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FE OXIDE-CU-AU DEPOSITS IN PERÚ
AN INTEGRATED VIEW

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Abstract - Within Perú, Fe oxide-Cu-Au deposits are found mainly in the Western Andes range and on the coast, associated with the Jurassic-Cretaceous alkaline to calc-alkaline volcanism of the aborted ensialic Cañete-Huarmey marginal basin. They also exist in the calc-alkaline plutons of the Coastal Batholith and the tholeiitic Patap Super-unit, associated with continental margin processes. The exception is Cobriza (100 Mt[1] @ 1.5% Cu, Fe oxide-Cu-Au type; Cu calcic distal skarn) which is located in the eastern range, associated with Permian late-Hercynian extensional tectonics and alkaline granites.

Marcona (apatite-magnetite type; Callovian-Oxfordian), an orebody of >1500 Mt with 60% Fe, and Raúl-Condestable (Fe oxide-Cu-Au type; Hauterivian-Barremian), with ~50 Mt of 1.5% Cu, are Fe calcic skarns, characterised by a pattern of stratabound calc-silicate alteration, coinciding with a fissure intrusive-volcanic centre. This is the reason why they are classified as geothermal skarns. The Cañete Basin is characterised by the presence of ocoites[2], a thick crust, with 20 to 30°C/km geothermal gradients, burial greenschist to zeolite facies metamorphism, and a moderate intrusion of mantle into the crust. Further to the north, deeper oceanic conditions resulted in the formation of VMS deposits. Marcona also has a direct relationship with the dextral northwest-trending Treinta Libras Fault, similar to the Atacama Fault in Chile.

Fe-Acarí and Yaurilla (magnetite-apatite type) contain 40 Mt of 66% Fe, while Eliana, Monterrosas and Cata Cañete (Fe oxide-Cu-Au) comprise to 2.5 Mt with 1.5 to 2.6% Cu. All of these skarns are Fe-calcic type and late-tectonic. The first-mentioned examples are related to the Albian Patap Super-unit while the latter is associated with the Late Cretaceous Cochahuasi Pluton. Cobrepampa is a Cu calcic skarn (Fe oxide-Cu-Au) containing 5 Mt with 2 to 5% Cu, associated with the alkaline Linga Super-unit, and with local dextral faulting. All these deposits are auto-reaction skarns.

The district wide alteration associated with most of these deposits comprises an outer zone of propylitisation with abundant albite, surrounding an internal halo of clinopyroxene, amphibole, sodic-scapolite, epidote, chlorite and garnet. The exception is Cobrepampa where the alteration is K feldspar with biotite, amphibole, garnet and tourmaline representing the most important accessory minerals. The mineralogy of these deposits is characterised by actinolite, chlorite, biotite, phlogopite, sericite, apatite, sphene and minor amounts of rutile, albite, tourmaline, K feldspar, quartz and calcite. The dominant metallic minerals are magnetite, pyrite, chalcopyrite, and variable contents of pyrrhotite, with less abundant bornite, chalcocite, covellite, ilmenite, molybdenite, galena and sphalerite. Cobriza however, has silver and bismuth by-products and significant amounts of arsenopyrite that are generally very scarce in Andean deposits. In addition, tungsten and tin appear at Cobrepampa and Cobriza, suggesting a relationship with felsic and alkaline magmas. However, in the coastal belt, gold (native, electrum and solid solution), silver (in galena), and traces of cobalt and nickel are frequently present.

Editor's note: This paper integrates the observations and characteristics of the important Peruvian magnetite-apatite deposits, many with associated iron and copper sulphides, and the primarily copper (-gold) occurrences with significant accompanying iron oxides within the same districts. Some of the former are among the largest hydrothermal iron-oxide systems in the world, although many, particularly of the latter have been, and still are, classified as skarns. The information provided allows the reader to draw their own conclusions on the inter-relationship and classification of these ores, and their association with the other deposits described within this volume.

Introduction

The Fe oxide-Cu-Au deposits of Perú (Fig. 1) have been known since ancient times, although they were not exploited by modern mining in most cases until the end of the 1950s and the early 1960s, with the exception of Eliana and Monterrosas, where production commenced a decade later (Samamé, 1992).

Marcona was the only producer of iron ore in Perú from the very beginning, except for a small contribution from the Fe-Acarí Mine in the 1960s, which was quickly depleted.

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[1] Mt = million tonnes. Tonnage includes past production and remaining reserves.

[2] Ocoite (Ocoita) is the name given in Chile to andesites or basalts with phenocrysts of large plagioclase (>1 cm.) which seem to be regional tectonic guides of abortive ensialic marginal basins in thick crustal areas with environments favourable to Manto-type Cu deposits (Injoque, 1999, 2000).

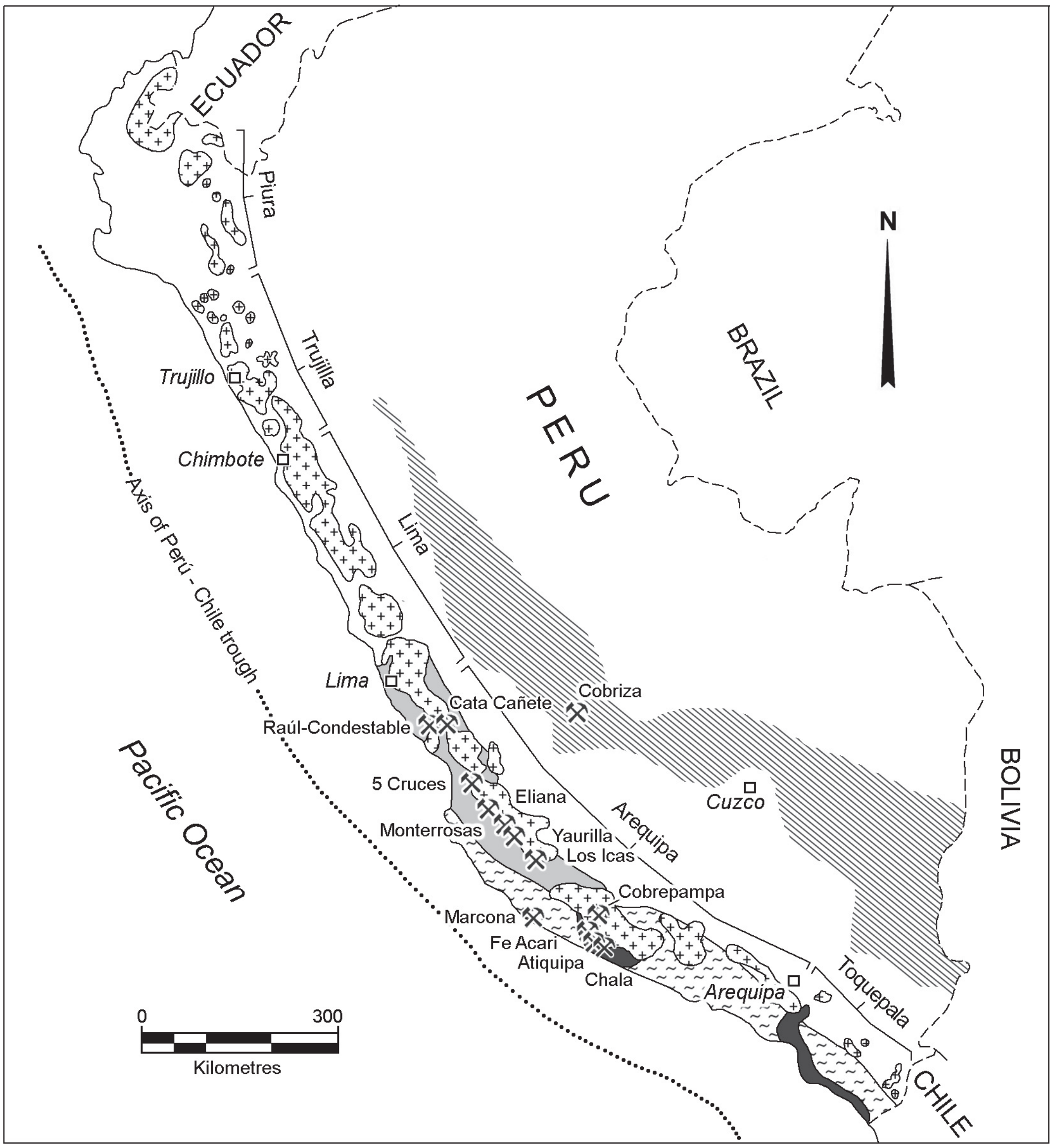

Figure 1: Summary geology of Peru for the mineralised Hercynian and Andean belts.

The main sources of Perúvian copper are the Cu-Mo porphyries. The Fe-Cu-Au deposits only accounted for 5 to 6% of total production in the 1990s (www.snmpe.org.pe).

The study of these deposits commenced in the 1950s with a PhD on Marcona (Atchley, 1956) and another in the 1960s on Cobriza (Petersen, 1965). Subsequently, in the 1970s and 1980s, there was an important research pulse fostered by mining operations, but also by regional works performed in Perú by INGEMMET, ORSTOM from France, BGS and Liverpool University from the United Kingdom, and the University of Heidelberg from Germany, as well as a number of other institutions. This research produced an important body of descriptions of these deposits as well as genetic interpretations by both syngenetists and epigenetists which significantly expanded the available knowledge. The main papers from this period are referenced later in this contribution, while a search of the reference lists from each will provide a supplementary bibliography.

This paper does not discuss genetic issues, which are well supported in the works cited. It is assumed that individual deposits were generated by late magmatic-hydrothermal activity within the respective district. Within this context, these deposits were classified in the past as Fe and/or Cu skarns or as hydrothermal deposits, but with no clear understanding of the regional geology and metallogenic context. This synthesis aims at filling in this blank, summarising the particular, district and regional characteristics of each deposit to place them in a modern geotectonic-metallogenic framework.

Regional Geology

The deposits of this family in Perú (Fig. 1) are related with the Andean Orogeny and Mesozoic rocks in the western range and in most of the Perúvian coast, except for Cobriza which is related to the Hercynian Orogeny and Paleozoic rocks in the eastern range.

A metamorphic Precambrian basement forms the eastern range and Lower Paleozoic continental clastic rocks cover it. These rocks, metamorphosed into slates during the Eohercian deformation and were covered by molasses and some marine deposits during Carboniferous times. During the Late Hercynian, deformation was reactivated in a soft and coaxial manner and in Permian-Triassic times, there was extensional and block-faulting tectonics followed by a deposition of red beds, as a transition to the Andean Cycle (Laubacher and Megard, 1985). This extensional stage coincided with the activation of an ensialic rift, the deposition of alkaline and per-alkaline lavas and intrusion of sub-alkaline crustal-derived granodiorites and monzogranites (Kontak *et al.*, 1985; Soler, 1991).

Mesozoic and Cenozoic Andes are built over the rocks of this mountain range, but towards the coast; the deposition and Mesozoic volcanism started in the Jurassic and followed through the Cretaceous in the Cañete-Huarmey Marginal Basin (Cobbing, 1999), extending to the north into the Lancones Basin (Injoque, 1999, 2000). This basin is the result of the breaking of the continental crust along a continental rift, that has a structure similar to an oceanic rift, in which the axial zone contributed filling the basin with volcanic material through a process of extension and subsidence. In the central part, this basin shows a quasi-ophiolitic character, while towards the south, in the surroundings of the Precambrian Coastal Basal Complex, this is an abortive ensialic marginal basin with alkaline to shoshonitic affinities. Transition from volcanism to the Coastal Batholith intrusion occurred at the end of the Cretaceous volcanic activity, during the intrusion of early tholeiite gabbros and diorites called Patap Super-unit, precursors of Batholith; this event coincided with the Mochica Deformation Phase in the Albian. The Coastal Batholith intruded along the coast, from 100 to 60 Ma, coinciding partially with the Perúvian late Cretaceous Deformation Phase, existing also late eastern units of about 40 Ma. The Coastal Batholith intrusion and the volcanic activity in the area seem to have been the result of a "mantle plume" formed in the continental margin, even though their relationship with subduction processes (Cobbing, 1999) may not have been necessary to its formation (Atherton, 1990).

Hercynian Deposits

Cobriza

(Petersen, 1965; Cerro de Pasco Corporation, 1969; Valdez, 1983b; Rivera *et al.*, 1989)

The Cobriza deposit (Fig. 2), currently developed by Doe Run Perú, is located 300 km to the ESE of the city of Lima, near to the town of Coris. The mine produces about 10 000 tpd of copper ore with silver and bismuth by-products.

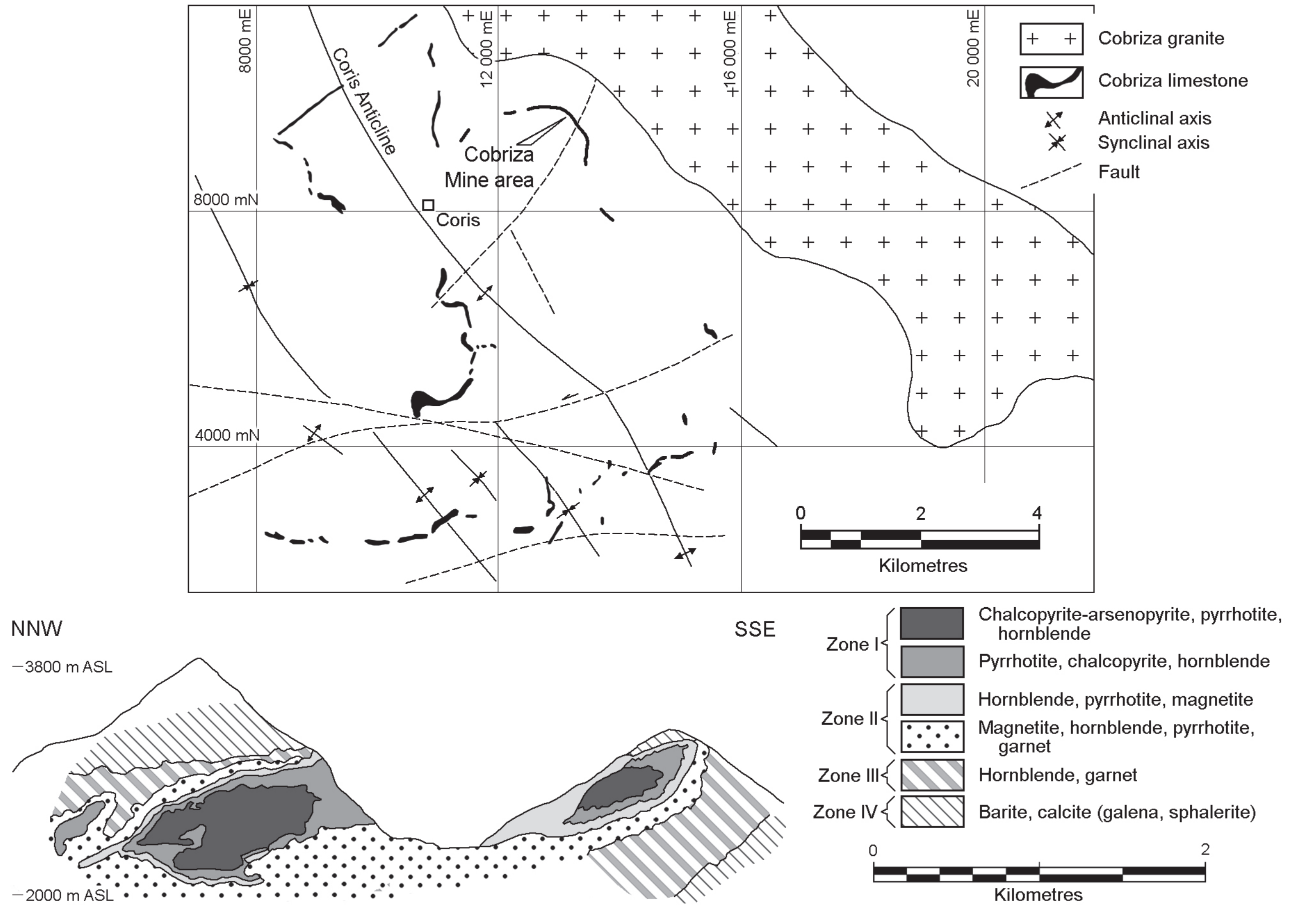

Figure 2: Cobriza regional geology and manto zoning in a projected longitudinal section through the Cobriza Mine area (approximately NNW orientation, after Rivera *et al.*, 1989)

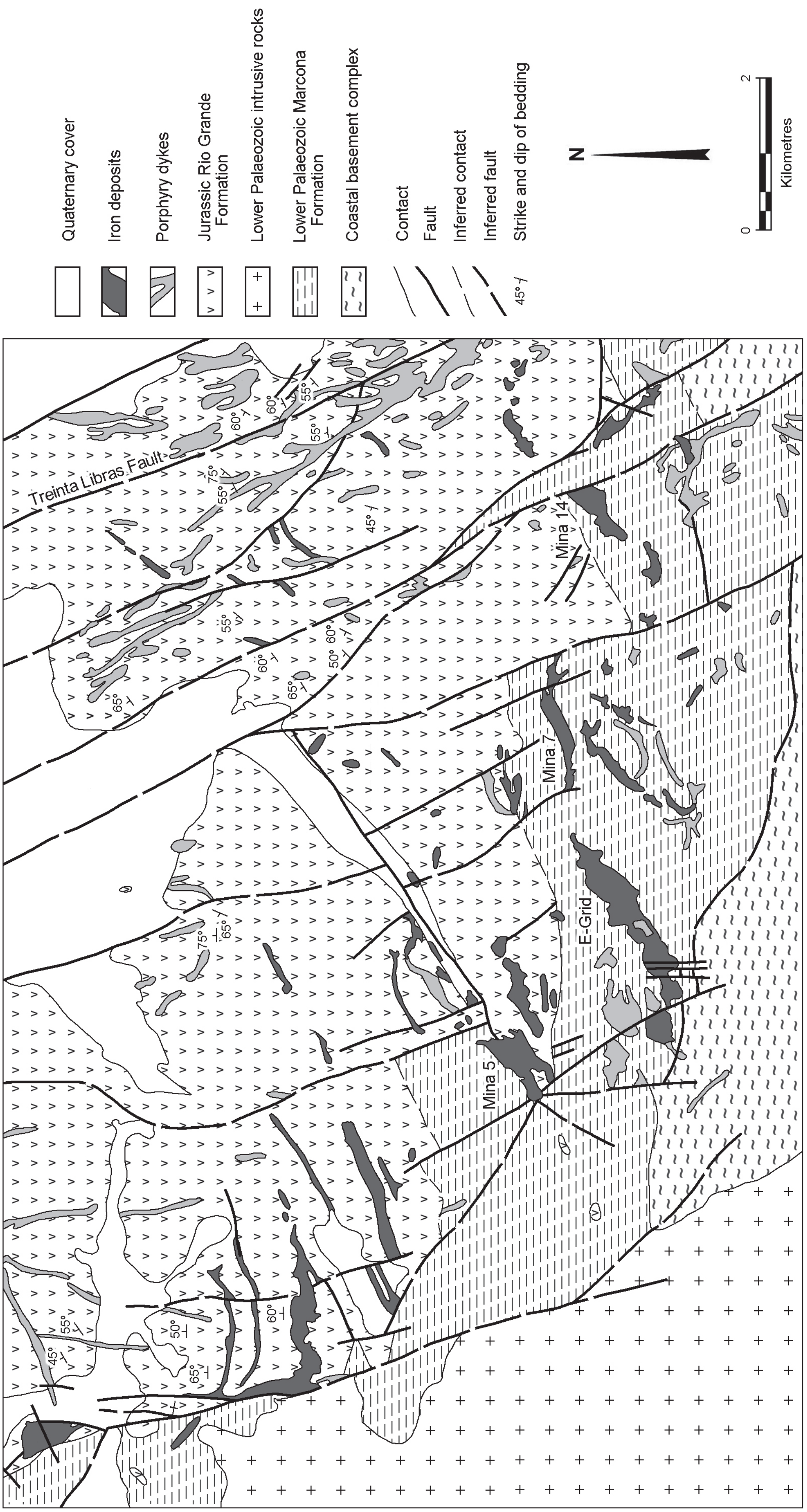

Figure 3: Geology of the Marcona iron deposits

Mineralisation is hosted within a 2000 m thick calcareous package, mainly composed of shales, sandy- and calcareous-shales and limestones, that belongs to the Carboniferous (Pennsylvanian) Tarma Group. Up to six concordant mineralised horizons have been recognised within this sequence. The most important of these is the Cobriza limestone, which is some 800 m above the base of the sequence. The other. less well developed mineralised bands are also conformable to the stratification and are associated with calcareous and calc-silicate bands intercalated with quartzite, slates and slaty-mudstones (Megard, 1978).

The host sedimentary package is folded, forming the northwest-oriented Coris Anticline, which is part of a regional anticlinorium. The sequence is intruded to the northeast by the Cobriza two-mica granite, which is part of the 253±11 Ma Villa Azul Batholith (Noble *et al.*, 1995), and by minor apparently Miocene-Pliocene dykes of basalt and diorite (Valdez, 1983b). Late Hercynian, northwest-trending reverse faults cut the whole district.

The deposit is a Cu-calcic skarn consisting of a large mineral lens (manto) with a strike length of 5500 m, 15 to 25 m thickness and over 2000 m depth extent, replacing a favourable calcareous horizon sandwiched by impermeable shales. The orientation of the manto is 315° with a 30 to 50°NE dip. It comprises magnetite, pyrrhotite, arsenopyrite and chalcopyrite in a matrix of diopside, garnet, hornblende, actinolite, phlogopite and quartz. The principal ore mineral is chalcopyrite, which carries silver in solid solution (Valdez, 1993a). The zoning described for this manto is complex, with an apparent high temperature core towards the northwest (Cerro de Pasco Corp., 1969), although subsequent work suggest the existence of 4 to 5 superimposed foci located at intersections of high angle reverse northwest faults (Valdez, 1983b).

The zoning comprises a core rich in diopside and garnet, successively and subsequently replaced towards the margins by hornblende, actinolite-tremolite and talc, passing finally in a periphery to dolomitic marble. Among the minor minerals in these assemblages, there are varieties of epidote, sodic-scapolite with calcite, predominatly towards the core, and phlogopite towards the border. From the core outwards, there are successive zones of (1) magnetite-actinolite with accessory hematite, (2) pyrrhotite, with rare pyrite, (3) arsenopyrite-pyrite-quartz-phlogopite and minor bismuthinite, native bismuth and lollingite, and, finally, (4) the external zone of chalcopyrite with exsolutions of marmatite and stannite. However, it is outstanding to find at the base of the deposit a more or less continuous, centimetres in thick manto of galena-sphalerite-baryte-calcite, with an unclear relationship to the Cu ores, although it seems to be late (Huamán, pers. comm.).

Reserves plus past production are estimated to be 100 Mt (Samamé, 1992) with 1.4 to 1.6 % Cu and 14 to 19 g/t Ag (Centromin Perú, 1995) and the age of the mineralisation as determined by K-Ar on non-deformed gangue amphibole is 263.4±8 Ma (Noble *et al.*, 1995). The presence of gold, although it is not reported at Cobriza, is evidenced by the name of the associated town, Coris, which in quechua means 'gold', and was also reported in mineragraphic studies at the laboratories of La Oroya (Gagliufi, pers. comm.). Finally, there are reports of the presence of 0.5 to 1 g/t Au in the prospects surrounding the mine site (Centromin Perú, 1995).

Pb isotope studies of these minerals indicate that the Pb and, perhaps other metals, originated in the ancient Precambrian crust present in the neighbourhood (Noble *et al.*, 1995).

It is not clear if there is relationship between the Cobriza mineralisation and the Cobriza Granite. However, the age of both is close and the latter intrusive belongs to the group of granites within the region, which have alkaline affinities and anorogenic characteristics, products of an extensional regime (Soler, 1991) in a intracontinental rift, with no relationship to subduction (Kontak *et al.*, 1985).

Andean Deposits

The Andean deposits of this family known in Perú correspond to two types. Those related to Jurassic and Cretaceous volcanism of the Cañete-Huarmey Marginal Basin in the Perúvian coast and those related to the Coastal Batholith and associated early gabbros and diorites.

Jurassic-Cretaceous Volcanic-related Deposits

Marcona and Minor Jurassic Prospects

(Atchley, 1956; Adrian, 1958; Atkins *et al.*, 1985; Injoque, 1985; Injoque *et al.*, 1988)

The Marcona Mining District (Fig. 3), located 500 km to the south of Lima, consists of major Fe and medium sized Cu deposits, located in pelitic rocks of the Upper Precambrian to Lower Paleozoic Marcona Formation, and volcanic-sedimentary rocks of the Callovian-Oxfordian (Jurassic) Río Grande Formation. This district has been commercially exploited for iron since 1956, while the upper portions, which are rich in copper have been worked in by artisanal miners since the 1960´s. The deposit has reserves plus past production of more than 1500 Mt of @ 60% Fe (Samamé, 1992), comprising magnetite ore with associated Cu, Ag and Au byproducts, and traces of Co and Ni. Its K-Ar age is 160 to 154 Ma, corresponding to the late-Río Grande Formation (Injoque *et al.*, 1988). The Marcona mine is currently operated by the Chinese state-owned Shougang Hierro Perú company.

The geological environment consists of dolomites and pelites of the Marcona Formation, which are overlain above an angular unconformity by the lavas and volcano-sedimentary rocks of the Río Grande Formation. Together these two formations make up the elevated coastal block, subdivided into the Coastal Andean Range to the west, and the Pre-Andean Depression to the east where the conformable Río Grande, Jahuay (Kimmeridgian-Tithonian) and later formations are represented. The transition between these two blocks is marked by the Treinta Libras Fault, which dates from ancient times and has at least two known pulses: an early dextral transcurrent movement followed by later normal displacement. This fault controlled volcanism and intrusive activity in the area during Lower Jurassic-Cretaceous times. Effusive activity is evidenced as a rift, a large swarm of dykes and regional subvolcanic plugs.

The Río Grande and Jahuay volcanics and the subvolcanic instrusives of the area exhibit alkaline to shoshonitic affinities, clinopyroxene, hornblende and plagioclase fractionation and a "within plate" character.

The iron ores are stratabound and conformable, comprising 9 major deposits and 35 to 40 minor occurrences, with east-west to northeast strikes and 35 to 65°NW dip orientations. However, in detail, they are irregular and discontinuous, partially due to the irregularity of surrounding layers, but also to faults and intrusives that cut them.

All of the Marcona ore is hosted by the Marcona Formation as magnetite mantos. The magnetite is massive, with dodecahedral grains of up to 1 mm across and a saccharoid texture. The mantos are located in two favourable levels reaching 1 to 2 km in length. The upper level, known as "E-grid", is structurally persistent with a thickness of up to 150 m, and is enclosed by dolomitic marble on both sides. The lower level or "Mina 7", occurs towards the base of the formation with manto thicknesses somewhat less than those at the "E-grid" level. The depth extent of the mantos has not as yet been determined, although it is known to exceed 500 m.

In the Río Grande Formation, magnetite mantos are predominantly localised within 3 favourable horizons: "N-13", "Flor del Desierto" and "Cerritos de la A", where their thicknesses are characteristically 160, 40 and 60 m, respectively. These mantos are composed of massive magnetite intergrown with copper minerals. None have been developed as iron ores as the accompanying copper constitutes a deleterious metallurgical contaminant. Haloes of disseminated magnetite commonly surround these mantos with grades of up to 15% Fe. In addition there are also veins and minor stockwork bodies within the Río Grande Formation. All of the styles of mineralisation within this younger unit are in general characterised by the abundance of copper.

Residual sedimentary and volcanic structures are observable within the ore and surrounding metamorphic rocks that have been formed as a result of the hydrothermal replacement mineralising process. Mineralisation commenced with the formation at lower stratigraphic levels of diopsidic-clinopyroxene, garnet, cordierite, and hornblende. These assemblages were subsequently replaced by actinolite-tremolite, and minor amounts of Na-scapolite, phlogopite, chlorite-sericite, and apatite-epidote, which also developed towards the upper levels. Finally massive magnetite formed mineralised mantos with interstitial fillings of late pyrite (~0.1%), pyrrhotite, chalcopyrite (~0.01%), bornite, pentlandite, sphalerite, galena, molybdenite, gold, rutile, tourmaline, sphene, prehnite, albite and quartz.

Sulphur isotopes ($\delta^{34}S$) from two samples of pyrite, yielded values of -1.76 and +4.72‰ (Baruj Spiro, BGS; pers. comm.), suggesting a partially magmatic source and maybe some contribution from sea water for sulphur.

Mineralisation within the immediate Marcona district has also been reported cutting the younger Jahuay Formation ocoites. Similarly, 15 km to the northwest of Marcona, the Huaricangana copper Prospect comprises swarms of small secondary copper deposits hosted by Jahuay ocoites with strong associated thermal metamorphism represented by the development of actinolite, scapolite, magnetite, pyrite and oxidised chalcopyrite. The copper grade averages 0.25%, with accompanying traces of Au.

Pampa Pongo is another major prospect with a similar style of mineralisation and tonnage potential to that at Marcona. It is some 20 km southeast of Marcona and is completely concealed, but reflected by a large magnetic anomaly. Mineralisation at Pampa Pongo cuts both Marcona Formation dolomites and Jahuay ocoites similar to those seen at Marcona. These two deposits, together with the late mineralisation at Marcona, indicate that along a 50 km northwest-trending corridor, there are at least 4 mineralising foci corresponding to at least two separate mineralising pulses: One late-Río Grande phase generating Fe-Cu mineral in Marcona and a late-Jahuay phase, responsible for the mineralisation of Huaricangana, Pampa Pongo and part of the Jahuay level Cu-mineralisation at Marcona. Detailed information on Marcona. Pampa Pongo and related prospects are covered by Moody *et al.*, in this volume.

The Río Grande-Jahuay geological environment represents an alkaline to shoshonitic fissural volcanic backarc regime, characterised by northwest-trending dyke swarms that run parallel to the main Treinta-Libras Fault. This fault has a dextral transcurrent sense of movement and controls the eastern border of the Coastal range where Marcona is located. This structural-magmatic system was active from Jurassic times when volcanism started in the area, and continued to at least the Aptian (117 Ma) when the later felsic dykes appear in that system. This ensialic rift marks the break-up of continental crust and the beginning of volcanic activity in the region.

Considering the stratigraphic distribution of metamorphic and alteration minerals observed in the sequence and their association with the late Río Grande events, Marcona has been interpreted to have formed as a geothermal system, in the sense described by Bird *et al.* (1984) and Schiffman *et al.* (1984). This coincides with dextral movement along the Treinta Libras Fault, during the final stages of the Río Grande volcanism.

In the same region, there are two minor prospects: Chala and Los Icas. Chala, which only has a meagre tonnage potential, is located 620 km to the south of Lima. It comprises around 10 separate mantos of magnetite each of up to 10 m in thickness and several tens of metres in length (Olchauski, 1980), located in the middle of a complex of ocoite lavas, dykes and volcanic-sedimentary rocks associated with the Liassic age fissural-effusive Chocolate Formation arc. Los Icas has only produced copper from artisanal workings and consists of a series of discrete copper dissemination zones and mantos, in a sub-volcanic environment associated with a generally north-south-trending Río Grande age fissure-rift (Osterman, 2001).

Raúl-Condestable and Minor Cretaceous Prospects

(Atkin *et al.*, 1985; Injoque, 1985; Vidal *et al.*, 1990)

The Raúl-Condestable deposit is hosted by the Upper Valanginian-Barremian (early Cretaceous) age Chilca Formation, part of the Copara Volcanics that extend for 500 km to the south of Lima, and is the centre of a district that has been an active mining centre since the late 1950s. The deposit has a total endowment comprising reserves and past production, of approximately 50 Mt @ 1.5% Cu with Ag and Au by-products.

The volcanic-sedimentary Chilca Formation is distributed around a northeast-trending effusive fissure controlled centre located in Quebrada Calicantro, immediately to the South of the Raúl Mine. This fissure is flanked by a 1000 to 2000 m thick package of basalt-andesite lavas, tuffs and pyroclastics, which grade towards the north and south into marine limestones, shales, sandstone and volcaniclastics. The stratigraphic sequence contains exhalative pyrite as nodules, smokers and replaced fossils. This volcanic-sedimentary pyrite, which produces a reddish colouration in the surrounding volcanics, disappears to the north and south, and it is not associated with copper mineralisation. The volcanic centre, also hosts a set of dykes, sills and small stocks of andesite, dacite and granodiorite of 124 Ma in age (Vidal *et al.*, 1990).

Lavas and intrusives from the Raúl-Condestable Volcanic Centre have calc-alkaline to tholeiite affinities, with clinopyroxene, hornblende and plagioclase fractionation and a transitional arc basalt character. This deposit has chalcopyrite associated with pyrite, magnetite, actinolite and lesser apatite, forming disseminated orebodies, mantos and veins within the volcanic-sedimentary sequence of the host formation. Mantos (Fig. 4) are up to 250 x 200 m and have thicknesses of 1 to 5 m. They replace limestones, permeable tuffs and lava blocks. Veins extend for hundreds of metres and appear both in the volcanic-sedimentary sequence and in the dacitic intrusives. Finally, disseminated orebodies may be hundreds of metres across and appear as replacements in tuffs and andesitic lavas.

Mineralisation within the district is surrounded by a recognisable pattern of alteration. It commences as a thermal metamorphic suite, characterised by the presence of calcareous marbles, calc-silicate hornfels and sericite-biotite-talc hornfelses, surrounding cores of amphibolite and rocks rich in pyroxene and garnet. The amphibolites are composed of tremolite, actinolite, hornblendic-actinolite, tschermakite and hastingsite. These rocks are in their turn, extensively and irregularly replaced by tremolite, actinolite, chlorite and to a lesser extent by prehnite, albite, apatite and silica. Metallic mineralisation occurred at a late stage as disseminations, fracture fillings and replacements, following the typical skarn sequence. Alteration, is in general extensive and pervasive, but does not destroy the original rock textures, suggesting non-explosive and long lasting processes. The original fossils, nodules, sedimentary structures and geopetal textures are preserved in sedimentary protoliths, while volcano-clastic, pyroclastic and porphyritic textures are readily recognisable in rock of volcanic origin.

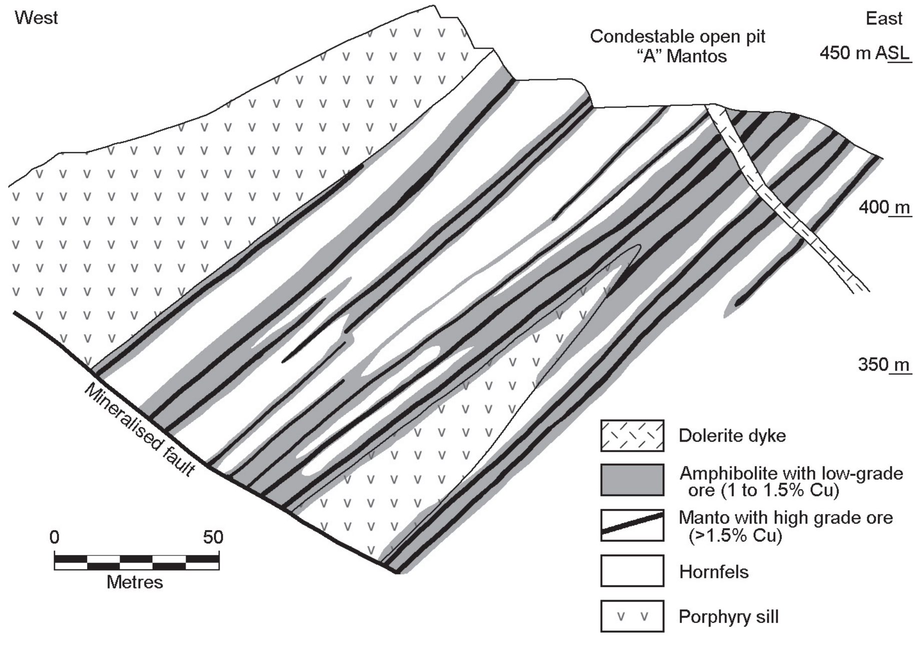

Figure 4: Geological section of Condestable mine.

The most important characteristic of this alteration is that the first stages of thermal metamorphism were zoned parallel to stratigraphy, with pyroxene, hornblende and garnet present towards the bottom of the stratigraphic sequence, while tremolite, actinolite, sericite, biotite and talc formed towards the top. This mineral distribution is similar to the one observed in active geothermal systems (Bird *et al.*, 1984; Schiffman *et al.*, 1984). Therefore, the pattern of alteration is considered to be the product of an ancient volcanic geothermal system.

Metallic mineralisation occurs in two associations. The first of these, iron-copper comprises chalcopyrite ore, together with pyrite, magnetite and minor amounts of pyrrhotite, galena, sphalerite, ilmenite, molybdenite, bornite, mackinawite, valleriite, marcasite, electrum and cobaltite. silver and gold are common by-products. Lead-zinc is the later association and it occurs as subsequent and minor veins and veinlets of galena and sphalerite with minor amounts of pyrite, chalcopyrite, tetrahedrite, melnikovite, gold and calcite. There are no exhalative iron-copper nor lead-zinc occurrences. The maximum formation temperature was around 320 to 414°C and isotope geochemistry (S, O, H) and fluid inclusion studies indicate that sulphur and the mineralising fluids had a sea-water source and that there was no boiling (Ripley and Ohmoto, 1977, 1979).

Within the district, metamorphic and hydrothermal alteration, mineralisation, volcanic activity and the emplacement of dacitic subvolcanic and hypabyssal intrusions are virtually all centred on the northeast-trending Calycantro Fault, which apparently controlled fissure volcanism, alteration and mineralisation.

Other minor copper-prospects of this kind are 5 Cruces, hosted in the Albian-Cenomanian Quilmana volcanics and Cerro La Loza, hosted in the volcanic-intrusive Bella Union Complex of Upper Cretaceous age.

Plutonic-related Cretaceous Deposits

The Coastal Batholith is composed of a large number of smaller granite plutons which have been grouped into super-units, while the batholith has been sub-divided into five lateral segments along its length as shown in Fig. 1. The early gabbros and diorites of this batholith, commonly known as the Patap Super-unit, occupy the same locus as the granite units of the batholith, but because of their tholeiitic nature are not considered to be part of the batholith from a geochemical and petrographical viewpoint (Pitcher *et al.*, 1985).

Fe oxide-Cu-Au deposits are associated with the early Albian (mid Cretaceous) gabbros and diorites of the Coastal Batholith and also with Cenomanian-Santonian (mid to upper Cretaceous) felsic super-units. They all occur in the Arequipa Segment of the Coastal Batholith, except for minor prospects in the Piura Segment, which are not described in this work.

Deposits Associated with Early Gabbros and Diorites of the Coastal Batholith (Patap Super-unit)

(Injoque, 2001; Injoque, 1985; Atkin *et al.*, 1985; Vidal *et al.*, 1990)

These deposits fall into two groups, iron and copper deposits. Yaurilla and Fe-Acarí (Fig. 5) belong to the first group (Dunin-Borkowski 1970; Zevallos, 1966) and are located 300 and 550 km respectively to the south of Lima. Both deposits were worked on a small scale in the 1960s and their production and reserves are of the order of 19 Mt @ 60% Fe and 20 Mt @ 66% Fe respectively.

Both Yaurilla and Fe-Acarí are associated with pyroxene-bearing diorite plutons having the geochemical characteristics of continental margin tholeiites and containing mineral veins of between 1 and 10 m in width

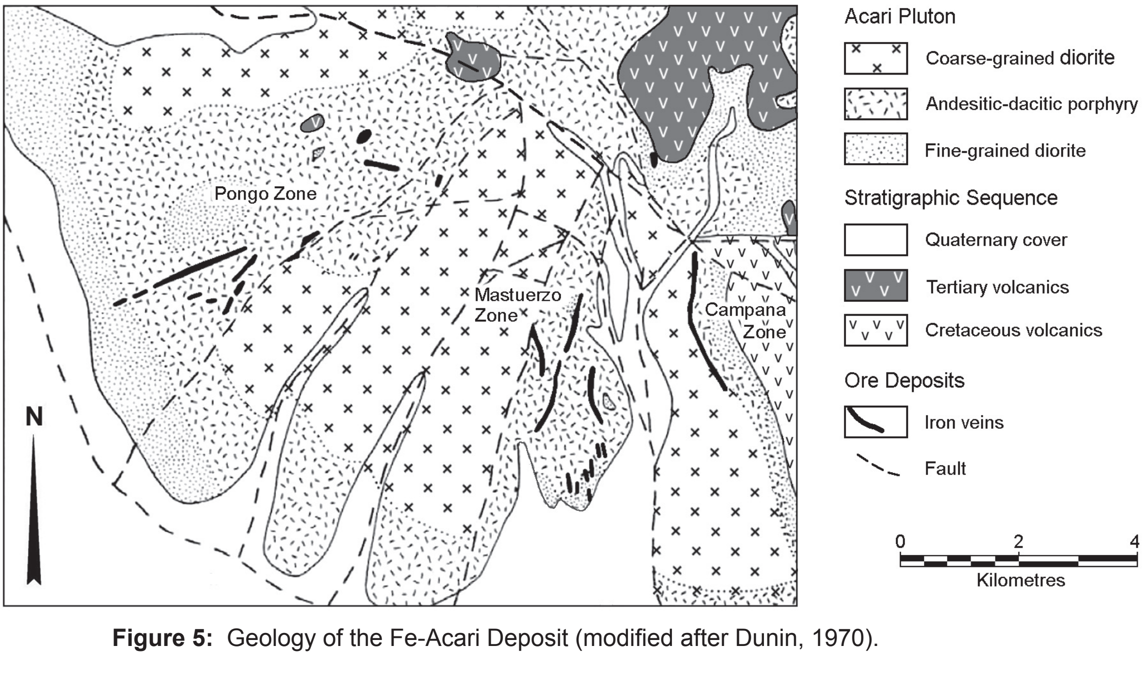

Figure 5: Geology of the Fe-Acari Deposit (modified after Dunin, 1970).

and up to 1 km in length. These veins show a vertical zoning pattern, with pyroxene dominant towards the lower levels and magnetite toward the upper sections.

The associated alteration is propylitic with magnetite disseminations farthest from the mineralised structures, while magnetite and associated epidote, clinopyroxene and amphiboles becoming more abundant towards the veins. The magnetite veins frequently have a banded appearance. This banding is made conspicuous by the less frequent occurrence of apatite, quartz and calcite accumulations between the magnetite bands. In the pyroxene rich magnetite veins of the lower levels, pyroxene has clearly crystallised first, from the walls of the host rock, while the magnetite has filled the space between pyroxene crystals. Many of these veins exhibit symmetric crustiform textures and marked poly-ascendant stages, with pyroxene or amphibole growing normally to the host rock, a clear indication that the veins were open-space during deposition. The delicate growth of magnetite and pyroxene, together with fault controls in the main veins and the transition from fresh diorite to altered diorite towards the contact with mineralisation, are a clear indication that the mineralising process was not magmatic as suggested by other authors, but that it was in fact metasomatic to hydrothermal (Injoque, 1985).

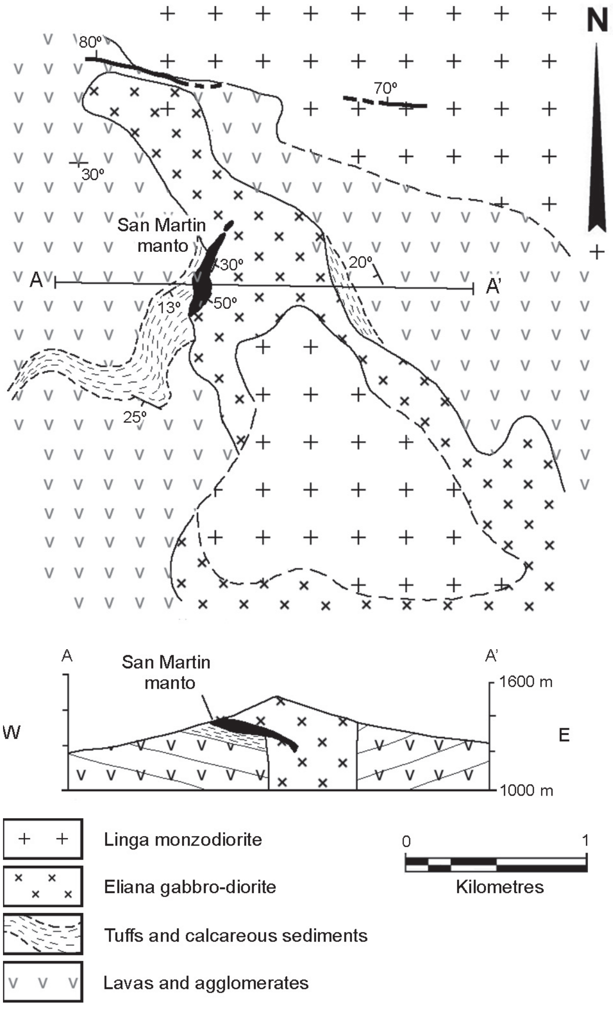

Figure 6: Geology of the Eliana Mining District (after Vidal, 1980)

The K-Ar age of the porphyry immediately preceding the iron mineralisation at Fe-Acari is 109 Ma (Vidal *et al.*, 1990).

The Cu deposits are represented by the San Martin Manto at the Eliana mine (Fig. 6) and by Monterrosas (Fig. 7; Vidal *et al.*, 1990), located 230 and 300 km to the south of Lima respectively. Both are now exhausted. Eliana produced 0.4 Mt @ 2.7% Cu from an up to 12 m thick manto located at the contact between a folded gabbro-dioritic sill and the andesite volcanics of the Albian Casma Volcanics. Monterrosas, on the other hand, is a 1.1 to 2% Cu vein linked to the sinistral Canzas fault. The vein is 430 m long, 150 m deep and up to 20 m thick and it is hosted by diorites. In both deposits, intrusives are continental margin tholeiites, but in contrast to those related to the iron deposits, they are hornblende- and biotite-bearing.

The alteration at Eliana includes of an outer zone of amphibole, chlorite, calcite and titanite. At the contact with the mineralised structure there is abundant amphibole and scapolite (Mei 25 to 33), together with disseminations of apatite, magnetite, pyrite and chalcopyrite, while the three latter and actinolite dominate within the mineralised structure. K-Ar dating of alteration amphiboles (hastingsite) associated with the Cu mineralisation, yielded ages of between 112 and 114 Ma (Vidal *et al.*, 1990), indicating a relationship between the gabbro and mineralisation. Furthermore, sulphur isotopes ($\delta^{34}S$) from 2 samples of pyrite gave values of -3.245 and -7.801‰ (Baruj, Spiro, BGS, personal comment) suggesting a source in part magmatic and perhaps partly sedimentary(?) for the sulphur, probably related to the surrounding Casma rocks.

At Monterrosas, late magmatic-hydrothermal alteration of the diorite generally resulted in the replacement of magmatic clinopyroxene and plagioclase by actinolite, with chalcopyrite and variable amounts of chlorite, epidote, scapolite (Me 25 to 29), tourmaline, sphene, apatite, magnetite and traces of K feldspar, calcite and muscovite.

Petrographic textures in both the diorite and ores indicate that metasomatic replacement was important, as well as fracture filling. The dominant mineral assemblage consists of chalcopyrite, magnetite, pyrite and actinolite in variable proportions, together with smaller quantities of clinopyroxene, Na-scapolite, tourmaline, quartz, pyrrhotite and cubanite. Underground mapping reveals a transitional zoning from the diorite walls towards the centre of the vein. The contact is irregular and gradational and is occupied by vein swarms composed of an outer zone of Na-scapolite and then by actinolite inwards. Immediately following is an interval of crystalline acicular actinolite, changing further toward the centre to massive magnetite in which small sulphide veins and disseminations appear and increase to form a central ore zone of massive chalcopyrite. Silicates, magnetite and sulphides are sigmoidal, while supergene processes replaced chalcopyrite with covellite and martitisation of magnetite.

A geochemical comparison of the total rock (balance) between fresh and altered diorites (Sidder, 1981, 1984), shows that the total iron content increases towards the central ore zone, while silica is reduced. Metals such as copper and cobalt are found at a background levels in diorites while abnormal concentrations of these elements and of Au, Ag and Mo characterise the actinolite and sulphides.

Fluid inclusion studies of quartz and sulphur isotope studies of pyrite and chalcopyrite indicate hydrothermal alteration and ore deposition temperatures of between 300 and 500ºC, salinities of 30 to >50 wt.% $NaCl_{equiv.}$ and values of 1.6 to 3.3‰ for $\delta^{34}S$. High temperature, saline and magmatic fluids produced by the Patap Super-unit gabbro-diorite crystallisation are considered to have originated, transported and deposited the Monterrosas amphibole-copper-iron ores as a consequence of a drop in temperature and acidity of the mineralising fluid (Sidder, 1984).

Deposits Associated with the Coastal Batholith

The known iron oxide copper-gold family deposits of the main Coastal Batholith (other than the Patap Super-unit) occur within the Linga Super-unit (Cobrepampa) and the Cochahuasi Pluton (Cata Cañete).

Linga Super-unit: Cobrepampa District: (Hudson, 1974; Lavado, 1973; Valera, 1982) The Cobrepampa copper deposit is located 550 km to the south of Lima and consists of a cluster of veins hosted in the Cobrepampa Alkaline Monzonite, a 15 x 10 km northwest oriented pluton, belonging to the Linga Super-unit of the Coastal Batholith. The district has produced copper on small scale from the late 1950s to early 1960s, but at present is abandoned. The pluton varies from monzonite to grey-pink quartz-monzonite with dioritic facies.

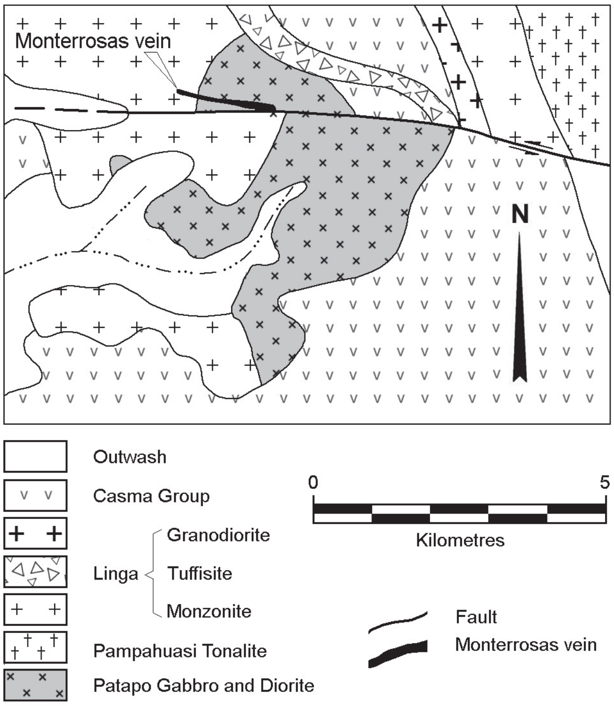

Figure 7: Geology of the Monterrosas Mining District (after Vidal, 1980)

The most primitive facies show 30 to 35% orthoclase and 40 to 45% andesine plagioclase, with hornblende, clinopyroxene and quartz as accessory minerals, while in the more evolved facies orthoclase becomes dominant with abundant biotite, usually forming aplitic dykes.

The principal structures of the district are northwest-trending faults that crosscut the entire area, with important dextral and normal components of displacement. The movement on these faults was in general late relative to the consolidation of the pluton and in part synchronous with the mineralisation.

Towards the mineralised zone, secondary biotite occurs at the transition from the magmatic to the late magmatic stages, and towards the core of the pluton. Subsequent abundant K feldspar alteration is widespread throughout the pluton but especially close to the mineralised bodies and takes the form of small veins and dissemination, increasing in density to finally alter the whole rock. This alteration has associated amber and brown garnet, actinolite and tourmaline as accessories. Towards the periphery of the feldspathised zone, transitional and sequential zones of quartz-sericite and, finally, propylitisation are developed.

The mineralisation occurs as a cluster of northwest-trending veins dipping at from 60 to 70°NE to subvertical, crosscutting practically the whole central zone of the intrusion. These veins form orebodies that are 100 to 300 m long, 5 to 10 m thick and 100 to 200 m deep, distributed in a sigmoidal pattern. On average, ore occupies 33 to 50% of the length of the veins. In total the vein swarm, spread throughout the pluton, covers an area of at least 10 x 5 km. It is suggested that the historic production (Samame, 1992; Valera, 1982; Lavado, 1973) plus reserves within the district may be of the order of 3 to 5 Mt with of 2 to 5% Cu, ~15 g/t Ag and Au as by-products.

The ore worked in these veins is mainly chalcopyrite and bornite, which associated pyrite and minor specularite, sphalerite and magnetite. However, during the early phase of mining activity in the district, the main ores were chalcocite, covellite and copper-oxides. The vertical zonation within the veins, commences with copper- and iron-oxides over the first 50 m below the surface. This is followed downwards by a secondary enriched copper-zone with chalcocite, covellite, digenite and Cu-oxides overprinting the primary ores in the lower sections to form bornite-chalcocite to a depth of 100 m. The next lower zone is a 50 to 100 m pyrite-chalcopyrite interval, which is followed downward by a magnetite-rich zone. Subordinate amounts of tungsten and tin are also found at depth (Samame, 1992).

The non-metallic gangue is K feldspar-rich towards the more potassic sections of the pluton with clinopyroxene and actinolite as the dominant gangue and some quartz towards the periphery. There are also smaller quantities of tourmaline, apatite, garnet, biotite, chlorite, quartz and calcite. The principal orebodies are associated with propylitic alteration. The gangue minerals grow mainly towards the host rocks, with a comb-like texture while the sulphides and magnetite grow towards the centre of the structure. Nevertheless, towards the central and wider parts of the orebodies, the sulphides and gangue grade into a crackled zone, followed by a breccias with a high concentration of sulphides, indicating a relation between mineralisation and the dextral movement that formed the veins.

At Atiquipa, which is some 600 km to the south of Lima, there is a prospect comprising 10 to 15 smaller veins. Mineralisation occurs as Cu-oxides, magnetite, clinopyroxene, actinolite, Na-scapolite, epidote, quartz and chlorite. The veins are hosted within the alkaline Chala gabbro, which also belongs to the Linga Super-unit. These veins have been worked by artisanal miners to extract the Cu oxides which contain traces of Au and have a potential of a few thousand to tens of thousands of tonnes.

Cochahuasi Pluton, Cata Cañete District: (Injoque *et al.*, 1995) The Cata Cañete District is located 100 km to the southeast of Lima and consists of veins and small clusters of Cu minerals within the Cochahuasi Pluton of the Coastal Batholith.

The Cochahuasi Pluton is an northwest-trending, elongate, 20 x 10 km body composed of two principal units. The Mafic Unit is melanocratic, mainly monzo-dioritic, intruding and metamorphosing the surrounding Mesozoic volcanic-sedimentary formations to the south and west. It is intruded by the later leucocratic quartz-dioritic Felsic Unit. Both units have subsequently been intruded by swarms of lamprophyric dykes and are strongly affected, especially the Mafic Unit, by a northwest-trending, Cretaceous, amphibolite facies, dynamo-metamorphic event. The whole pluton was then intruded to the east by the late post-tectonic felsic Tiabaya Pluton.

The Cu mineralisation is distributed virtually throughout the pluton and into the neighbouring Mesozoic formations, as veins containing defined orebodies and as minor vein-swarms. The veins display sigmoidal patterns. The orebodies within the pluton attain lengths of several hundred metres and have widths of 2 to 10 m, although in the surrounding Mesozoic formations they only reach some tens of metres in length.

The mineralisation towards the base of the veins and within the host rock develop clinopyroxene, garnet, epidote and hornblende assemblages, which are generally obliterated by later mineralisation comprising chalcopyrite, pyrite, magnetite, quartz, chlorite, biotite and calcite, with minor bornite, sphalerite, galena, pyrrhotite, cobaltite, molybdenite, ilmenite, arsenopyrite, marcasite, melnikovite and gold.

This district has been mainly worked by informal and small miners and reserves plus historic production is believed to only be of the order of some hundreds of thousands of tonnes @ 1.5% Cu with Ag and Au by-products, although the upper oxidised levels are generally richer.

Discussion

Geotectonic Environmental and Sources of Magma and Metals *(Refer to Tables 1 and 2)*

Iron oxide rich deposits with variable amounts of accompanying copper and/or gold are found in two very different environments within Perú.

The first of these is represented by the Cobriza deposit which is found in the Hercynian eastern range, hosted by the Tarma Group that occurs within an ensialic rift subsequent to Hercynian deformation, together with anorogenic intrusions (Soler, 1991; Kontak *et al.*, 1985).

In the western range, volcanic related deposits occur in the southern sector of the Cañete-Huarmey Marginal basin (the Cañete Basin proper), where its ensialic character produced volcanism of alkaline and shoshonitic affinities with markedly inter-plate (Jurassic) to arc basalt (Cretaceous) character. The plutonic related deposits associated with the Patap Super-unit and the Coastal Batholith, have also formed in this section of the Andes, are localised in the Arequipa Segment, and are also ensialic in nature. The plutons of the Coastal Batholith are generally arc-related magmas, indicating a possible relationship with subduction processes, as are the Cretaceous volcanics.

The REE signatures of the Coastal Batholith hosts indicate plagioclase, clinopyroxene and hornblende fractionation in different proportions, but no garnet fractionation, implying that the magmas originated at depths of less than 40 to 60 km in the mantle (Injoque, 1985; Pitcher *et al.*, 1985). The exception is the Cochahuasi Pluton (Cata Cañete) where garnet fractionation was important. Nevertheless, the magmas of this segment of the batholith are enriched in radiogenic Pb and LIL-elements (Atherton and Plant, 1987), because of their emplacement within the Precambrian crust. This enrichment is not recorded in the Lima Segment, where Precambrian crust is absent.

The Pb isotopes in the deposits also indicate that they originated in the mantle but with enrichment from the upper sedimentary layers of the crust, except for Marcona and Cobriza where Precambrian crustal Pb is important (Mukasa *et al.*, 1990; Noble *et al.*, 1995). This suggests that basement crustal sources may have contributed by providing copper and iron at Cobriza, while deposits formed away from this ancient crust, have derived metal from more mantle-related sources.

The source of sulphur and water for Raúl-Condestable was predominantly seawater (Rypley and Ohmoto, 1977, 1979). In contrast, the source of sulphur at Monterrosas (Sidder, 1981, 1984), Eliana and Marcona is magmatic, although minor sedimentary (Eliana) or marine (Marcona) sources cannot be discounted.

The relationship between deformation and mineralisation is another interesting aspect of these deposits. Cobriza, in the eastern range of the Andes, appears to be a post-tectonic deposit and coincides in time with the late Hercynian

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[1] REE: rare earth elements

Table 1: Plutonic related deposits

	Hercynian Cycle: Cobriza	Andean Cycle: Cata Cañete	Eliana	Yaurilla	Monterrosas	Fe-Acari	Cobrepampa
Regional Aspects							
Regional Igneous Body	Villa Azul Batholith	Coastal Batholith	Coastal Batholith	Coastal Batholith	Coastal Batholith	Coastal Batholith	Coastal Batholith
Associated Type Pluton	Two mica granite	Cochahuasi diorite	Patap Gabbro, Diorite	Patap Diorite	Patap Diorite	Patap Diorite	Linga Monzonite
Geotectonic Character	Anorogenic	Extensional, continental margin	Extensional, continental margin	Extensional, continental margin	Extensional, continental margin	Extensional, continental margin	Extensional, continental margin
Petrochemistry	Alkaline	Calcalkaline-alkaline	Tholeiite	Tholeiite	Tholeiite	Tholeiite	Alkaline
Magma Fractionation	Plagioclase*	Garnet	Plagioclase, (clinopyroxene)		Plagioclase, (clinopyroxene)	Plagioclase, (clinopyroxene)	Plagioclasa, (hornblende)
Regional Tectonics	Intracontinental rift	Late Cretaceous	Late Albian	Late Albian	Late Albian	Late Albian	Late to deformation
Important Structures	NW Reverse faults	Dextral NW faults	NW Synclinal		E-W sinistral Canzas Fault	NW & NE normal faults	Dextral NW normal faults
Exposed basement	+	-	+	+	+	+	+
Local Aspects							
Type of structures	Manto	Multiple	Manto	4 Veins	1 Vein	15 Veins	Multiple veins
Alteration							
External			Propylitic, albite	Propylitic, clinopyroxene	Propylitic, albite	Propylitic, clinopyroxene	K-feldspar, biotite, tourmaline
Internal	Diopside, garnet, hornblende, skarn type	Chlorite, sericite, silica, pyrite	Diopside, hornblende, Na-scapolite (skarn), pyrite	Clinopyroxene, actinolite	Diopside, hornblende, Na-scapolite skarn type, pyrite	Clinopyroxene, actinolite	K-feldspar, actinolite, tourmaline
Ores, by products	Chalcopyrite, Ag, Bi	Chalcopyrite, Ag, Au	Chalcopyrite, Ag, Au	Magnetite	Chalcopyrite, Ag, Au	Magnetite	Chalcopyrite, bornite, chalcocite, Ag, Au
Metallic Gangue	Magnetite, pyrrhotite, arsenopyrite	Magnetite, pyrite, pyrrhotite	Magnetite, pyrite, pyrrhotite		Magnetite, pyrite, pyrrhotite		Magnetite, pyrite
Non-metallic Gangue	Actinolite, phlogopite, quartz	Quartz, chlorite, calcite	Actinolite, chlorite, apatite, quartz, calcite	Clinopyroxene, apatite	Actinolite, chlorite, apatite, quartz, calcite	Clinopyroxene, apatite, quartz, calcite	Actinolite, chlorite, albite, K-feldspar, apatite, quartz, calcite
Trace Elements	W, Sn	Co, Ni	Co, Ni		Co, Ni		Co, Ni, W, Sn
Main Metasomatism					Fe, Mg, Al, K	Fe, Mg, Ca, (-Mn)	
Minor Metasomatism					Si, Na, Ca	Si, Al, Na, P	
Pressure, Kbars			0.5		0.5	0.5	
Ore Source			Patap Diorite		Patap Diorite	Patap Diorite	
Sulphur Source			Magmatic, (-sedimentary?)		Magmatic		
Lead Source	Precambrian crust	Enriched Mantle & upper sedimentary crust	Enriched Mantle & upper sedimentary crust		Enriched Mantle & upper sedimentary crust		Enriched Mantle & upper sedimentary crust
Fluid Source							
Salinity, NaCl eq. %					30-50		10-60**
Size and grade	100 Mt @ 1.5% Cu (Ag, Bi)	~1 Mt @ 1.5% Cu (Ag, Au)	0.4 Mt @ 2.6% Cu	19 Mt @ 60% Fe	1.9 Mt @ 1.6% Cu (Ag, Au)	20 Mt @ 66% Fe	5 Mt @ 2-5%Cu
Metallic Cu content (Mt)	15	~0.3	0.12		0.34		~1.5
Age (Ma)	263	>66***	114-112			<109	>96***
Deposit Type							
Skarn (Einaudi et al., 1981)	Cu calcic skarn	Fe calcic skarn	Fe calcic skarn	Fe calcic skarn	Fe calcic skarn	Fe calcic skarn	Cu calcic skarn
Other	Distal skarn	Autoreaction/hydrothermal	Autoreaction skarn	Autoreaction skarn	Autoreaction skarn	Autoreaction skarn	Autoreaction skarn
Hitzman et al. (1992)	Fe oxide-Cu-Au	Fe oxide-Cu-Au	Fe oxide-Cu-Au	Magnetite-apatite	Fe oxide-Cu-Au	Magnetite-apatite	Fe oxide-Cu-Au

* Soler, 1991; ** For the Linga Superunint Linga, Pisco Pluton, Agar, 1981; *** Estimated after Beckinsale *et al.*, 1985

extensional event, although the deposit is apparently focused on a northwest-trending reverse fault set (Valdez, 1983b). Marcona is associated with the transcurrent Treinta Libras Dextral Fault and a localised Jurassic rift which was the source of local volcanism (Injoque *et al.*, 1988). In this same period, volcanic activity in northern Chile coincided with the initial activation on the Atacama Fault (Brown *et al.*, 1991; Scheuber and Adrienssen, 1990), and with important mineralisation such as at Mantos Blancos and Michilla (Munizaga *et al.*, 1991; Venegas *et al.*, 1991). Raúl-Condestable (Injoque, 1985) and los Icas (Osterman, 2001) display a similar association with local rifts, but so far have no apparent relation to transcurrent faults. The plutonic related deposits however, are later associated with the Albian Mochica Deformation (Patap Super-unit; Injoque, 2001) or the Late Cretaceous Perúvian Deformation (Cata Cañete; Injoque *et al.*, 1995). For Monterrosas (Injoque, 1985) and Cobrepampa (Valera, 1982) however, there is a clear relationship with district scale transcurrent faults. Thus there appears to be a correlation between transcurrent faulting and mineralisation, the main mineralisation coinciding with the most notable fault (eg., Marcona).

Table 2: Volcanic Related Deposits

	Andean Cycle:	**Raúl-Condestable**	**Marcona**
Regional Aspects	*Type of basin*	Ensialic aborted marginal basin	Ensialic aborted marginal basin
	Petrochemistry	Calc-alkaline	Alkaline-shoshonitic
	Magma fractionation	Clinopyroxene, hornblende, (plagioclase)	Clinopyroxene, hornblende, (plagioclase)
	Thickness of the basin (m)	1000 to 2000	>4000
	Geothermal gradient (°C/km)	<100°	
	Type of metamorphism	Burial Type	Burial Type
	Metamorphic facies	Prehnite-pumpellyite to zeolite	
	Geotectonic character	Extensional, continental margin	Extensional, continental margin
	Regional tectonics	Extensional, local rift	Dextral transcurrent, local rift
	Important structures	Calycantro NE Extensional Fault	Treinta Libras NW Dextral Fault
	Ocoite presence	No	Yes
	Mantle intrusion into the crust	Yes	No
	Basement in the vicinity	No	Yes
Local Aspects	*Type of structures*	Mantos, veins, disseminated ore bodies	Mantos, veins, disseminated ore bodies
	Alteration		
	External	Propylitic, albite, K feldspar, hematite	Propylitic, albite, K feldspar, hematite
	Internal	Diopside, garnet, hornblende, Na-scapolite (skarn type), biotite, sericite, talc, pyrite	Diopside, garnet, hornblende, Na-scapolite (skarn type), Phlogopite (skarn type), pyrite
	Ores, by-products	Chalcopyrite, Ag, Au	Magnetite, chalcopyrite, Ag, Au
	Metallic gangue	Magnetite, pyrite, pyrrhotite	Pyrite, pyrrhotite
	Non-metallic gangue	Actinolite, chlorite, albite, K-spar, apatite, quartz, calcite	Chlorite, albite, K-spar, apatite, quartz, calcite
	Trace elements	Co, Ni	Co, Ni
	Metasomatism - addition	Fe, Mg, Cu, Co, Ni	Fe, Cu, Co
	Metasomatism - depletion	Na, P	
	Prograde stratigraphic zoning		
	Upper Part	Biotite, chlorite-sericite, talc	Phlogopite, chlorite-sericite
	Lower Part	Diopside, garnet, hornblende, Na-scapolite	Diopside, hornblende, Na-scapolite
	Maximum formation temp. (°C)	414	500
	Pressure, Kbars	0.5	1
	Local gradient (°C/km)	~100°	~100°(?)
	Ore metal source	Surrounding Volcanics	
	Sulphur source	Sea water, magmatic	Magmatic, sea water?
	Lead source	Enriched mantle and upper sedimentary crust	Precambrian crust
	Mineralising fluid source	Sea water	
	Salinity, equivalent % NaCl	20 to 30	
	Size (millons of tonnes & grade)	~50 Mt @ 1.5 % Cu (Ag, Au)	>1500 Mt of Fe; 0.01% Cu, Ag, Au
	Metallic Cu content in Mt	~7.5	1.5?
	Age (Ma)	124 to 127	154 to 160
Deposit type	*Skarn type (Einaudi et al., 1981)*	Fe Calcic skarn	Fe Calcic skarn
	Other classifications	Geothermal skarn, CuTM Peruvian type*	Geothermal skarn, CuTM Peruvian type*
	after Hitzman et al. 1992	Fe oxide-Cu-Au	Magnetite-apatite

*Copper Manto-Type deposits, Peruvian type (Injoque 1999, 2000)

Mineralogy and Formation Conditions *(Refer to Tables 1, 2 and 3)*

The principal alteration associated with these deposits of the coastal volcanic environment and the Patap Super-unit intrusives is propylitisation, with albite present to a greater or lesser extent and minor proportions of K feldspar. Immediately adjacent to the mineralisation clinopyroxene, amphiboles (hornblende and tremolite-actinolite), Na-scapolite, epidote, chlorite and garnet alteration patterns become important.

At Cobrepampa, however, K feldspar alteration and weak secondary biotite are observable on a district scale. At Marcona and Raúl-Condestable, furthermore, pyrite disseminations can be found surrounding the mineralisation giving way to an outer halo of weak pinkish hematite.

The mineralogy of these deposits generally consists of actinolite, hornblende, Na-scapolite and chlorite, with variable amounts of biotite, phlogopite, sericite, garnet (grandite), diopsidic clinopyroxene, apatite, sphene and minor presence of rutile, albite, tourmaline, K feldspar, quartz and calcite, the latter being developed mainly towards the hydrothermal stage. The dominant metallic minerals are magnetite, pyrite, chalcopyrite and variable quantities of pyrrhotite, with bornite, chalcocite, covellite, ilmenite, molybdenite galena and sphalerite being generally less abundant. Cobriza, however, contains Ag and Bi as by-products as well as noteworthy contents of arsenic minerals that are otherwise absent or very rare in Andean deposits. Trace amounts of W and Sn are also present, elements that are only found on the coast at Cobrepampa, which appears to indicate a relation to felsic alkaline magmas in both cases. On the coast, however, almost all of the deposits contain by-

Table 3: Comparative mineralogy table for the main Fe Oxide-Cu-Au Deposits of Perú.

	Hercynian Cycle	**Andean Cycle**						
	Cobriza	**Raúl-Condestable**	**Eliana**	**Monterrosas**	**Marcona**	**Fe-Acari**	**Cata Cañete**	**Cobrepampa**
Garnet	●	O			O		O	O
Clinopyroxene	●	O		Tr	O	●	O	O
Scapolite	O	O	O	O	Tr	Tr		O
Amphibole	●	●	●	●	●	O	O	●
Apatite		O	O	O	O	O	O	O
Sphene	O	O	O	O	O	O	O	O
Biotite/phlogopite/sericite	O	O	O	O	O	Tr	O	O
Albite		O	O	O	Tr	Tr	O	
Prehnite		O			Tr			
Tourmaline/axinite	O	Tr	Tr	O	O			O
Chlorite	O	●	O	O	O	Tr	●	O
Epidote	O	O	O	O	Tr	Tr	O	Tr
K-Feldspar		O	Tr	Tr	Tr			O
Quartz	O	O	O	O	Tr	Tr	●	O
Calcite	O	O	O	O	O	O	●	O
Talc	O	Tr			Tr	Tr		
Barite	O							
Magnetite	●	●	●	●	●	●	O	●
Hematite	O	Tr			O	O	Tr	O
Ilmenite		Tr	Tr	Tr	Tr		Tr	
Molybdenite		Tr	Tr	Tr	Tr		Tr	Tr
Pyrite	●	●	●	●	●	O	●	●
Cobaltite/Gersdorfite		Tr	Tr				Tr	
Pentlandite					Tr			
Pyrrhotite	●	O	Tr	Tr	Tr			
Arsenopyrite	●	Tr	O				Tr	
Lollingite	Tr							
Rutile	●	Tr	Tr	Tr	Tr	Tr		
Chalcopyrite		●	●	●	●	Tr	●	●
Bornite	Tr	Tr	Tr	Tr	Tr		O	O
Cubanite		Tr	Tr	Tr				
Sphalerite/Marmatite	Tr	O	O	O	Tr		O	Tr
Galena	Tr	O	Tr	Tr	Tr		O	Tr
Mackinawite/valerite		Tr	Tr		Tr		Tr	
Au/electrum	Tr	Tr	Tr	Tr	Tr		Tr	Tr
Marcasite	O	Tr	Tr	Tr	O		O	
Tetrahedrite		Tr						
Bismuthinite/Native Bi	Tr							
Melnicovite		Tr	Tr		Tr			
W, Sn	Tr							Tr

Principal = ● Minor = O Trace = Tr

products gold (native, electrum and solid solution), silver (in galena) and traces of cobalt and nickel, indicating an association with basic magmas (Injoque *et al.*, 1985).

The formation temperature for these deposits is generally estimated between 400 and 500ºC considering their mineral assemblages. Only at Raúl-Condestable there are temperature estimations based on isotope geochemistry (320 to 414ºC). The formation pressure for the coastal deposits has been estimated from the stratigraphy at around 0.5 Kbars although it appears that Marcona was somewhat deeper (1 Kbar).

Classification *(Refer to Tables 1 and 2)*

The iron oxide rich deposits with variable amounts of accompanying copper and/or gold found in Perú are considered to be classical Fe and/or Cu skarns. According to the classification used by Einaudi *et al.*, (1981) they are "Fe calcic skarns", except for Cobrepampa which, because of its relationship with the Cobrepampa monzonite is a "Cu calcic skarn". Cobriza, because of its mineralogy and proximity to granitic rocks also belongs to the second group. Cata Cañete, however, although it has skarn roots, is volumetrically an hydrothermal deposit.

On the other hand Raúl-Condestable and Marcona are deposits formed at sub-volcanic levels in the final stages of the Chilca and Río Grande volcanisms, respectively. Their initial stages of thermal metamorphism produced a zoning pattern that parallels the stratigraphy, with pyroxene, hornblende and garnet development towards the base of the sequence, while tremolite, actinolite, sericite, biotite and talc occur towards the top. This mineral distribution is similar to that observed in active geothermal systems (Bird *et al.*, 1984; Schiffman *et al.*, 1984). For this reason the pattern of alteration is considered to have originated in an ancient volcanic geothermal system and deposits are classified as geothermal skarns or Perúvian Manto type Cu deposits (Injoque, 1985, 1999, 2000). These deposits coincide on a regional scale with the presence of ocoites, a thick crust, geothermal gradients of 20 to 30ºC/km, green schist to zeolite facies metamorphism and a moderate intrusion of the mantle into the crust in the Cañete Basin. To the north however (Huarmey Basin), ocoites are absent, although there is an association with episodic burial metamorphism, geothermal gradients of >300ºC/km, an oceanic environment within the basin, together with a deep intrusion of the mantle into the crust (Aguirre *et al.*, 1989). Under these conditions VMS type deposits occur instead (Injoque, 1999, 2000), with Raúl-Condestable being found at the transition between the two basins.

The deposits related to the Coastal Batholith, however, are classified as auto-reaction skarns in the sense of Zharikov (1970).

Hitzman *et al.* (1992) separate this family into two groups. The magnetite-apatite or Kiruna-type deposits, which include Marcona, Chala, Fe-Acari and Yaurilla, given the massive presence of magnetite in these deposits. The second group corresponds to the Fe oxide-Cu-Au deposits because of their greater copper content, although of these only Cobrepampa and Cobriza are related to felsic rocks. Cata Cañete, however, has developed further towards the hydrothermal stage and is richer in quartz and calcite, corresponding to higher systems as described by Ray and Lefebure (2000). The development of these deposits towards systems rich in magnetite or rich in copper appears to be related to the evolution of pyroxene-rich magmas or hornblende-rich magmas respectively (Osborn, 1959; Helz, 1976; Oyarzun, and Frutos, 1984), within the typical metallogenic evolution processes of island arcs (Stanton, 1978).

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