plagioclase phenocryst outlines are well preserved in the pale-green cores of the clasts, but are extensively replaced by buff albite, and the andesitic groundmass is strongly chloritised. Black alteration selvages are dominated by biotite (inner) and chlorite (outer) . DDH 001-86.9m.

0.1-0.2 wt.% Co in solid solution, Co-rich pentlandite and lollingite. Microprobe analysis reveals up to 0.15 wt.% Ni in the hexagonal pyrrhotite. The magnetite contains very minor Ti (< 0.1 wt. %) and V was not detected (*ie.*, < 0.05 wt.%).

Emplacement of these texturally-unusual magnetite-pyrrhotite veins and breccias was almost everywhere associated with the development of black to dark-green and locally dark-brown alteration selvages (Plates 1 and 3) comprising an extremely fine-grained association of various phyllosilicate minerals and minor magnetite. These average 8-10 mm in width and locally reach several cms. X-ray diffraction analysis shows these selvages include various proportions of biotite (Annite₈₂₋₉₀), Fe-rich chlorite (clinochlore), talc and clinochrysotile. Biotite is most widely associated with chlorite, talc with chlorite, and occasional biotite-clinochrysotile. The alteration envelopes exhibit abrupt interfaces with the variably albitised host-rocks and some display a fine layering paralleling the contact with the overgrowing magnetite. Textural relationships, and hence crystallisation sequence, are difficult to determine, but in two samples the biotite content increased outwards relative to chlorite, *ie.*, towards the andesite. On this basis, biotitisation, and hence K-, and possibly Fe metasomatism probably occurred prior to the development of chlorite and other K-free minerals. Moreover, because brown to buff clinochrysotile is locally concentrated at the contact between the alteration selvages and the later magnetite, and serpentine was locally precipitated as pale apple-green sheaves in cavities in the magnetite, the suggested overall order of phyllosilicate formation was biotite → chlorite → talc → serpentine. In the upper-part of the deposit the main deposition of

magnetite took place during serpentine development. The inferred sequence of alteration events that coincided and overlapped with magnetite mineralisation in this part of the Pampa de Pongo deposit, although in broad conformity with retrograde processes in magnesian skarns, is entirely unlike that at Marcona. Thus, Ca-amphiboles have not been observed in association with the magnetite and/or sulphide minerals in the upper part of the deposit. Carbonell (1996 and pers. comm. 2002) observed minor tremolitic amphibole in association with Cu-rich sulphide mineralisation. These are reported as late stage and occurring on the margins of the deposit.

Sulphide-Calcite Stage

The commonly euhedral surfaces of the magnetite crystals are widely overgrown by coarse and vughy white carbonate (Plate 1). Taylor (1996) interpreted this as dolomite, but X-ray and acid testing suggests that calcite is much more abundant. Locally, the magnetite-calcite contact is “hazy”, owing to the development of extremely fine-grained chlorite in both minerals. The calcite, representing the final stages of dilation of the ore-zones, is widely intergrown with subhedral to granular pyrite, showing no evidence of an origin through replacement of pyrrhotite, and minor chalcOPYrite. However, as noted above, Taylor (1996) describes an Au-rich chalcOPYrite-pyrrhotite zone, implying sulphidation conditions varied markedly at this stage. Single grains of sphalerite, galena, tennantite and arsenopyrite have also been observed or reported previously. Petrographic work shows pale-mauve anhydrite overgrows calcite in one sample. Valleriite has been confirmed as a coating on several late-stage fractures, intergrown with finely platy magnetite.

	Albite	Magnetite-biotite	Chlorite-talc with Magnetite-pyrrhotite	Sulphide-calcite (serpentine)	Valleriite
ALBITE	=====	-----		-----	
BIOTITE		=====	-----		
Fe-CHLORITE (Clinochlore)			=====	-----	
TALC			-----	=====	
SERPENTINE (clinochrysotile)				=====	
CALCITE				=====	
Ca-AMPHIBOLE	-----			-----	
GARNET (Grossular-andradite)				-----	
DIOPSIDE				-----	
EPIDOTE	-----			-----	
ORTHOCASE		-----		-----	
MAGNETITE		=====	=====	=====	
HEMATITE			=====		
PYRRHOTITE			=====	-----	
PYRITE			-----	=====	
CHALCOPYRITE			-----	=====	
MARCASITE			-----		
MACKINAWITE			-----		
PENTLANDITE			-----		
LOLLINGITE			-----		
TENNANTITE				-----	
VALLERIITE					-----

Note: The above list is not exhaustive. Other sulphides include : galena, sphalerite and arsenopyrite. Titanite sericite, quartz, gold are also present.

Table 2: Pampa de Pongo deposit - Summary mineral paragenesis of Fe oxide and principal sulphides

Discussion

Both the Marcona and Pampa de Pongo deposits share many characteristics of Iron Oxide-Copper-Gold deposits. These include abundance of iron oxide with anomalous and locally ore grade copper and gold, a generally low-sulphidation state, widespread precursor albitisation / Na metasomatism, and more erratic K-metasomatism and Ca-metasomatism. Despite the subordinate development of brittle stockwork, hydrothermal breccias are a major ore-host. Control by large scale, and probably multiply reactivated, fault systems is also a characteristic feature. Both Marcona and Pampa de Pongo incorporate carbonate replacement domains but we argue that andesitic country rocks were at least as widely metasomatised and mineralised. Pampa de Pongo apparently differs from all other Fe-oxide deposits of the Peruvian Coastal Belt in the sparse development of Ca-amphibole alteration. In this context, it is of interest that its overall Cu content appears lower than those with greater amphibole. Considered overall, the paragenetic evolution of the Pampa de Pongo deposit appears simpler than that at Marcona. Although brecciation and replacement was important in both centres, no evidence has been found for more than a single major fragmentation event in the former.

Lead isotope data suggest the Marcona ore has a composition differing markedly from that of broadly coeval Mesozoic granitoids from southern Peru which, although also intruded into the Arequipa Massif, show only minimal evidence of AFC processes (Barreiro and Clark, 1984). The ore-Pb compositions of the largest lower Eocene porphyry Cu deposits of southern Peru, Toquepala and Cuajone, similarly record only minimal crustal contamination, implying a marked metallogenetic difference between these centres and Marcona (Clark, 1997). All of these deposits, however, have Pb isotopic compositions indicative of mixing of lead derived from deep crustal and/or upper mantle and upper crustal reservoirs.

Hydrothermal activity occurred during construction of a major Jurassic volcanic arc, represented locally by thick successions of largely andesitic strata assigned to the Río Grande Formation. Dates for mineralisation at Marcona and the age of host formations at Pampa de Pongo suggest iron oxide mineralisation commenced around 160 Ma, >20 my. before the formation of the Pampa de Pongo iron deposit. Although Pampa de Pongo is within the contact aureole of the Coastal Batholith, a genetic affiliation with iron mineralisation has not been established. It is postulated likely that the later stages of the hydrothermal system at Marcona may have overlapped in time with the development of the Pampa de Pongo deposit. Extensive high-level iron oxide-Cu-Au veins in the Coastal Batholith, such as at Cobrepampa, suggest that this style of mineralisation may have continued well after Pampa de Pongo was formed and possibly after considerable uplift. The numerous small iron and copper deposits in the coastal batholith show alteration characteristics and vein orientations similar to Marcona and Pampa de Pongo, suggesting a common origin and genesis that is independent of host rock except on a very local scale.

There is a very close relationship between the timing of the mineralisation at Marcona and the intrusion of porphyritic andesite sills and dykes (including the ocoites). Some have intruded just prior to the main mineralisation event, and some shortly afterwards but are affected by waning stages of the alteration and mineralisation. These high-level intrusives and Fe-oxide associated copper gold in the Marcona District potentially share a common deep magmatic source. The combined effect of both deep and high level intrusives are postulated as the causative bodies for the widespread alteration assemblages characteristic of low grade thermal metamorphism.

The role of the Abancay Deflection on Mesozoic mineralisation remains obscure, as does the significance of the intersection with the other major crustal linear, the Dorsal de Nazca. The close proximity of the mineralisation of the Marcona district to these structures is consistent with the observations of Hitzman (2000) who recognises that Fe-oxide-Cu deposits are generally located on splays off deep structural features. The Dorsal de Nazca has certainly played an important role in the erosional and supergene history of the deposit but it is believed very unlikely that this structure was present in its current form during the Jurassic. Nevertheless it may be an indication of a far longer lived deep crustal suture in the region.

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