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**EXOTIC DEPOSITS DERIVED FROM PORPHYRY COPPER  
SYSTEMS IN CHILE**

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**This dissertation is submitted as an integral part of the Exploration Geology course for the degree of Master of Science at Rhodes University, Grahamstown, South Africa.**

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## A B S T R A C T

The exotic orebodies, related to cal-alkaline porphyry copper deposits, are sub-horizontal lenticular bodies of secondary copper minerals that impregnate Tertiary gravels and bedrock of different ages. They lie immediately downslope of the porphyry copper deposits, that is to say, they are related to the propylitic halo of the main deposits, and are considered to have originated with the deposition of copper minerals from solutions that overflowed during the secondary enrichment process. Supergene alteration took place between the late Oligocene and Miocene, by which time both orebodies (exotic and porphyry copper) were established.

The paucity of the denudation since the Miocene in the Andean segment from 21° to 26° latitude S. due to the dominance of a hyperarid climate explains the remarkable preservation of the shallow porphyry copper systems, supergene enriched blankets and associated deposits. This is reflected in the limonites, where the typical boxworks have been partially or totally destroyed on surface by the superleaching.

As a result of the lateral migration of the copper-bearing solutions, the exotic deposits show a zonation, alteration and mineralization whose characteristics depend among other factors, on the reactivity of the bedrocks and the Cu/S ratio of the mother deposit. In these deposits three zones can be recognized: Proximal (0 to 2 km), Intermediate (2 to 3) and Distal (3 to 8-14 km) with palaeodrainage control.

The associations and mineralogical abundance are related to the climate (rain, temperature). In some deposits two important units are detected and they are the Cu-phosphates and Cu-lixivable (to sulphuric acid) units.

The size of the Chilean exotic deposits varies between 100 and 3,500,000 ton of copper, with a total known resource of 8 M tons of copper. The large exotic deposits are comparable to the resources of a medium-sized porphyry copper- type deposit.

The discovery of the exotic deposits is related to the exploration of porphyry copper deposits, where a mass balance of the leached column must be done. Moreover the lithology and alteration of the propylitic halo, permeability, structures, geophysics and geochemistry should be considered. The diorite model is not compatible with a supergene enrichment process, expressed by the absence of colour anomalies, exotic deposits and in the presence of secondary minerals like jarosite, which is coherent with the pyrite deficiency of the system.

The projects are for exploitation of reserves by open pit methods. The projects plan to extract and to

crush copper oxide ore which will be pre-treated with concentrated sulphuric acid prior to heap leaching, solvent extraction and electrowinning. The copper output varies between 10,000 and 50,000 ton per year of cathode copper. The total investment varies between 20 and 100 millions dollars.

For project calculations, estimation of 65% - 82% copper recovery and 37 - 40 kg/ton net acid consumption can be used due to the nature of ore. The leaching time is estimated as 30 to 180 days for heaps of 4,5 to 30 metres high. As a result of this, the plant capacity is determined by an annual equivalent of 10,000 to 25,000 ton Cu per year.

Pit planning has been carried out using diverse software on the basis of 5 x 5 x 5 m and 10 x 10 x 10 m block models, evaluated using a kriging package built into the program, giving an overall waste/ore ratio (including pre-stripping) of 0:1 (in an outcrop) to 3:1. The location of the mine and plant sites are associated with the porphyry copper in production, for this the already installed facilities can be used. So there is no need to build a new mine camp or access.

The environmental impact is summarized relating to the characterization of the physical, biological and socio-cultural effects, using the framework of the Base Line study and the Impact evaluation derived from the construction and project operation phases. The conclusions and recommendations will diminish, mitigate and/or eliminate impact derived from the specific activities.

## CHAPTER I.- INTRODUCTION

Mining development in Chile of the last decade has been amazing. Copper is particularly significant. Different copper projects will mean a production increase of nearly 70% of this metal by the year 2000.

Against this background, hydrometallurgical operations will head the list of mining projects for the next few years with an investment of over US\$ 3,000 million. If the total amount of mining investment in copper projects is considered to be over US\$ 4,500 million, it could be concluded that the share of the hydrometallurgy in this development is about 70% (Reghezza, 1993; Table 1). In other words, for every US\$ 10 invested in copper projects in Chile, at least US\$ 7 are related to leaching projects, solvent extraction and electrowinning.

Most of these new projects contain low investment processes and unit costs which, with the present world trends in supply and demand, should lead to a balanced price of between 0.70 and 0.80 US\$ per pound of produced copper. Under these circumstances, to keep oneself in the market, companies should aim at a cost of between 0.60 and 0.65 US\$/lb, including expenses and depreciation.

Assuming that greatest investment costs and operations are inherent in the conventionally processed ore, it is considered that the search for applications of hydrometallurgical processes, particularly with the use of sulphuric acid, is the most effective way to attain the cost mentioned above.

The mining legislation (Law 18097 of 1983) and foreign investments (Law decree 600 of 1974 and Chapter XIX Law of the Central Bank of 1985) have created favourable economic conditions for the investment of foreign capital. The mining legislation establishes a clear and public procedure of the mining property constitution, which ensures assigning of the concessions for an indefinite time.

Among the derived benefits from this new legislation are the following: "the right to re-export the invested capital cost (after the tenth year from capital cost investment) and the utilities (after the fifth year from capital cost paid off) that this generates. The re-exportation is carried out with charge to the official changing market, previous authorization of the Central Bank of Chile.

### 1.1.- OBJECTIVES

The aim of this dissertation is a view to generalize the knowledgement of the geology, metallurgy, exploitation methods and the environmental impact of these deposits which have been classified exotics, related with rich-silica porphyry copper deposits. Figure 1 shows the 13 most important exotic deposit in Chile.

In the mining-geologic field only the deposit "Mina Sur" ex "Exotica" was known. It was related to the Chuquicamata porphyry copper deposit.

The exotic orebody is considered to have originated with the deposition of copper minerals from solutions that overflowed during the porphyry copper secondary enrichment process.

### 1.2.- CUPRIFEROUS PROJECTS IN CHILE

A total number of 22 projects by private investors are presently being evaluated in the country, most of them, in production towards 1997. Table 1 shows the value of investment associated with these different projects and their technical data respectively. The greatest investments come from countries such as: United States, Australia, Canada, South Africa, Japan, England and Finland.

The incorporation of these copper projects has meant virtually a drastic change in the Chilean mining map. The northern part of the country is particularly prominent in this transformation.

El Abra and Collahuasi are the biggest projects with large amounts of money invested (over 1,000 million dollars each). El Abra aims to exploit leachable ore to obtain a production of the order of 225,000 tpa of fine copper in cathode shape, during 20 years and with an operational cost of about 0.40 and 0.45 US\$/ pound (Reghezza, 1993). Production will start in 1998.

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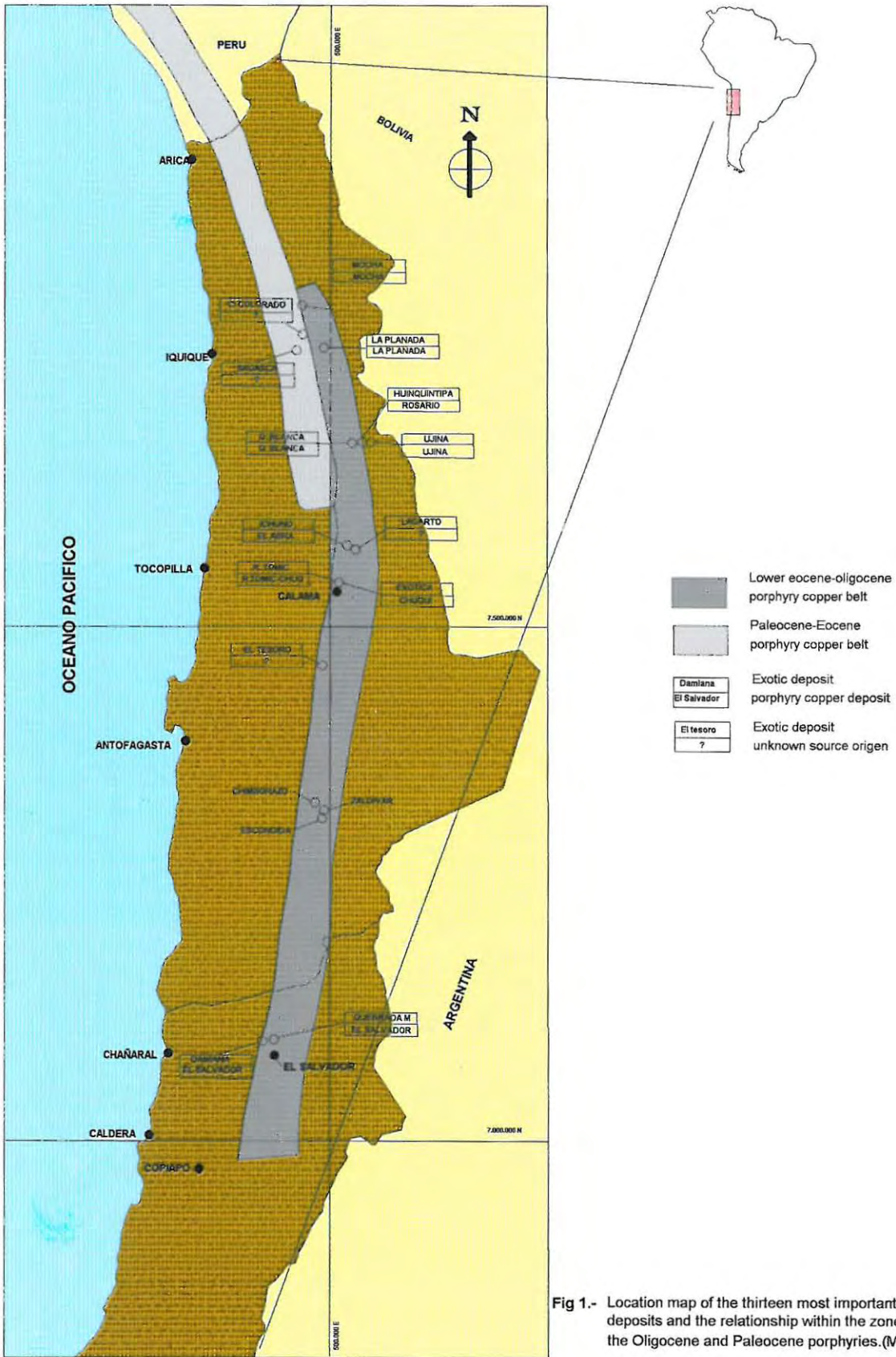


Fig 1.- Location map of the thirteen most important exotic deposits and the relationship within the zone between the Oligocene and Paleocene porphyries. (Munchmayer, 1995)

TABLA N° 1.- INVESTMENT IN THE MAIN COPPER PROJECTS IN CHILE (Reghezza, 1993)

PROJECT	RESERVES (Mt) GRADE (% CuT)	OWNER	INVESTMENTS		Metallurgical		COST (ct/lb)	STAGE
			(%)	M US\$ (ESTIMATED)	Process	Ton/Year (Cu) x 1000		
Cerro Colorado (porphyry copper)	79 1.4	Rio Cerro Inc. Rio Chile Inc.	0.03 99.97	286	SX - EW	40	42	Pre-Development
Collahuasi (Rosario, Ugina, Huiniquinta, La Grande) [Porphyry copper]	1,000 0.92	Falconbridge Shell Chile M.M.minorco	33.0 33.0 33.0	1000	Flotation SX - EW	320 47.5	55 41	Feasibility Study
Quebrada Blanca (porphyry copper)	250 1.5	Cominco R. Teck Corpora. S.M.Pudahuel Enami	44.0 32.5 13.5 10.0	373	SX - EW	75	43	PRODUCTION 1994
El Abra (porphyry copper)	1,000 0.65	Cyprus Codefco	51.0 49.0	1000	SX - EW	225	45	In study
Mantos Blancos (Santa Barbara) (stratabound?)	50 1.0	Marvis C.S.A. Anglo Amer.C. Inver. Sudam. Other	47.9 20.6 5.7 25.8	75	Flotation SX - EW	45 38	60 50	In study
Estefania (stratabound?)	17 1.8	Carolina de Michilla	100.0	50	SX - EW	20	--	PRODUCTION 1994
Leonor (exotic deposit)	24 1.6	Equatorial Mining N. L.	100.0	80	SX - EW	28	--	Feasibility study
Lince (stratabound, breccia)	16 1.56	Grupo Luksic	100.0	60	SX - EW	22.7 (50)	45	PRODUCTION 1993
Ivan-Zar (vertical breccia-stratabound)	6 2.50	Ray Rock	100.0	36	SX - EW	10	56	PRODUCTION 1994
Tuina (stratabound)	6 1.6	North Lily Int. Corp. Vancouver	50.0 50.0	7	SX - EW	7 (10)	--	PRODUCTION 1994/1995
Chimborazo (porphyry copper?)	100 1.0	Cyprus	100.0	80	SX - EW	50	--	Feasibility study
Zaldívar (porphyry copper)	240 1.67	Outokumpo Placer Dome	50.0 50.0	600	SX - EW Flotation	125 340	--	PRODUCTION 1995
Las Luces (stratabound, Breccia)	4 2.2	Citibank Las Cenizas	40.0 60.0	20	Flotation	10	--	PRODUCTION 1994
La Candelaria (skarn- porphyry copper?, stratabound)	350 1.15	Phelps Dodge Sumitomo Corp.	80.0 20.0	540	Flotation	115	56	Production 1994
Manto Verde (breccia)	85 0.86	Marvis C.S.A. Anglo Amer.C. Inver. Sudam. Other	47.9 20.6 5.7 25.8	150	SX - EW	42	50	Pre-development
Amolanas (stratabound)	7 1.6	Mincar	100.0	13	Flotation SX - EW	2 2	--	Production 1993/1994
Andacollo (porphyry copper)	224 0.64	ENAMI	100.0	53	--	--	--	pre-Feasibility
Los Pelambres (porphyry copper)	124 1.25	Anaconda	100.0	70	Flotation	20 (40) (60)	--	Production 1992. Ampliacion 1996 and 2007

## CHAPTER II.- PARENT SOURCE EXOTIC DEPOSIT. THE PORPHYRY COPPER SYSTEM.

One of the most interesting features in the vicinity of the porphyry copper deposit, in the Central Andes, is the presence of "exotic" copper deposits, derived from porphyry copper deposits in arid to semiarid environments.

### 2.1.- Introduction

Porphyry copper deposits are formed initially as closed systems which later become open with the large scale introduction of both magmatic and hydrothermal solutions along structural breaks in the rock. These breaks are formed both by regional forces and localised magmatic forces. The regional forces may be important in controlling the location and shape of igneous intrusions, and are evident in orthogonal veins and fault sets. Breccias, random crackling and radial-concentric veins are evidence for the action of magmatic forces. The shifting of intrusive centres, telescoping of igneous events and the location of fracture permeability during the evolution of hydrothermal activity are important factors controlling whether resultant mineralisation-alteration zoning is concentric or asymmetric. As a result porphyry copper mineralization (byproducts: Au, Mo, Re, Ag, Pb, Zn, P, and other metals) is disseminated over large volumes of rock. The physical chemical conditions of ore, alteration and mineral deposition change through the geologic history of the system. The degree of leaching is controlled largely by the sulphide content of the deposit and the degree of oxidation and acid production. The most significant disseminated porphyry deposits are associated with the main belt, situated around the Circumpacific and in the Alpine Mediterranean areas. Convergent plate boundaries constitute the most favourable setting for emplacement of porphyry deposits: 1).- Subduction related environments: Andean type and Island Arc type, and 2).- Continental Setting related to Inactive Subduction zones: Western North America.

Models showing alteration and mineralisation features of porphyry metal systems have been developed by numerous authors e.g. Lowell and Guilbert (1970), Sillitoe (1973), Gustafson and Hunt (1975), Hollister (1978) and McMillan (1992, in Gendall, 1994) (Figures 2, 3, 4, 5 and 6 respectively). These models allow generalised predictions to be made concerning the properties of the porphyry system.

McMillan (1991) outlined three classes for Cordilleran porphyry deposits: Classic, Volcanic and Plutonic types. Christopher and Carter (1976) three distinct types for Western North America porphyry deposits: Diorite, Granodiorite and Quartz monzonitic.

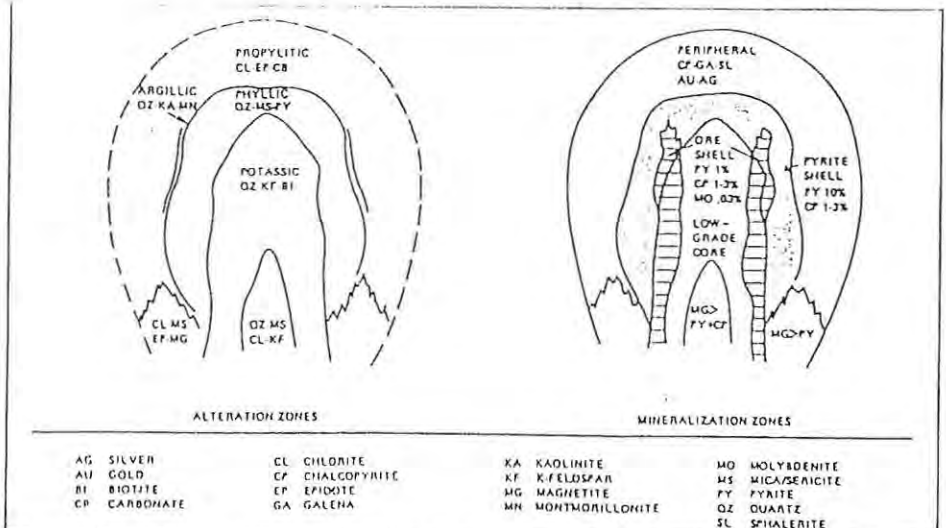


Figure 2. The Lowell and Gilbert model for porphyry deposits indicating the alteration and mineralisation zones (after Lowell and Gilbert, 1970).

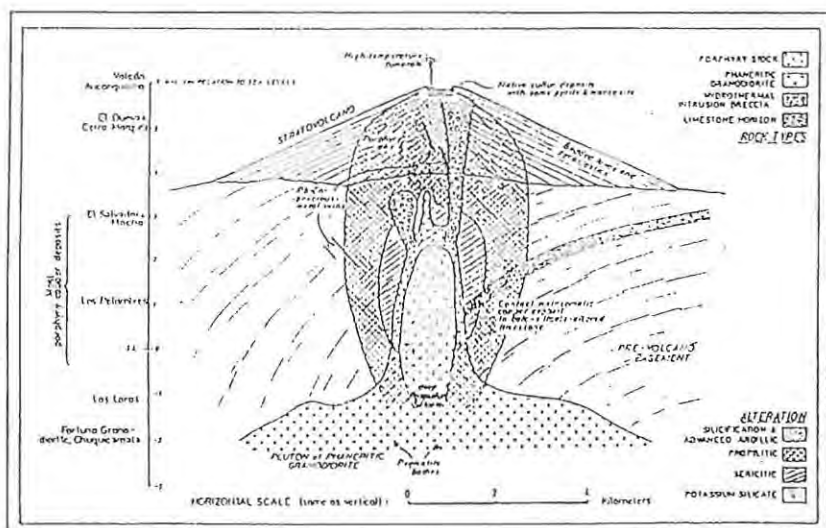


Figure 3. Generalised cross-section of a simple porphyry copper deposit showing its position between plutonic and volcanic environments (after Sillitoe, 1973).

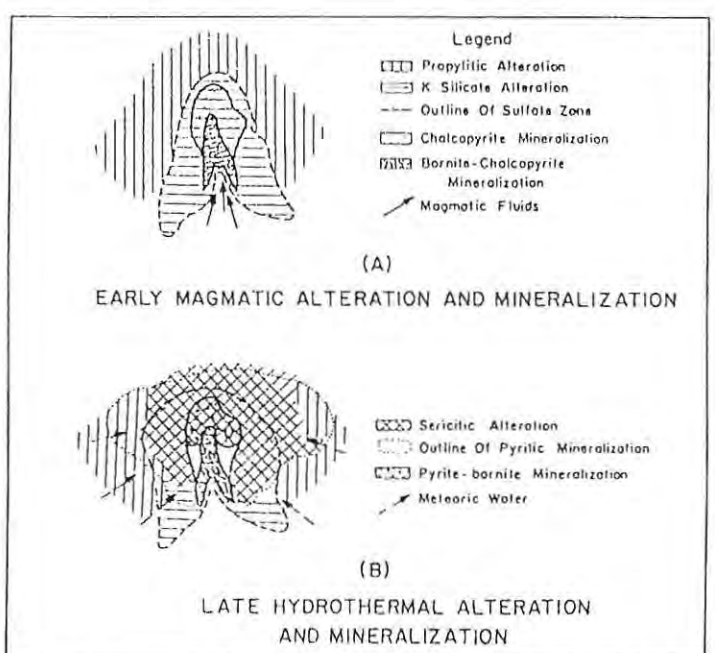


Figure 4. Model showing the stages of alteration and mineralisation about the porphyry system (modified after Gustafson and Hunt, 1975).

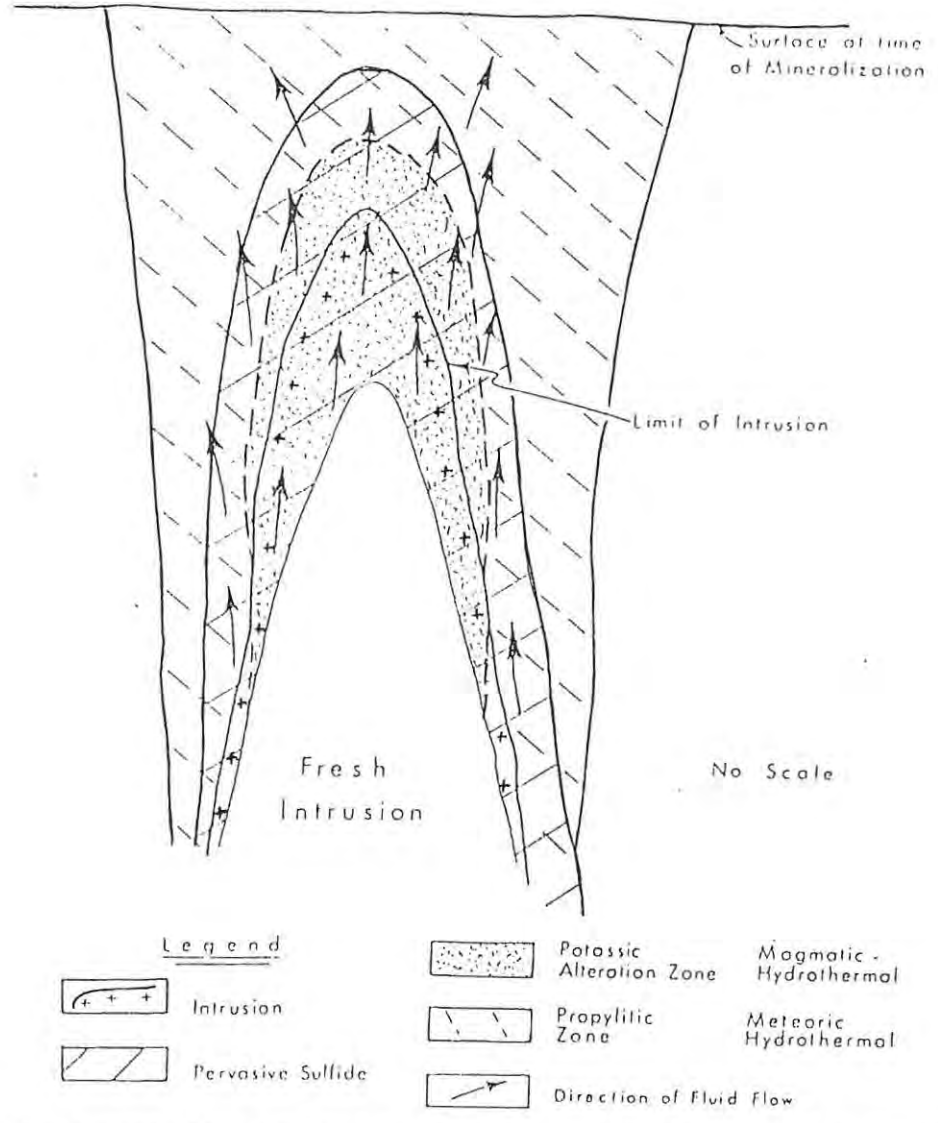


Figure 5.- Diorite model. Flow direction during simultaneous action by the magmatic hydrothermal and meteoric-hydrothermal systems is indicated by arrows. Activity by the later after cessation of magmatic-hydrothermal fluid flow may result in substantial destruction of the previously formed potassic zone (as at Copper Mountain-Ingerbelle, British Columbia). (After Hollister, 1978).

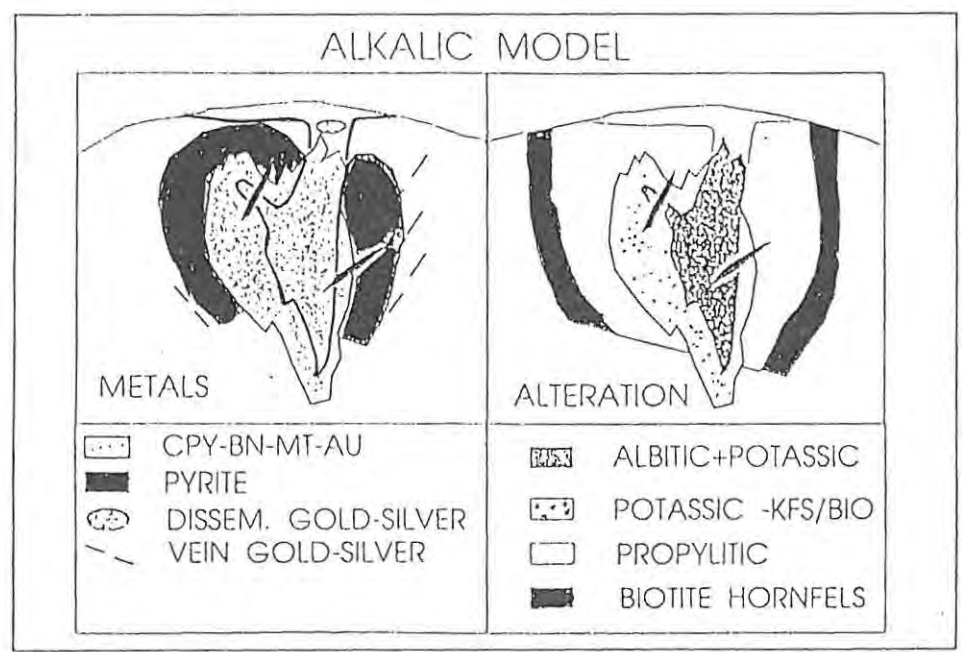


Figure 6.- Idealised alkalic model showing metal and alteration zonation (After McMillan, 1992).

Alteration and mineralization result from the complex interplay of mechanical, magmatic and hydrothermal processes in and around the porphyry body. The early potassic and propylitic alteration overprinted by phyllic and later argillic alteration are characteristic of the calc-alkaline or silica-rich porphyry copper deposits (Figures 2, 3 and 4). Alteration associated with alkalic deposits or Diorite model or quartz-deficient porphyry copper deposits (Figures 5 and 6) also have a central potassic zone and/or, an albitic plagioclase envelope surrounded by a chlorite-dominant propylitic zone and no phyllic zone is developed (Hollister, 1978; McMillan, 1992 in Gendall, 1994).

Figures 2, 3 and 4 show the typical metal zonation within the calc-alkaline porphyry system. However, Jones (1992) recognises that porphyry copper deposits may display some of the following metal zonation characteristics: Barren core-molybdenum-bornite and gold-chalcopyrite-pyrite with gold in shear zones-lead, zinc and silver-gold/silver veins-disseminated to replacement epithermal gold in distal areas.

Copper sulphide, in diorite model porphyry copper deposits, is accompanied only rarely by molybdenum but commonly by abnormally high gold/copper ratios (Hollister, 1978). Large amounts of magnetite accompany chalcopyrite. Pyrite occurs as a dissemination in the potassic and propylitic zones. Fox (1975 in Hollister, 1978) indicates the following metal zonation: a central biotite zone carrying chalcopyrite-bornite-magnetite or bornite-magnetite gives way to a peripheral zone of chlorite-epidote-albite with associated pyrite-chalcopyrite. Gold is concentrated in the bornite-magnetite zone. Zinc and lead occurrences attributed to zoning are rare in a copper-zinc-lead sequence around the copper heart of diorite deposits.

As has been mentioned above, the difference between the two models (Silica-rich and quartz deficient porphyry copper deposits) are the phyllic and argillic alterations. The phyllic alteration assemblage (sericite, quartz, pyrite) in silica-rich porphyry copper deposits in general are associated with the fractured, brecciated and well-mineralized intrusive porphyries which presumably drove fluid convection, and are superimposed upon a pre-existing potassic alteration assemblage. Argillic alteration is only pervasively silica-rich porphyry copper deposits; intense silicification accompanying the advanced argillic alteration that is responsible for the preservation of topographically high areas.

## 2.2.- Belt of Porphyry copper deposits of northern Chile.

Major, "classic" porphyry copper deposits of northern Chile were formed within a distinct period that lasted about 10 Ma during the Late Eocene - Early Oligocene (Fig. 1 and 7). These intrusion-related copper deposits are an anomaly in the long-lasting magmatic history of the Andes of northern Chile (Latitude 21°-26° S). There is a conspicuous spatial relationship between these porphyry copper deposits and the domain of the trench-linked Domeyko Fault System. This regional strike-slip fault system and associated structures provided loci for emplacement of shallow copper-bearing porphyritic intrusions, and for focusing hydrothermal and supergene processes leading to the formation of one of the largest concentrations of copper in the world.

Maksaev and Zentilli (1994) indicate that the restricted variation of Sr, Nd and Pb isotopes (data from Tilton et al., 1981; Longstaffe et al., 1983) in the porphyry copper system of northern Chile, and other copper-bearing porphyries of different ages and various locations along the Andes indicates either a homogeneous sub-crustal magma-source, or an effective homogenizing mechanism, compatible with a MASH process (Magma: Melting, Assimilation, Storage and Homogenization), during porphyry copper magma genesis.

The overall petrochemical characteristics of the copper-bearing stocks are similar to other Andean arc-related calc-alkaline igneous rocks, but some reduced ranges of granodioritic to quartz-dioritic composition and significant depletion of heavy REE relative to that of pre-porphyry igneous rocks are apparent (Maksaev and Zentilli, 1994). Maksaev and Zentilli (1994) indicate that this information suggests a change within the magma-source region involving the emergence of garnet control and/or reduction in the degree of partial melting, which implies an increase of pressure or decrease of temperature of the source region, compatible with a thicker crust during the generation of porphyry copper magmas.

Thus, the origin of porphyry copper mineralization is thought to be related to a period of "anomalous" deep magma generation during the Late Eocene-Early Oligocene (Fig. 1) following crustal thickening produced in the Mid-Late Eocene Incaic compression (Maksaev and Zentilli, 1994). Thermochronological data support the hypothesis of a genetic relationship between anomalous copper concentration and crustal thickening in the Andes of northern Chile.

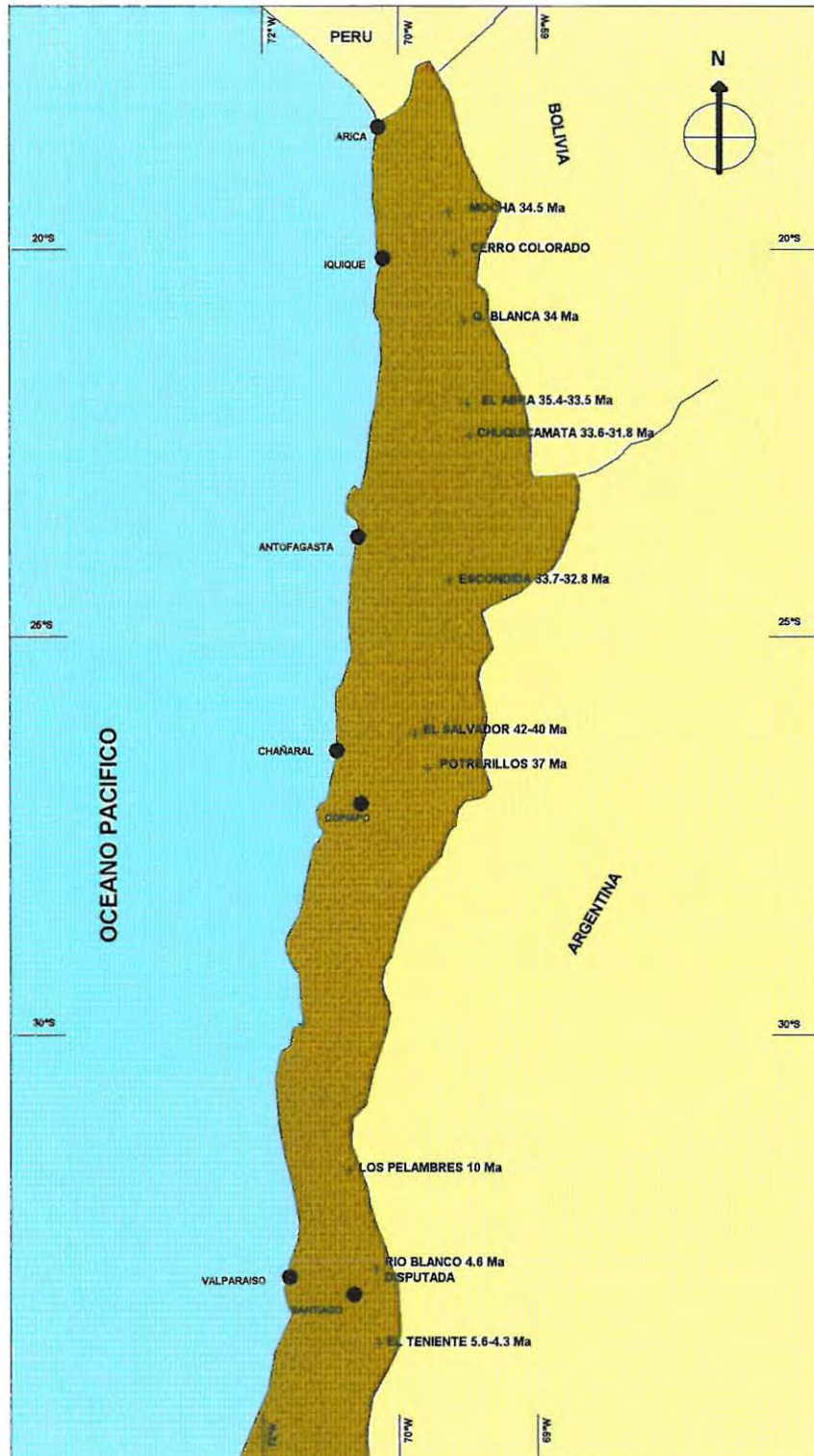


FIG. 7.- Location and K-Ar ages of major porphyry copper deposits in Chile. Ages from Quirt et al (1971; Mocha, Los Pelambres, Rio Blanco and El Teniente), Gustafson and Hunt (1975, El Salvador) Olso (1984 in Olso, 1989; Potrerillos), Internal report CODELCO CHILE, Division Chuquicamata (in Olso, 1989; Chuquicamata), Ambrus (1977; El Abra), Alpers and Brimhall (1988; Escondida), and Hunt et al (1983; Quebrada Blanca).

Maksaev and Zentilli (1994) indicate that the apatite fission-track data from basement rocks of the Domeyko Cordillera are compatible with rapid cooling during Mid-Late Eocene times (45-50 Ma), which may be related to erosion and uplift of the crustal block that hosts the porphyry copper deposits during the Incaic event. The fission track data are also consistent with a shallow emplacement of these copper-bearing porphyries.

### **2.3.- Leaching columns of the porphyry copper deposits**

Erosion activated by tectonic uplift, contributed to the rapid exhumation of the deposits and concomitant development of supergene enriched blankets. The paucity of the denudation since the Miocene in the Andean segment from Latitude 21° to 26° S due to the dominance of a hyper-arid climate explains the remarkable preservation of the shallow porphyry copper systems and supergene-enriched blankets (Maksaev and Zentilli, 1994; Munchmeyer, 1994; Arias, 1985; Mortimer, et al., 1977; Mortimer, 1973). The dominant presence of kaolinite marks the supergene alteration, which formed extensively throughout the zone of the copper leaching and in the underlying zones of strong to incipient copper enrichment.

The oxidation and supergene enrichment process has to be understood as a continuous process in time which is directly controlled by; climatic conditions, erosion levels, wall rock characteristics, etc.

The process itself occurs at and beneath the water table which constitutes a redox front under which secondary sulphides are precipitated and above which oxides of copper and iron.

The resulting horizons are oxidized in the proportion that the erosion progresses, the water table levels fluctuate and the liberated copper gets again into solution, percolates and precipitates under the new water level, increasing the enriched horizon. This percolation and vertical precipitation phenomenon *can also have a horizontal component producing simultaneously vertical and lateral migration of the solutions.*

#### **2.3.1 Some mineralogical consideration in the Supergene process**

The hypogenous sulphide ore minerals hypogenous experience supergene reactions due to their instability at the surface, in air-saturated porous rocks in the zone of capillary water above the water table and in

groundwater of exogenous environment.

Thermodynamic data indicate the formation of more stable phases in supergene conditions, for example covellite is transformed into chalcocite (Fig. 8) (Arias and Guerra, 1991). This reaction is strongly favoured and it tends to occur spontaneously. Therefore chalcocite is more frequent, abundant and stable in supergene conditions.

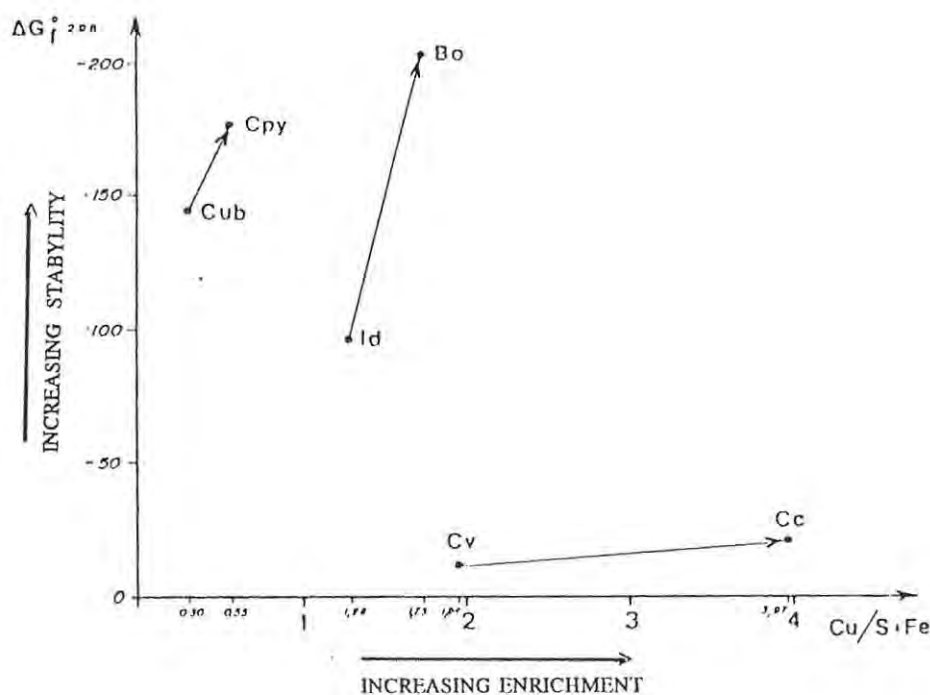


Fig 8. Thermodynamic tendency of copper sulphide to stability (Arias and Guerra, 1991)

The overall, large-scale reaction sequence of chalcopyrite  $\rightarrow$  covellite  $\rightarrow$  digenite (-anillite)  $\rightarrow$  djurleite  $\rightarrow$  chalcocite with increasing elevation (Fig. 9) can be explained most simply by an increasing oxidation potential (hE) within the stability field of  $(\text{SO}_4^{2-})_{aq}$  (Alpers and Brimhall, 1989). Analysis of natural waters in oxidizing sulfide systems has shown that these waters are sulfate dominated (Sato, 1960), that is compatible with  $(\text{SO}_4^{2-})_{aq}$  environment for the large-scale reaction between chalcopyrite and chalcocite.

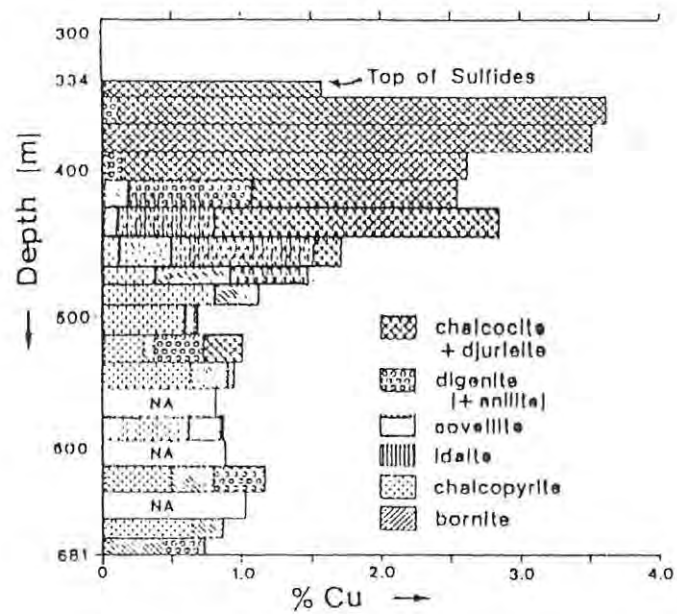


Fig. 9 Vertical profile of copper (-iron) sulphide mineralogy in La Escondida porphyry copper deposit, Chile. (after Alpers and Brimhall, 1989).

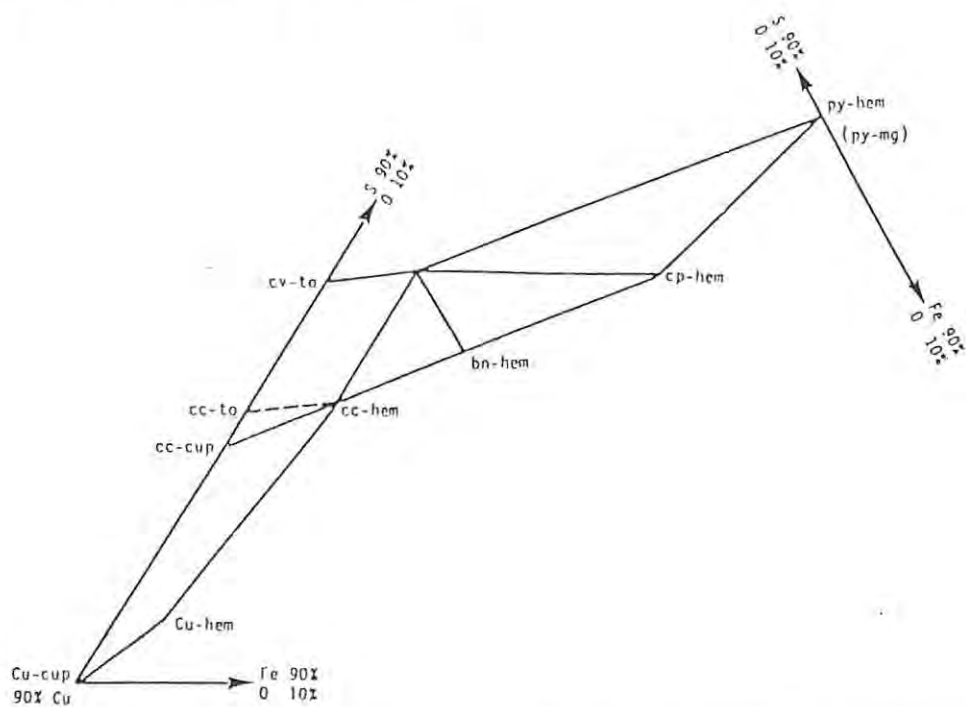


Fig. 10 Mineral assemblages in the system Cu-Fe-S-O in the supergene conditions sectioned through the tetrahedral model at composition 10% O (After McKinstry, 1959)

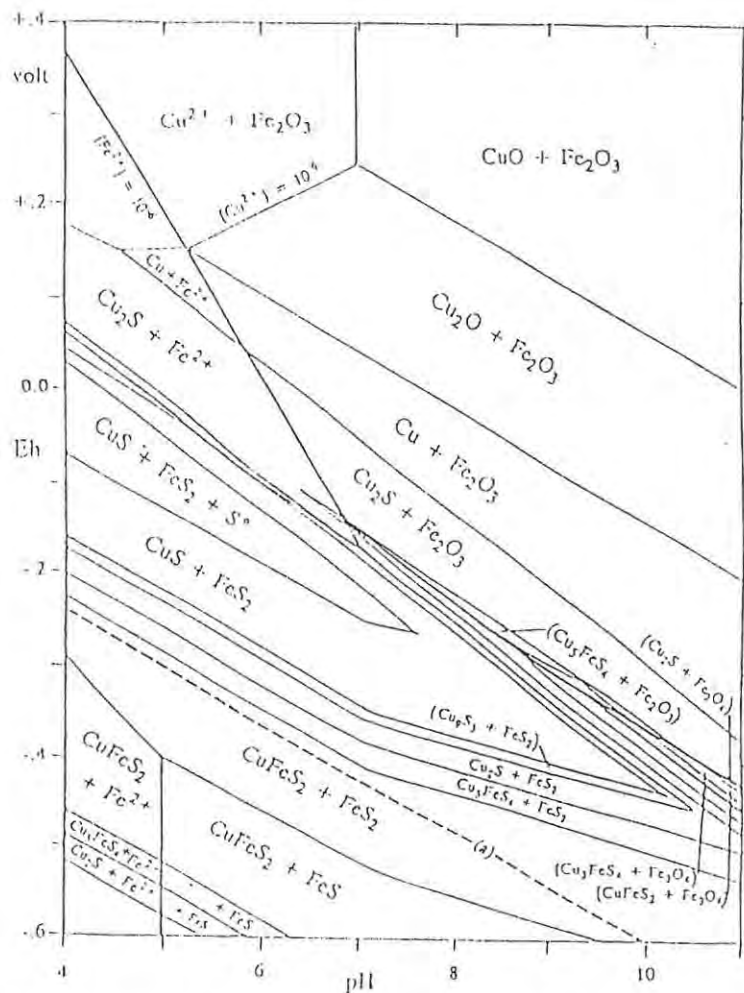


Fig. 11 Composite stability Eh-pH diagram for the system Cu-Fe-S-O-H at 25°C and 1 atm for total dissolved S of 0.1 activity within and nears stability field of hematite (after Natarajan and Garrels, reproduced in Garrels, 1960) (from Sato, 1992).

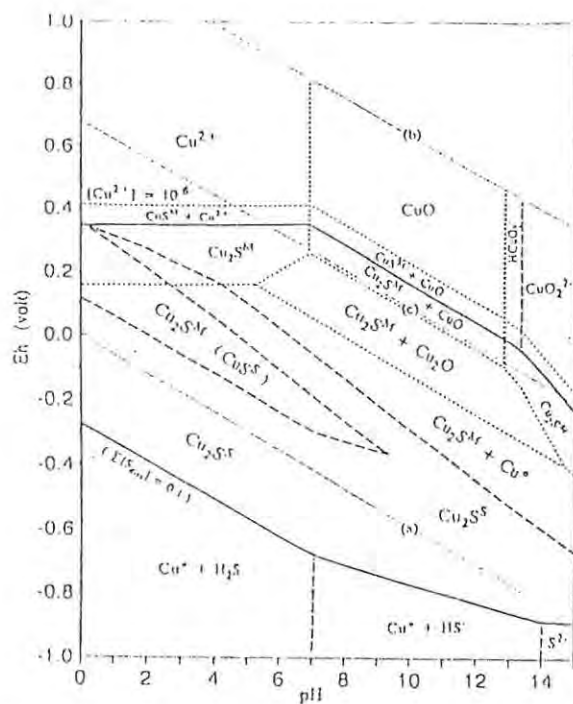


Fig. 12 Persistence - field Eh pH diagram for chalcocite. The possible oxidation of chalcocite to djurleite is ignored. The wedge of CuS stability field in acid solution makes this region metastable for Cu<sub>2</sub>S. The log (Cu) in the coexisting Cu-bearing solids is greater than -6.62. (from Sato, 1992)

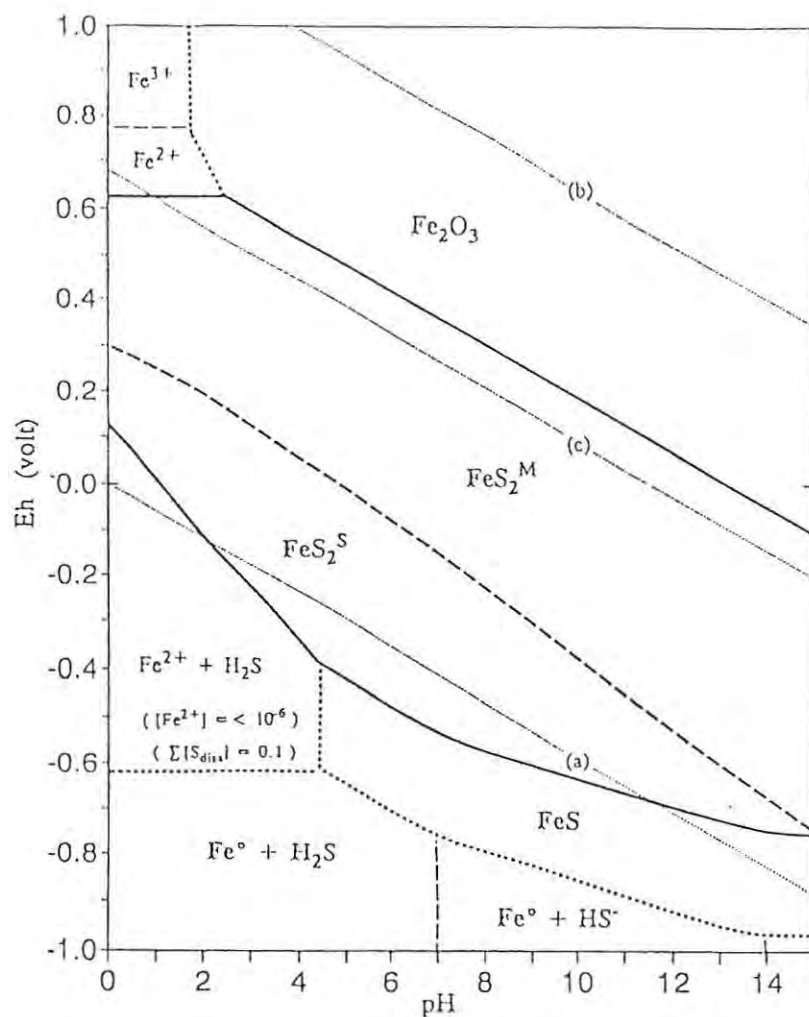


Fig. 13 Persistency- field Eh-pH diagram for pyrite  $FeS_2$ . (Sato, 1992).

Key for figures 11, 12 and 13:

"S" = Superscript on the chemical formula of the solid phase. The persistency field is subdivided into the stability field.

"M" = Superscript on the chemical formula. Path-dependent metastability field.

(a) = Eh-pH reduction boundaries of the stability field of  $H_2O$  at 1 atm.

(b) = For the oxidation boundary

(c) = The minimum condition for oxygenated environment

Reactions that occur in or near of the water table are responsible of the supergene enrichment of primary sulphides and they are controlled by pH and Eh in low temperature and pressure conditions ( $P < 1$  atm;  $T < 100^{\circ}\text{C}$ ) (Arias and Guerra, 1991). Habashi (1966) and Sivenas and Beales (1982b) show that the sulphur reactions that occur in groundwater are analogous to the anodic corrosion; moreover it is necessary that electrochemical deposition occurs; both reactions are possible due to the semiconducting nature intrinsic to the sulphide and to pH and Eh conditions typical of the supergene environment.

The supergene mineral assemblages are metastable. In the Cu-Fe-S-O-H system, the overwhelming inconsistency between the Mckinstry (1959) diagram (Fig.10) and the Eh-pH stability diagram arises from the fact that the latter excludes the association of  $\text{Cu}_2\text{S}$  with  $\text{Cu}_2\text{O}$  or  $\text{CuO}$  and that of  $\text{CuS}$  with  $\text{Fe}_2\text{O}_3$ ,  $\text{CuO}$ ,  $\text{Cu}_5\text{FeS}_4$ , or  $\text{CuFeS}_2$ , as shown in Fig. 11 (Natarajan and Garrels, 1960 in Sato, 1992).

The persistency field of  $\text{Cu}_2\text{S}$  overlaps with the stability fields of  $\text{CuO}$  and  $\text{Cu}_2\text{O}$  within the boundaries of the hematite field (Fig. 10 and 11), indicating that  $\text{Cu}_2\text{S}$  can maintain metastable equilibrium with the oxides in natural Eh-pH conditions of oxidizing ore bodies. The metastable association of  $\text{CuS}$ - $\text{CuO}$  in the supergene condition is likewise permitted (Fig. 12).

Certain associations are excluded in both the McKinstry (1959) diagram and the Eh-pH stability diagram, although they may appear to be permissible in the persistency field diagrams. One such case is the nonassociation of  $\text{CuS}$  with  $\text{Cu}^{\circ}$  or  $\text{Cu}_2\text{O}$  (Sato, 1992). This is caused by the incompatibility of Cu activity between  $\text{CuS}$  and  $\text{Cu}_2\text{O}$ . The range of  $\log [\text{Cu}]$  is from -6.62 to -8.60 in  $\text{CuS}$ , whereas it is from 0 to -2.89 in  $\text{Cu}_2\text{O}$  (Sato, 1992). *Therefore, only  $\text{Cu}_2\text{S}$  can coexist with  $\text{Cu}_2\text{O}$  and  $\text{Cu}^{\circ}$*  (Sato, 1992). Another case involves the nonassociation of  $\text{FeS}_2$  with,  $\text{Cu}^{\circ}$ ,  $\text{Cu}_2\text{O}$  or  $\text{CuO}$ , which again appears permissible in the persistency-field diagram of pyrite (Fig. 13). The problem arises from the fact that there are stable Cu-Fe sulfides (Sato, 1992). How to deal with these cases in two dimensional graphic forms is not completely resolved at present.

All oxidizing systems have species of sulphur, silica, carbon dioxide, and oxygen present so these compounds can always occur. If foreign anions ( $\text{CO}_3^{2-}$ , and others) are available, copper minerals in which they occur will usually appear as both sulphates and carbonates in an ideal scheme.

The sulphates are the largest group and usually occur in extremely arid climates, resulting in a fluctuating water table, which causes transformation of earlier enriched chalcocite in the form of

sulphates. The best known are: antlerite (formed directly on sulphides), brochantite, chalcantite and kroehnkite.

Copper may be present in the oxide zone with no apparent Cu-minerals present. It has been noted in earthy transported haematite (up to 5% Cu) with no visible minerals other than haematite. It may also be enriched in the secondary biotite zone where biotite is altering to montmorillonite: here copper enters the montmorillonite yielding a so-called medmontite.

## MOLYBDENUM

In an acid environment, one with pyritic ores, ferrimolybdate may form. As the system becomes more alkaline, ferrimolybdate disappears and any Mo retained is that coprecipitated with iron compounds. Substantial amounts of Mo have been found in earthy haematite or in akagenite (up to 3% Mo) but not in goethite or hisingerite. Molybdenum species are readily soluble and migrate in alkaline waters but may be fixed by  $Pb^{+2}$  or, much less efficiently, by  $Ca^{+2}$  (Swayne, 1969; Fuster, 1983).

Lindgrenite,  $Cu_3(MoO_4)_2(OH)_2$  is found in assemblages such as cuprite-brochantite and is also abundant with chenevixite at Chuquicamata.

## IRON

The pH-Eh diagrams for Fe-H<sub>2</sub>O system and Fe-CO<sub>2</sub>-H<sub>2</sub>O system were originally presented by Pourbaix (1945 in Sato, 1992). R. M. Garrels and other geochemists constructed a number of pH-Eh diagrams for the Fe-S-CO<sub>2</sub>-H<sub>2</sub>O system (e.g., Krumbein and Garrels, 1952; James, 1954; Krauskopf, 1957; Huber, 1958; all references in Sato, 1992).

In spite of much effort spent by scientists of various disciplines, however, the redox behavior of iron sulfides at low temperatures still remains somewhat uncertain. Between the compositions of Fe<sub>9</sub>S<sub>8</sub> and FeS<sub>2</sub>, at least twelve crystallographically discrete Fe-S phases have been identified (Power and Fine, 1976). According to Berner (1967), only stoichiometric pyrrhotite FeS and pyrite FeS<sub>2</sub> are thermodynamically stable. The extent of the persistency field for pyrite on the reduction side show in

the diagram 13 must thus be regarded as the minimum. The oxidation mechanism of pyrite is equally uncertain. The presence of pyrite in porphyry copper system cause high acidity in the oxidising solutions which are promoted in tropical and semi-arid climates, e.g.:



In pyrite ores, jarosite invariably forms early, altering in alkaline waters to oxides. The ideal scheme is jarosite - haematite - hisingerite but any of these steps may be missing, depending on wall rock type and other factors. Jarosite is often thalli and also may take up  $\text{AsO}_4^{3-}$  if minor amounts are present. The optics of jarosite is very sensitive to these impurities.

A high goethite content indicates weak acid leaching, no secondary enrichment of copper, and antlerite, brochantite and cuprite may be evident in the capping (Anderson, 1982). A high hematite and/or jarosite content indicates a strong acid leaching, possible secondary enrichment of copper at depth, and minerals such as pitch limonite, noticed and more rarely turquoise may be evident in the capping (Anderson, 1982).

According to Schwertmann (1985), the important factors influencing hematite vs goethite formation and transformation in soils include temperature, water activity (expressed as either humidity or degree of saturation), pH, organic matter, and release rate of Fe during weathering. In addition, the abundance of aqueous ferrous iron and sulfate may be important factors in determining the mineralogy of ferric iron precipitates (Brady et al., 1986). Ferrihydrite has been shown to be the necessary precursor to supergene hematite, to which it transforms by solid state dehydration (Schwertmann, 1985; Chukhrov et al., 1973 in Alpers and Brimhall, 1989). When this transformation takes place in water, there is a competing tendency for ferrihydrite to dissolve back into solution and for the ferric iron to reprecipitate as fine-grained goethite. Under weathering conditions, goethite and hematite are not related genetically by the simple hydration-dehydration reaction in:  $\text{Fe}_2\text{O}_3 + \text{H}_2\text{O} \rightleftharpoons 2\text{FeO}(\text{OH})$ ; rather, the two phases form by separate pathways (Schwertmann, 1985).

Akagenite is favoured with abundant Mo-FeS<sub>2</sub> and may be co-precipitate with Mo. Lepidocrocite is rare.

**The typical features of limonite.** The limonite textures that form in leached capping have been used as a tool in the preliminary evaluation of the porphyry copper deposits, for at least 60 years (Ortiz et al., 1985). The typical features of these supergene products that are examined and compared with the geochemical characteristics of the associated rocks are (Ortiz et al., 1985; Anderson, 1982):

- i) the total volume of original disseminated sulphides, which is reflected in the amount of relict cavities derived from veins;
- ii) pyrite/copper ore ratios according to the identification of the specific sulphide precursor of the limonite boxworks;
- iii) Cu/Fe proportion indicated by the content of haematite in the limonite;
- iv) the presence of chalcocite in association with pre-existing sulphide indicated by textures of the "indigenous limonite" type and by the typical colours (strong red) of the limonite derived from chalcocite;
- v) original content of chalcocite, as can be estimated by the volume of cavities filled by hematitic limonite;

At Escondida and in other leached capping in the north of Chile, the leaching makes it necessary to correct the criteria used to interpret this capping correctly (Fig. 14). The most well-known modifications are (Ortiz et al., 1985):

- i) the typical rectangular shape of the residual cavities of sulphides has experienced significant changes by the migration of the silica, so the resulting texture is more similar to a slag (with cavities of a spherical tendency);
- ii) the typical boxworks of pyrite, chalcopyrite and chalcocite have been destroyed;
- iii) limonite has been partially or totally destroyed by the super-leaching of the relict cavities, eliminating features required for a proper estimation of the Cu/Fe ratio and impeding an adequate evaluation of the pre-existing amount of chalcocite.

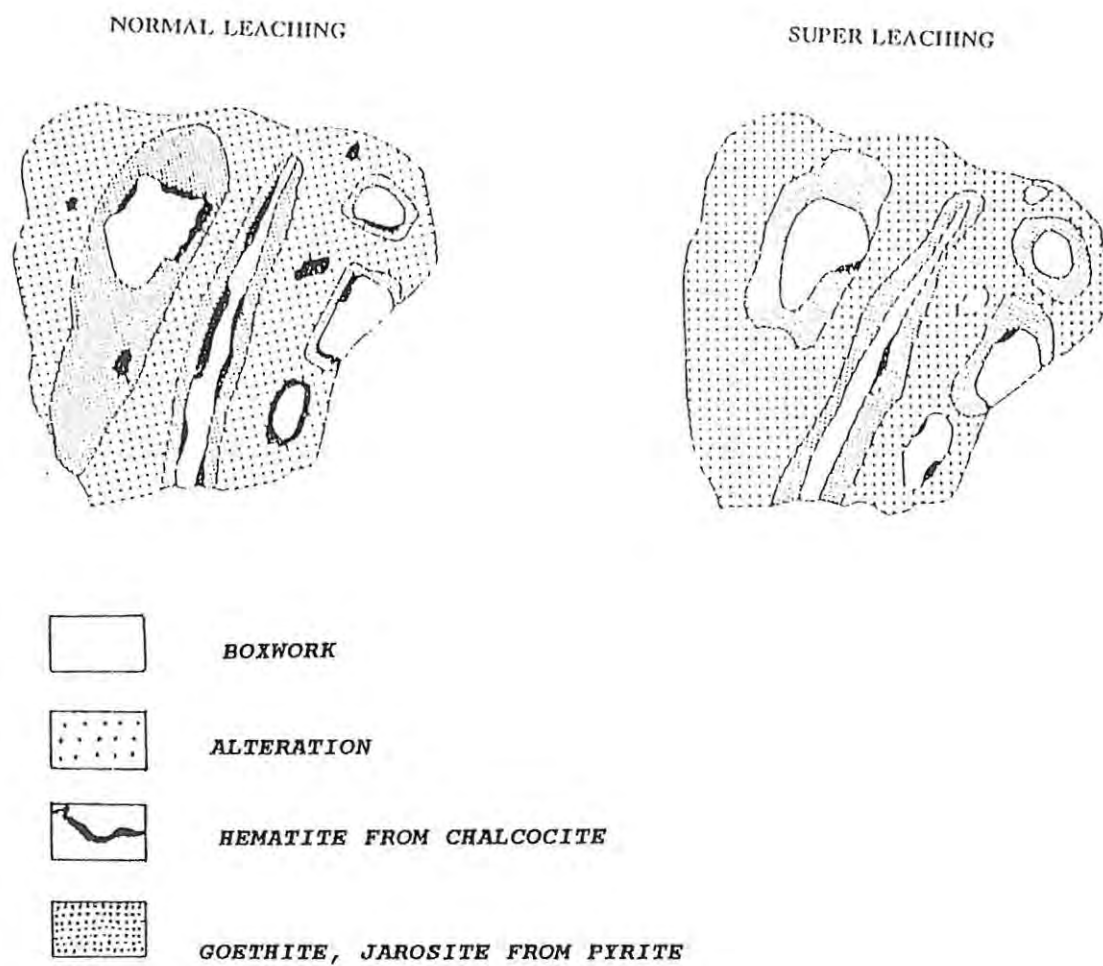


Fig. 14.- Super leaching in Northern part-Chile. Supergene alteration of Pyrite and Chalcocite. (Ortiz et al, 1985).

The final result of the super-leaching was that the interpretation of the leached capping became difficult, though it is possible to solve this problem by digging pits or trenches of 1-2 m depth.

Super-leaching has led to misinterpretations by specialists who have not worked in extremely arid conditions, as it was the case in La Escondida.

#### **Influence on supergene oxide and sulphide ore minerals due to Phyllic and Potassic alterations.**

The phyllic alteration has greater quantity of pyrite of a cal-alkaline porphyry copper system and that favoured the formation of sulphuric acid by supergene activity (meteoric water, silica, oxygen, etc), attacking the hypogenous sulphides and gangue ore minerals. This solution migrate vertically and laterally. The phyllic alteration is unreactive to acid copper sulphated solutions. However, the copper precipitates in reducing conditions close to the water table obtaining a column mainly with secondary copper sulphides (chalcocite over covellite diminishing the copper content in depth), underlaying to a thin of copper oxide body (tenorite, cuprite, brochantite, and others) separated by a thin native copper layer. Above the top of the copper oxide minerals there is a thick lixiviated rocks layer.

The dimensions of this secondary enrichment of copper are directly proportional to the size of phyllic alteration. Chuquicamata and Radomiro Tomic are examples of this alteration or supergene blanket of sulphides. Chuquicamata presents an area of 2 x 0.5 km at midpoint, at a depth of 900 m, while Radomiro Tomic (Ex Chuqui Norte) the phyllic alteration or supergene blanket of sulphides is restricted to zones of less than 10 m of thickness controlled by; faults, fractured zones and in contact among porphyries.

If lixiviation of hypogenous minerals occurs in potassic alteration, the copper in solution precipitates when being neutralized by potash feldspar and ions of  $K^+$  in mainly in oxidizing conditions forming bodies of oxidized copper ore minerals (see Fig. 15 and 16).

The dimensions of the layers of oxidized ore minerals are proportional to the size of the area of potassic alteration. The type of mineral that is formed is according to climatic and geomorphological conditions, type and depth of the water table, etc. Under copper oxidized minerals is possible to find a thin layer of sulphide minerals of secondary copper, with mineralization of chalcocite and covellite replacing preferently bornite and digenite, less often chalcopirite and rarely pyrite (Garay, 1983)

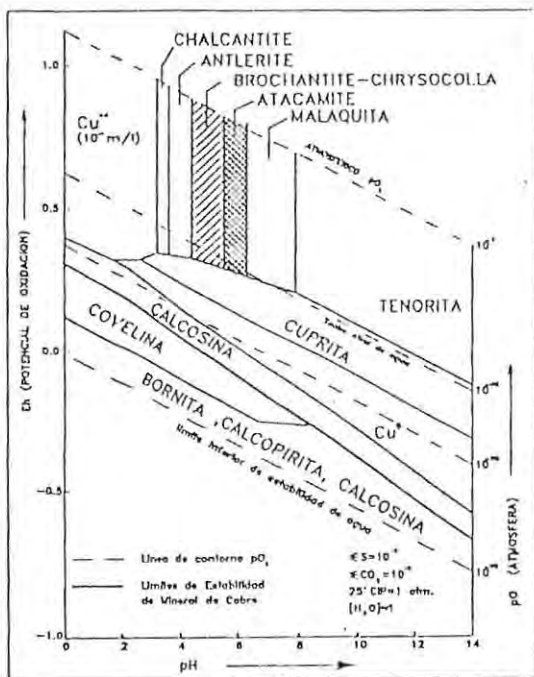


Fig. 15.- Eh-pH diagram according to Anderson (1982) showing the fields of stability of copper minerals in the Cu-S-H<sub>2</sub>O system. It includes the stability fields of atacamite and chrysocolla which are most abundant copper minerals in the exotic environment. Chrysocolla forms instead of the brochantite in the presence of abundant dissolved silica.

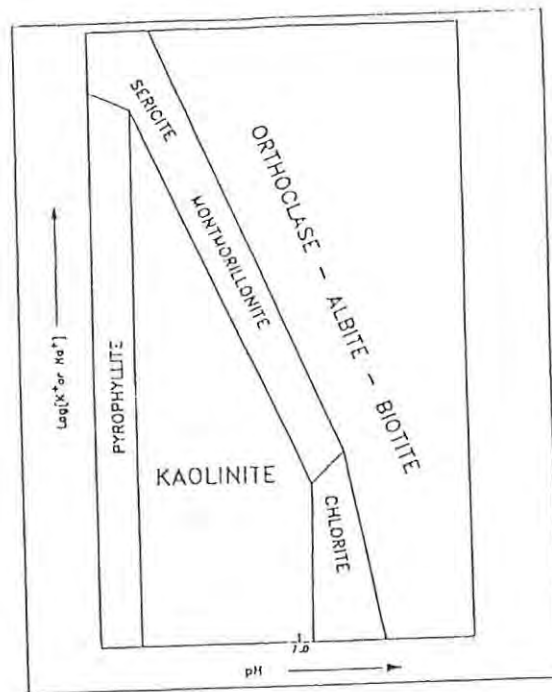


Fig. 16.- Stability fields suggested by silicate minerals as a function of the pH and activity of the dickite, according to Anderson (1982). It is used to show the environments of formation of kaolinite and montmorillonite, which are characteristic alteration minerals in the exotic deposits.

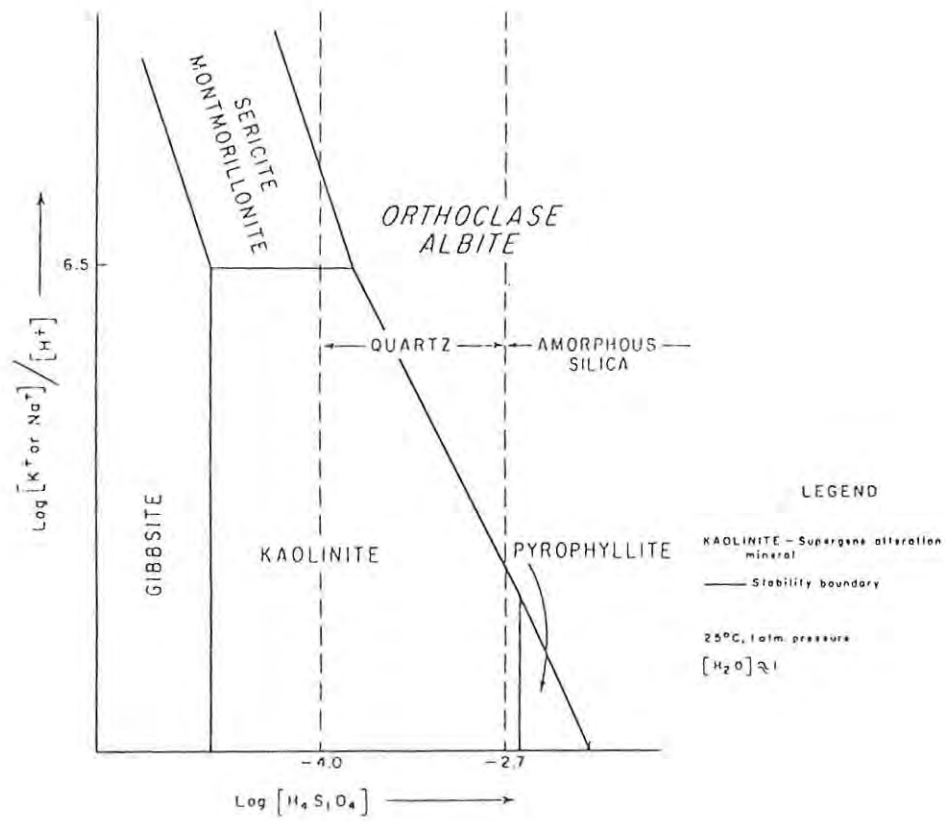


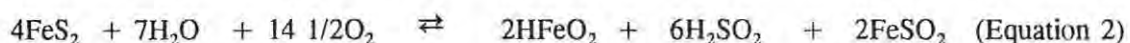
Fig. 17.- Suggested supergene stability fields of silicate and silica minerals shown as a function of alkali-hydrogen ion and silica activities. (Anderson, 1982).

Hypogenous mineralization of the central area of Radomiro Tomic, is similar to the potassic zone of Chuquicamata, as well as the volumen and spatial localization of copper oxide (on rocks with potassic alteration). The difference is found in the type and quantity of mineralogical species that were formed. In Radomiro Tomic there exists almost exclusively atacamite, less quantity of chrysocolla and oxidie copper impregnating argillic minerals, while in Chuquicamata a quantity of sulphides, chloride and copper phosphated were formed. This is explained by the morphological difference of the receiver basin of meteoric waters. In Radomiro Tomic there existed a basin of 4 km wide, with a constant discharge of chloridized waters northward. Nevertheless, in Chuquicamata the basin was restrictedly closed with a small drainage to the south and a great hillside that permitted the lixiviated waters to be a more direct support and thus it was easier for the sulphur ions to be generated from the deposit's primary sulphides (Garay, 1983).

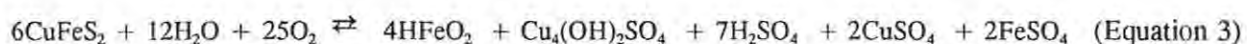
The existence of a mixt zone of minerals and of a zone of chalcocite-covellite is explained by the variation in the time of the position of the underground water level according to the regime of superficial water and for the second case. Moreover for differences in the copper content in the infiltrated solutions as its quantity. This same variations cause a lateral movement of the water in case of the water table raising and a consequent deposition of oxidized of copper in palaeochannels in the form of "exotic mineral".

**Influence on Supergene Silicate.** What was mentioned above is according to the figures 15 and 16 (Anderson, 1982). They indicate that in high pH there exists ortoclase in an oxidizing environment that permit to neutralize the copper in solutions in form of oxide of copper minerals very close to potassic alteration.

The pH of the solution exercises an important control over mineral stability, and the concentration of elements essential in silicate minerals exerts similar controls over mineral stability. The following equations (2 and 3) show the generation of sulphuric acid and copper and iron sulphates (Anderson, 1982):



Pyrite

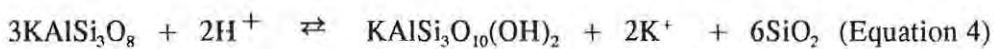


Chalcopyrite

The Eh-pH diagram of the figure 15, shows the stability relationship in the Cu - H<sub>2</sub>O - O<sub>2</sub> - S<sub>2</sub> - CO<sub>2</sub> system at 25° C 1 atm of pressure. It is observed that in oxidizing environment, the acid solutions keep the copper ions in solution. If the pH is risen the metallic ions diminish its solubility and are deposited in the form of oxides. If the solution is not neutralized the metallic ions continue in solution without depositing themselves in the oxidation zone, up to find a reducing or alkaline method, which makes to precipitate ions of copper as sulphide or oxides respectively. The first case is directly connected with the phyllic alterations and where the enrichment secondary zone reaches its maximum thickness.

If the copper precipitates in an alkaline environment, for example potassic alteration, the oxide ore minerals zone reaches its maximum thickness and the enrichment sulphides secondary zone reaches its minimum thickness (Garay, 1983; Flores, 1983).

Supergene silicate alteration is independent of the oxidation potential of the system because free oxygen is not required in silicate alteration reaction; Besides K<sup>+</sup> ions are liberated, and are added to the acid solutions which neutralize them, raising the pH and diminishing the copper solubility in an oxidizing environment (Flores, 1983). Thus the presence of sericite and clay minerals can be explained coexisting with copper oxide in the oxidation zone. The generated sulphuric acid reacts with the host rock and produces a supergene alteration, specially orthoclase according to the following possible reactions (Ambrus, 1979).



Potash feldspar

Sericite

As shown in figure 17 the concentration of silica in the solution also appears to control the presence or the absence of sericite and quartz in alteration assemblages.



Alunite

Kaolinite

This condition implies that supergene alteration is not confined to the oxide and supergene chalcocite enrichment zones of an oxidizing sulphide deposit. Supergene silicate alteration commonly extends for considerable depths into the primary sulphide zones. The mineralogy of supergene silicate alteration gradually changes with increasing depth in the hypogene sulphide zone. This change is attributed to reactive mineral acid consumption, which produces a downward increase in the pH of acid solutions originating in the oxide zone. Chlorite and biotite (magmatic or hypogene) serve as a measure of the extent of supergene acid attack because they are only stable under neutral or alkaline conditions at low temperatures and pressure (see Fig. 16). The upper limit of chlorite, biotite and possibly gypsum in the hypogene sulphide zone may, therefore, mark the depth limit of supergene acid alteration. Supergene gypsum precipitates from calcium-bearing sulfate solutions under neutral to alkaline conditions and may, therefore, occur with chlorite or biotite. X-ray studies of leached capping samples have shown that kaolinite is present in most leached capping located over chalcocite enrichment ore (Anderson, 1982). This observation of "unreactive clay" can be readily explained by considering the kaolinite to be the product of supergene acid attack on reactive gangue, including calcite, plagioclase, and mafic minerals.

The combined influence of pH and composition controls makes correlations between supergene silicate alteration and the nature and amount of original sulfides much less diagnostic than those for supergene copper and iron minerals. The sensitivity of the correlation is further complicated by the presence of hypogene sericite and clay minerals in some deposits

## ALUMINIUM

If aluminium is available during oxidation (neglecting silicates) supergene alunite may crystallize after haematite-before hisingerite. Other aluminous sulphates occur as alteration products of Cu-Al sulphates, forming gibbsite and numerous species of the basaluminite group.

### 2.4. - DIORITE MODEL

The diorite model is a variant of the porphyry copper model proposed by Hollister (1978) based on the observations carried out in British Columbia, Canada, where the presence of dioritic intrusives emplaced in a volcano-sedimentary area is common. This variant does not include the development of

a significant phyllic zone, with the propylitic zone occurring in direct contact with the potassic zone. The mineralization is distributed around this contact zone (Fig 5).

This type of system has been detected in Chile in the coastal zone, where porphyry rocks of dacitic and dioritic type intrude Palaeozoic quartzites and phyllites as well as dacitic and andesitic breccias of probable Jurassic age (Pacci, 1991). In this lithological context the propylitic phase is in direct contact with the potassic nucleus, expressed as secondary biotite. The copper-bearing mineralization occurs in both types of alteration.

The lithological characteristics of the intrusive rocks explain the type of alteration generated in the dioritic model. However, they do not explain the low sulphide concentration in the mineralizing fluids. This manifests itself, for example, in a low pyrite content and in the presence of pyrrhotite.

Burnham and Ohmoto (1980) have shown that sulphur liberation from the magma requires a moderately oxidizing environment in order to develop a hydrothermal sulphur phase. Otherwise the sulphur stays in the magma and there is no relevant sulphur development. Reduced magmas are characterized by their association with the poor sulphur mineralization, that includes pyrrhotite.

In Chile, on the contrary, at least during the Mesozoic magmatic episode, oxidizing conditions predominated (Ishihara and Ulriksen, 1980). However, the reduced character of the porphyry copper system of the Chilean dioritic model, has a reasonable explanation in the nature of the host rocks (El Toco Formation), which include carbonaceous levels (plant fossils). The interaction of these rocks with the intrusive magmas, gives a plausible mechanism to explain the reduced character of the system. As a result of the latter, most of the Fe remains in chlorite and biotite, instead of occurring in a sulphide phase such as pyrite.

#### **2.4.1.- Interpretation of the supergene processes.**

The borehole DDH-G-01, located in Galenosa project-Chile (Fig 18, Pacci, 1991), shows an excellent correlation of Cu and Mo distribution. This is not compatible with a supergene enrichment process, considering the different chemical behaviour of both elements in respect to the exogenous processes.

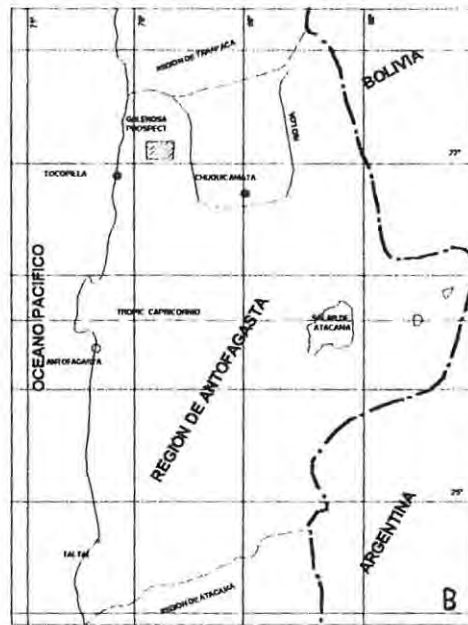
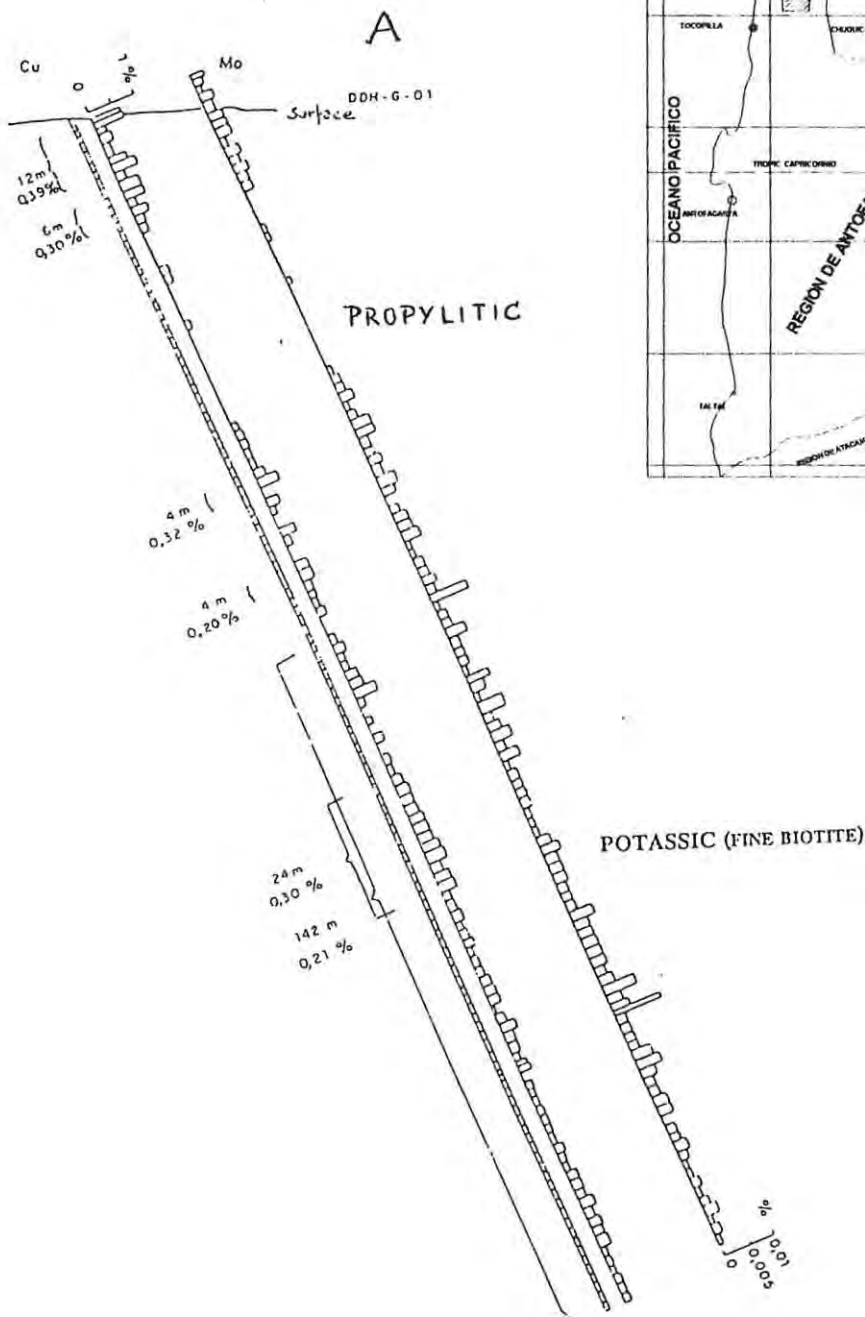


Fig 18.- A) Parallels between Cu and Mo in the borehole DDH-G-01, locate in B. A Diorite model Gelonosa Prospect- Chile. (from Pacci, 1991)

Effectively, even though Mo is soluble in oxidizing conditions, it tends to be retained by limonite, being concentrated in respect of the copper in the upper oxidized and leached zone of the porphyry copper deposits. In contrast, Cu tends to be removed from such zones and concentrates at a greater depth (as oxide or secondary sulphide). Consequently, the parallelism of the vertical Cu and Mo distribution suggests that the oxidized minerals have not significantly emigrated in respect to the sulphide from which they originated, i. e. they represent mainly oxide in situ.

This feature, and the lack of a zone of supergene alteration which manifests itself in the absence of colour anomalies and in the presence of secondary minerals like jarosite, is coherent with the pyrite paucity of the system, an essential mineral for the generation of a leaching acid environment during the sulphide meteorization process. Thus, the primary paucity in the sulphide system, which is reflected in the supergene enrichment process limits the development of economic supergene copper concentration in the porphyry copper deposits of the dioritic model (Pacci, 1991).

## CHAPTER III.- THE EXOTIC DEPOSITS

The acid solutions which migrate laterally from the supergene enrichment of the porphyry copper are very important in transporting dissolved copper through the water table and depositing the copper under suitable pH and Eh conditions. Depending on the pH of these solutions, the copper may be transported for distances that empirically have been determined to extend up to 14 kilometres from its source, producing mineralized horizons with copper oxides, that are extensions from the area of the porphyry copper deposit itself. (Fig 1, 23 and 24).

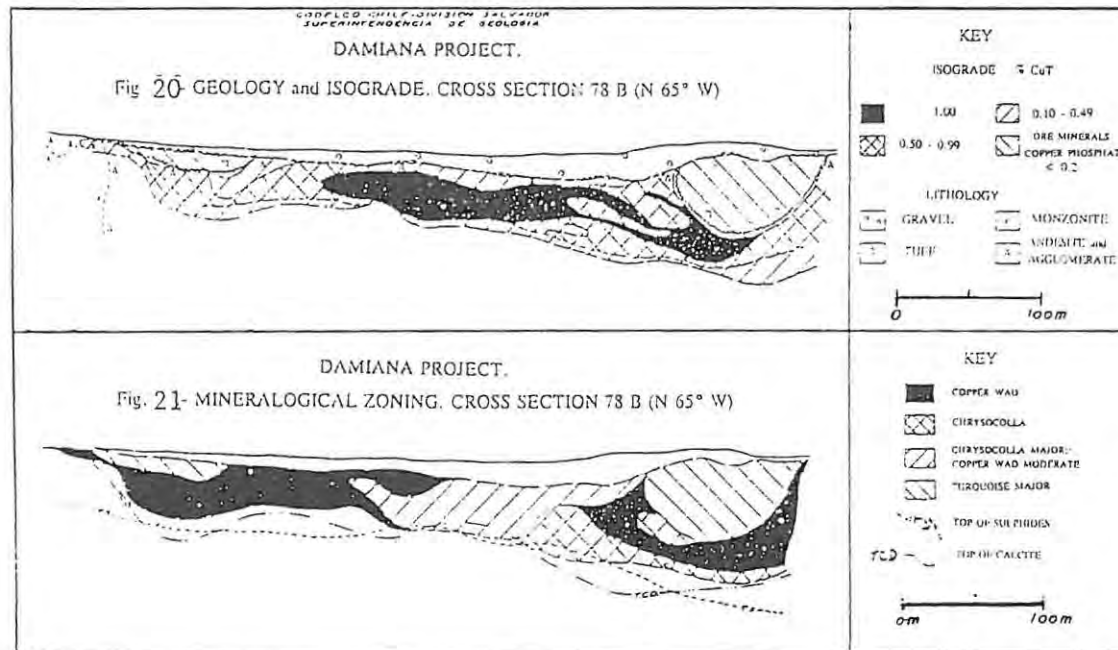
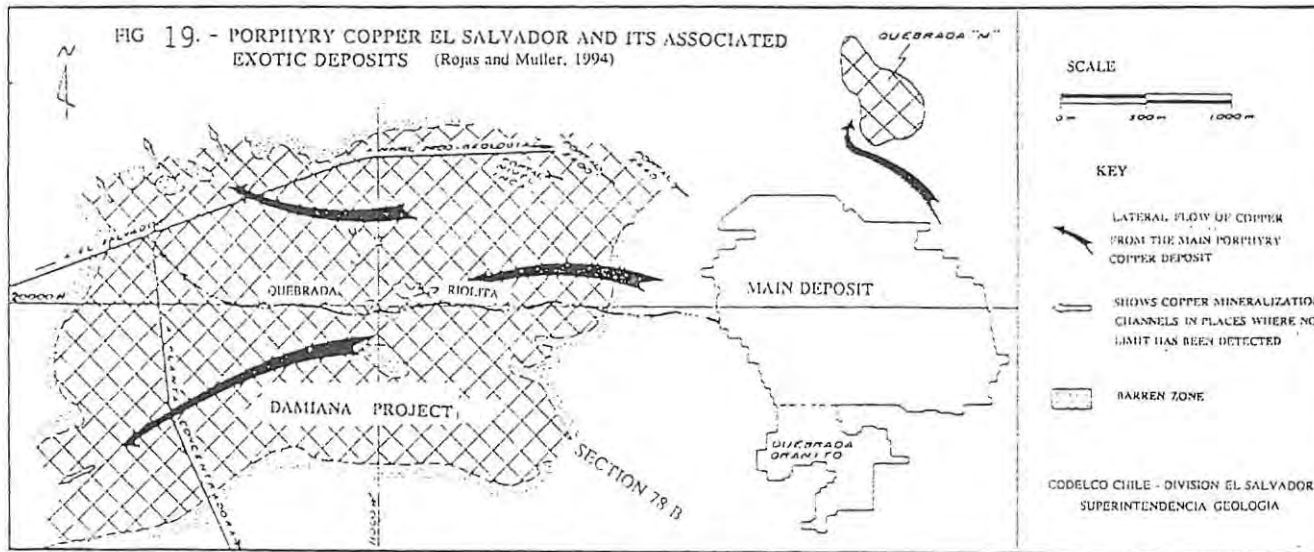
This copper may also be found as chalcocite and is usually deposited on pyrite in places close to its origin. Clear examples of these are: Mina Sur (ex Exotica), Damiana and Huinquentipa which are associated with the porphyry copper deposits of Chuquicamata, El Salvador and Collahuasi respectively (Fig 1, 19, 23 and 24).

### 3.1.- LITHOLOGY

In all the well-known examples of exotic deposits, the copper mineralization occurs as cementation of alluvial gravels and less often coating the fractures in the bedrock over which these gravels are lying (Fig. 23 and 24). There is evidence that suggests that the copper mineralization and the alteration of the underlying rocks occur contemporaneously with the deposition of the gravel. Evidence of such contemporaneity includes the presence of horizontal layers of stratified exotic mineralization exposed by erosion and the occurrence of fragmentation and mineralized blocks that are eroded and finally deposited together with barren fragments on top of the copper oxides which are exotic in nature (Munchmeyer, 1994; Arias, 1985; Mortimer et al, 1977). Situations such as these have been observed, for example in the Sagasca deposit (Munchmeyer, 1995). See figures 1 and 44.

### 3.2.- ALTERATION AND MINERALOGY

As a result of the lateral migration of the copper-bearing solutions, the exotic deposits show a zonation, alteration and mineralization whose characteristics depend, among other factors, on the reactivity of the bedrocks and the Cu/S ratio of the mother deposit.



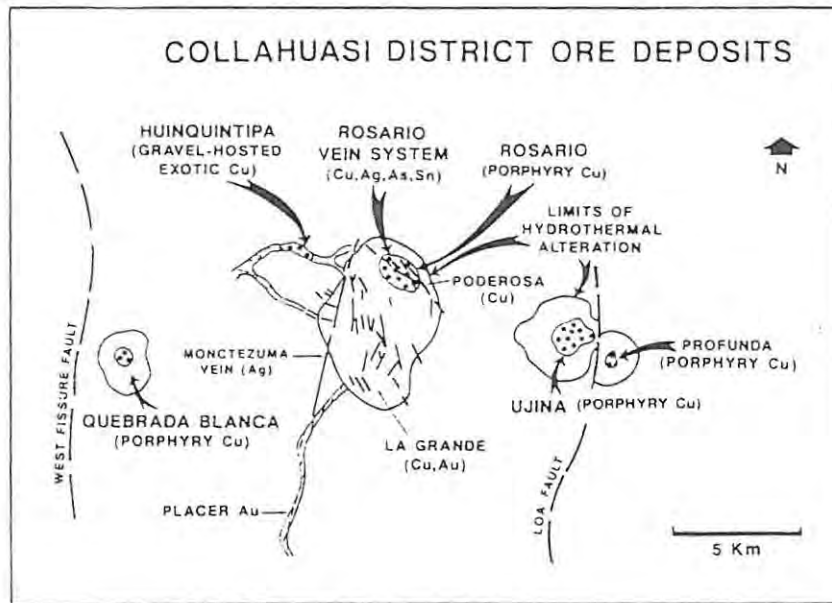


Fig. 22.- Porphyry - style deposits and their associated exotic deposit. (Dick et al, 1994).

The zonation is defined from the most relevant cases of exotic deposits studied such as: Mina Sur, Huiniquitipa and Damiana, it is possible to define this zoning (Fig. 23 and 24). In these deposits three zones can be recognized, based on distance from the source, and they are shown below (Munchmeyer, 1994):

ZONE	PROXIMAL	INTERMEDIATE	DISTAL
DISTANCE FROM IT'S SOURCE	0 to 2 Km	2 to 3 Km	3 to 8 (14) Km
ASSOCIATIONS	<ul style="list-style-type: none"> <li>a) Propylitic halo pyrite with a chalcocite powdery capping of exogenous origin (some examples are Damiana and Quebrada M);</li> <li>b) Gravels with abundant hematite but without copper oxides (Pampa Norte, Huiniquitipa and Ichuno);</li> <li>c) Kaolinized rocks with a copper wad (Mina Sur, Damiana);</li> <li>d) Gravels with atacamite (Mina Sur); and</li> <li>e) Leached and non-reactive horizons in which turquoise and sampleite are deposited (Damiana and El Abra).</li> </ul>	<ul style="list-style-type: none"> <li>a) Argillic rocks with copper wad (Mina Sur, Huiniquitipa, Ichuno and Damiana); and</li> <li>b) Gravels with chrysocolla-atacamite that coexist with rocks altered to kaolinite.</li> </ul>	<ul style="list-style-type: none"> <li>a) Do not present important mineralization in the bed rock and if it does exist, it tends to concentrate itself in the gravels;</li> <li>b) Chrysocolla predominates cover atacamite in the gravels; and</li> <li>c) There is deposit of copper wad in gravels in horizons separated from the previous one.</li> </ul>

The underlying, lateral or distal downstream disposition of the rocks and those mineralized with chrysocolla with respect to kaolinized and mineralized span with "copper wad" nearer to the resource is a result of silica, previously leached from the kaolinized rocks being incorporated into solution, so later it can be deposited as chrysocolla and to a lesser extent in copper pitch and atacamite and malachite, in conditions of increasing pH and in a predominately alkaline environment.

In addition to copper, the solutions may transport other elements and compounds such as Fe, Mn,  $\text{SO}_4^{=}$ , Na,  $\text{U}_3\text{O}_8$ , which produces joint deposition of iron and manganese oxides, and limonitic and gypsum halos.

Figure 21 shows an example of mineralogical zoning from Damiana. Moreover, in Damiana it has been observed that in the Main Deposit (porphyry copper) coexists Sericite-kaolin. In the proximal zone, kaolin is present with traces of sericite. In the intermediate zone, montmorillonite predominates as the major clay mineral and in the extreme distal zone, smectite. Thus a zonation of clay minerals is observed.

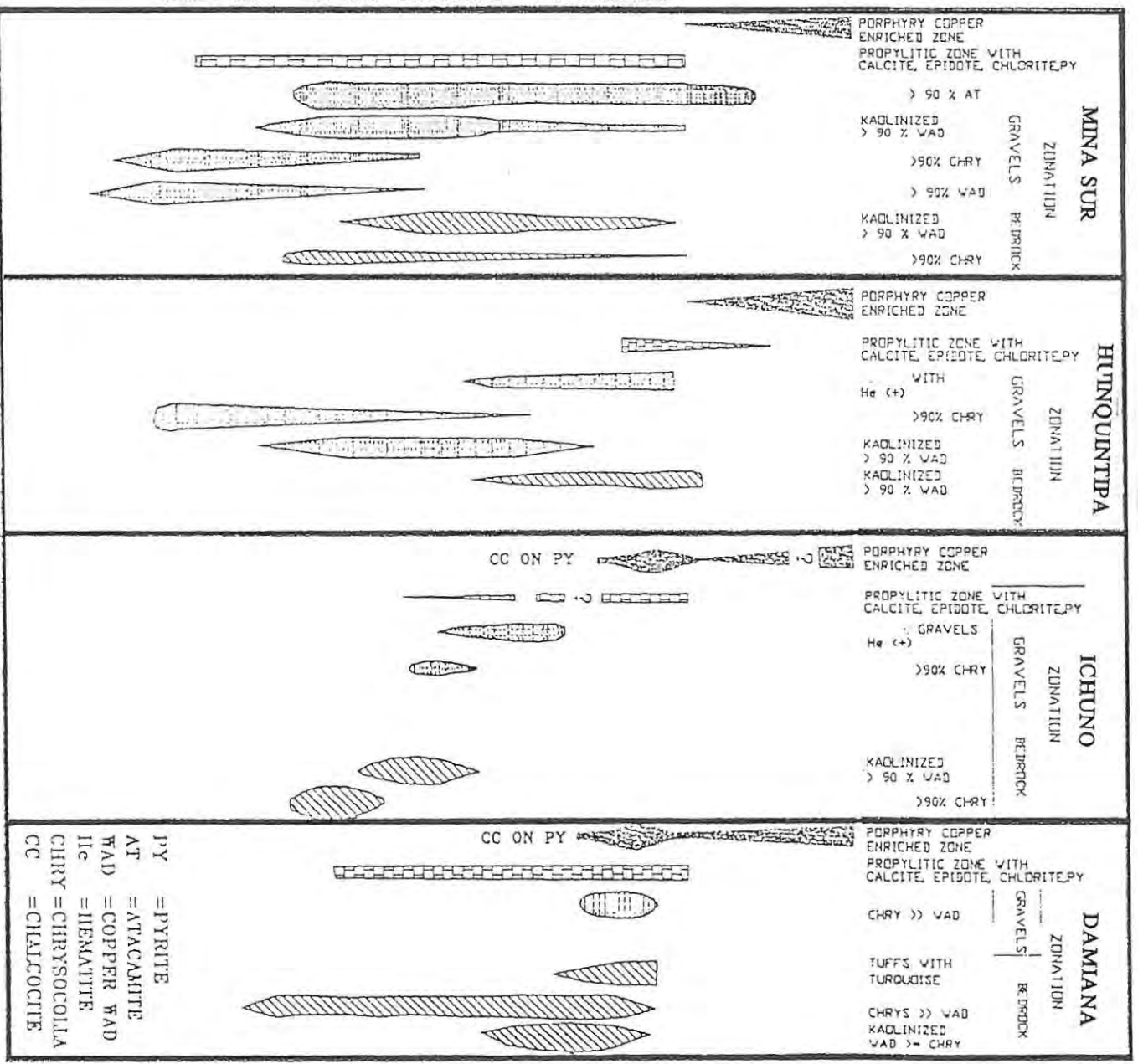


Fig. 23.- Sample of zoning of mineralization and alteration in the bedrock and gravels in 4 selected examples of exotic deposits (Munchmayer, 1995).

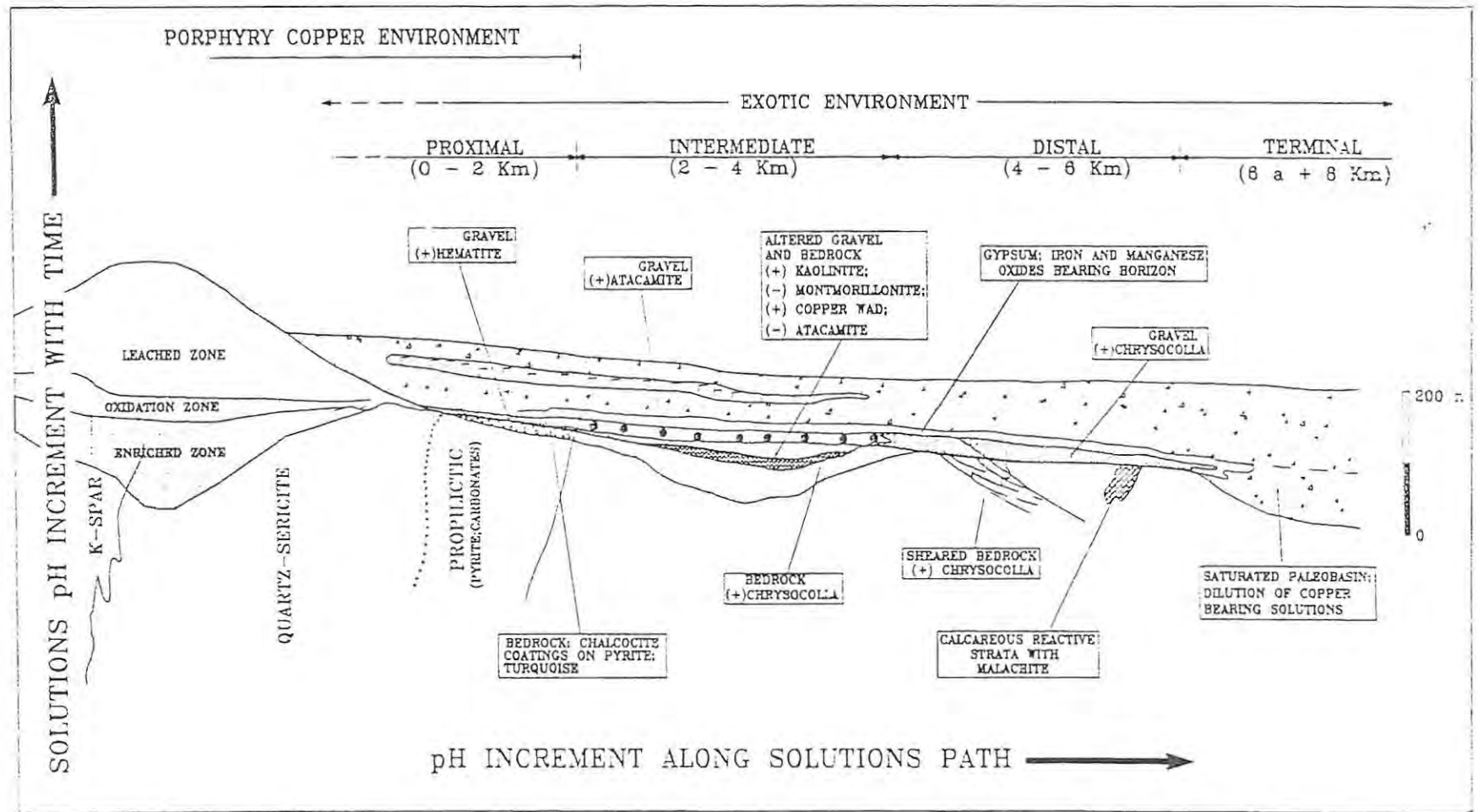


Fig. 24.- Corresponds to an empirical model in which the source of copper is a porphyry copper deposits with secondary enrichment and a pyritic halo. It is assumed that due to uplift caused by faulting, the headwaters of a paleodrainage intersect and interrupt the porphyry copper system in the supergene alteration and mineralization processes. Solutions with copper and decreasing acidity along its course over time within a paleodrainage precipitate alteration copper mineralization and association alteration assemblages. This makes it possible to recognize a "Close, intermediate, or Distal" environment in relation to the source deposit. (Munchmeyer, 1995).

### 3.3.- MORPHOLOGY

The geomorphologic conditions and the reactivity of the bed rocks determine the form of the resulting exotic deposits, which may be grouped into three distinctive types.

The first group is constituted by deposits formed along palaeochannels such as: Sagasca, Quebrada Blanca, Huinquentipa, Ujina, Lagarto and Mina Sur. In these cases there is a notable control of the mineralization by the palaeodrainage, in such a way that the final results are tabular bodies, of reduced size in section but that usually range from hundreds of metres to about eight kilometres in length.

Morphologically the second differentiated types are the fan-shaped deposits which are formed at the peripheries of topographically elevated primary deposits. Damiana and El Tesoro are important examples of this group. The orebodies cover a great areal extension, of the order of square kilometres and have relatively reduced thicknesses of the order of tens of metres.

Finally, the third group consists of irregular deposits, of which a typical case is the Ichuno deposit, associated with the El Abra porphyry copper deposit. It occurs partially in a strong, subhorizontal, structural zone. They are lenticular, equidimensional, a few hundred meters per side.

### 3.4.- SIZE

The size of the "exotic" deposits varies considerably. A total number of thirteen deposits have been recognized to date, ranging from those of very small size, such as the cases of Quebrada Blanca and La Planada (100 to 10,000-ton of fine Cu) to others of medium size, such as Huinquentipa and Sagasca (160,000 to 400,000-ton of fine Cu) and to the bigger deposits, such as Mina Sur, El Tesoro and the recently discovered Damiana (1,200,000 to 3,500,000-ton of fine Cu). The total amount of reserves plus production that is known is of about eight million tons of fine Cu.

*If these ranges of reserves are compared with the porphyry copper, it may be concluded that the large exotic deposits are comparable to the reserves of a deposit of medium size of the porphyry copper type.*

In appendix 1 seven of the most relevant exotic deposits related with porphyry copper deposits in Chile are described.

### 3.5.- PALAEOGEOGRAPHY

The close relationship of exotic deposits to their host rocks, described above, supports the idea that the formation of such deposits in the Central Andes is directly related to the transgressive tectonics which produced the Andes during the upper Oligocene - lower Miocene period (Mortimer, 1977; Maksaev and Zentilli, 1994; Munchmeyer, 1994). A product of the denudation generated by this uplift includes the gravels of Atacama, Calama Formation, and the sedimentary members of the Formation Altos de Pica (Munchmeyer, 1994). The resulting strong erosion controlled the formation of palaeorelief and influenced caused the subterranean water table to fluctuate, favouring the formation of the enriched layers and produced the resulting exotic deposits as a result of the lateral migration of acid solutions rich in copper (Figures 1, 23 and 24).

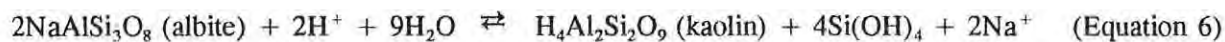
These conditions predominated in the norther part of the Chilean territory and in the south of Peru, approximately between latitudes 15° and 27° south. According to present knowledge, it is estimated that the period of supergene enrichment of the porphyry copper deposits occurred approximately between 23 and 14 Ma (Mortimer, 1977; Arias, 1985; Maksaev and Zentilli, 1994; Munchmeyer, 1994). In parts of the territory, this period overlaps (between the 16.5 and 8.0 Ma) with the accumulation of thick layers of gravel that infix the range front tectonic basins and are in turn preserved locally by the depositions of extensive ignimbrites which sealed the supergene activity.

The exotic deposits are associated with the palaeodrainage and with the alluvial filling. This infilling probably took place simultaneously with the enrichment processes. To this fact it may be also added that the raising of the Andes mountain also produced a climatic change from arid to semiarid conditions, in which periods the above-mentioned processes were initiated and terminated by the extreme arid climate thereby retarding the rapid erosion and permitted the preservation of the layers of enrichment and oxidation already formed.

### 3.6.- IDEALIZED SCHEME FOR THE FORMATION OF EXOTIC OREBODIES

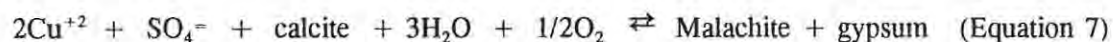
The lateral copper transport in acid solutions, originating from the lixiviation in the primary sources of copper sulphide via structures (faults, discordances, fractures) porous and permeable zones, changes in the pH of the rock, and in many examples is helped by the topographic slope. The genetic history of exotic deposit formation commences simultaneously with the oxidizing processes and supergene enrichment of the porphyry copper deposit (Newberg, 1967; Munchmeyer et al, 1977; Rojas and Müller, 1994; Munchmeyer, 1994).

Generally, the loss of acidity in the solutions is due to its reaction with the feldspar in the bedrock, in this way they result in the formation of residual clays and soluble monosilicic acid (Newberg, 1967)

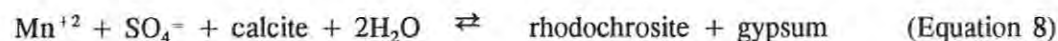


The propylitic haloes of the copper porphyries are usually subjected to low grade metamorphism, which is a fundamental requirement for the copper fixation, due to the existence of greater amounts of calcite (carbonates).

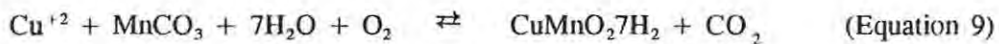
When the solutions which contain copper pass through a highly reactive gangue, copper can initially precipitate as **malachite**. The most likely chemical reaction is (Rojas and Müller, 1994):



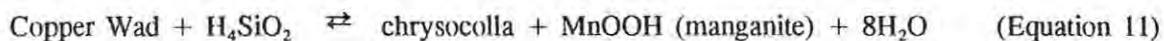
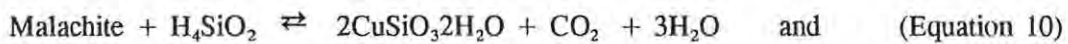
Johnson (1982) has established that in the presence of abundant calcite, a direct precipitation of **rhodochrosite** ( $\text{MnCO}_3$ ) is likely to happen, according to the following reaction:



Once the manganese has become established by the previous reaction, the copper which is still in solution is added to the rhodochrosite to originate "copper wad", through the following equation:



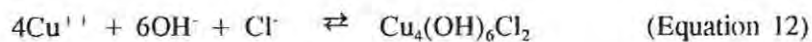
Subsequent processes, by which the solutions started to become enriched in silica by reaction with silicic acid ( $\text{H}_4\text{SiO}_2$ ), permit the eventual replacement of the pre-existing secondary minerals that resulted in the replacement of chrysocolla. The likely chemical reactions in order to replace the malachite and the copper wad by chrysocolla are the following.



In the latter situation, it is common for the chrysocolla to retain Mn, being denominated as: "copper pitch" or neotocite.

Maynard (1983) indicates that the **manganite** is quickly oxidized to **pyrolusite** ( $\text{MnO}_2$ ), starting again the fixation process of manganese by carbonate, which then reacts with the cupric ion to produce "copper wad". This can explain that the "copper wad" is an ubiquitous ore mineral, coexisting with the rest of the oxidized copper ores.

Barton and Bethke (1960, in Rodriguez, 1980) show that **atacamite** can be formed according to the following reaction:



**Atacamite** requires a more basic environment to precipitate than brochantite does, and the solutions must be copper-poor. In an acid environment, atacamite can be formed only from solutions with high copper contents. It seems that such concentrations can not be obtained in presence of sulphur in oxidation process, since it is rare to observe atacamite there (Rodriguez, 1980).

The **copper phosphated ore minerals** are present exclusively in strongly kaolinized rocks, montmorillonite contents (rocks of pH 4-5). It has been interpreted as a very late event, very superficial and when solutions are present with low copper contents. These very acid solutions, having the capacity to dissolve and transport phosphates, permit the precipitation of **turquoise, rashleighite and libethenite** and to change the pH and Eh conditions.

### 3.6.1.- Conditions of formation in some exotic mineralogy

Some geological characteristics of chrysocolla, malachite, atacamite, copper wad and chalcocite are described below.

Rodriguez (1980) emphasizes that the stability fields of chrysocolla, malachite and atacamite are deduced from the law of mass action and the existing relationship between pH and the copper concentrations in the solutions. Moreover, this same author indicates that this procedure has some limitations and only shows the "maximum field" of stability of these minerals, which varies in natural waters. This variation can also be observed if diverse concentrations are used. That is to say that the stability fields must be verified with the field observations.

The mineralogical associations and abundances that are observed in the field are related to the climate (rain, temperature).

It is important to mention the occurrence of minor quantities of uranium, especially in altered zones, in which tarberrite ( $\text{Cu}(\text{UO}_2)_2\text{P}_2\text{O}_8 \cdot 2\text{H}_2\text{O}$ ) has been recognized as a definite phase at Mina Sur (de Siegel and Valencia, 1982).

## CHALCOCITE

Chalcocite is associated with the proximal facies of an exotic deposit, that is to say, that it is the first mineral to be deposited in the lateral migration of copper-bearing solutions, which are favoured and controlled by the abundance of pyrite (from the pyritic halo) in the adjacent porphyry copper deposit.

It is possible to find chalcocite in the distal facies of an exotic deposit, and this occurs when the copper-bearing solutions pass through a pyrite-rich deposit, as for example Quebrada M, 2 km northwest of the porphyry copper deposit of El Salvador. This presents a reduced environment causing chalcocite to precipitate. Moreover, the pyrite was useful as a nuclear centre of chalcocite. In this case Quebrada M is an uneconomic porphyry copper, which has exotic mineralogy (Palacios et al, 1992).

The chalcocite occurs as a thin, powdery film over the pyrite and it happens that the soluble copper/Total copper ratio is very low in comparison to the porphyry copper ratio. Moreover, there is no correlation among such elements which do not follow the usual behaviour of the main body (porphyry copper). The grade ranges occurring in the porphyry copper, represented in geostatistic form, are different (e.g. standard deviation, covariance, correlation coefficient, etc). This implies that the factors which controlled the chalcocite precipitation in the main body are of a different nature than that of the exotic chalcocite.

## CHRYSOCOLLA

The chrysocolla, in general, does not have a chemical composition and defined crystalline structure. Nevertheless crystalline chrysocolla does exist, though it is not common (Rodriguez, 1980).

The investigations of Newberg (1967) show that under acid conditions, silica and copper can travel in solution until an increase in pH causes reaction of both (see equation No 6), depositing a silicate of amorphous copper.

There are several ways in which supersaturation of the silica in solution can occur (Newberg, 1967; Rodriguez, 1980): by evaporation or the addition of colloidal silica to the system; by the presence of concentrated solutions of electrolyte, etc. In any one of these cases, the monosilic acid is polymerized and precipitates as a gel. The evidence from field observations seems to confirm that the colloidal silica is able to absorb cupric ions, and this latter reaction with silica may lead to the formation of chrysocolla. However, chrysocolla can also be deposited, without the intermediate precipitation of colloidal silica (Newberg, 1967; Rodriguez, 1980).

Chrysocolla, can occur interstratified with malachite or copper wad. However, in order for chrysocolla to become abundant or the main mineral in an extensive area of the deposit, certain conditions are required (Rodriguez, 1980):

1.- Scarce or moderate precipitation in order that copper, silica and the acidity do not become excessively diluted. This last factor also prevents a zone rich in chrysocolla from being formed below the water table.

2.- Moderate depth, because (unless the oxidized sulphur mass had been exceptionally sulphur-rich), the supergene solutions cannot travel too far without losing their acidity and consequently do not precipitate the copper-bearing. This implies that chrysocolla forming from the oxidation of sulphur-poor bornite and chalcocite ore minerals must be found very close to its source, and that coming from the oxidation of a sulphur-rich pyritic ore can travel much greater distances from the copper source (up to  $\pm 14$  km).

In general terms, chrysocolla deposition is favoured by a pH from moderate up to high concentration; by solutions with low copper concentration; and, by a high concentration of silica and a low concentration of the other anions, with which copper might form insoluble salts.

## MALACHITE

The low copper concentration in the solutions, together with an almost neutral pH permits the precipitation of malachite, which can occur in the zone of calcite (propylitic alteration - low grade metamorphism), in fresh rocks containing plagioclase, and/or in zones associated with the water table.

In zones of abundant water (i.e. below the water table), the concentration of anions is probably low, and this makes it even more difficult for chlorides (atacamite), sulphates (chalcantite) and copper silicate (chrysocolla-copper pitch-neotocite) to precipitate. The Katanga deposits in Zambia are good examples of this situation, since they are subjected to high rainfall, so the oxidation of the copper sulphides gives rise dominantly to malachite (Bateman, 1961; Ellis and McGregor, 1967).

At the Damiana deposit, associated with the El Salvador porphyry copper deposit, abundant malachite is recognized. However, at Mina Sur, associated with the Chuqicamata porphyry deposit, it is scarce.

## ATACAMITE

Atacamite needs a high anion concentration  $\text{Cl}^-$  in the solutions and such brines will be diluted in regions with abundant rainfall. This makes atacamite a typical mineral of "absolute desert" (Rodriguez, 1980). For the same reason, this mineral is not formed in the fluctuation zone of water table. Atacamite occurs in scarce to trace amounts in the Damiana deposit, but is very common in Mina Sur deposit. In Los Pelambres and El Teniente porphyry copper deposits atacamite is totally absent.

The anion concentrations of  $\text{Cl}^-$  in the solutions is mainly carried out by dissolution of chlorides, which can have diverse origins. Among the supergene copper minerals atacamite is, almost always the last to be formed. It is deposited in open fractures, and commonly atacamite is developed over previously formed oxidized copper ore minerals such as chrysocolla and malachite.

## COPPER WAD

Copper wad was detected at Mina Sur in 1951 (Mortimer, et al 1977), and represents some 27% of the total copper of the deposit (de Siegel and Valencia, 1982). The concentration of copper wad at Damiana is more or less similar.

The copper wad is associated mainly with argillic alteration. In outcrop, together with this alteration, copper wad is associated with atacamite.

The copper wad occurs as veinlets, in botryoidal masses, in kidney-shaped concentric layers, finely disseminated, covering minerals (chrysocolla, malachite, calcite) and is interstratified mainly with chrysocolla. It is firm, shows earthy aspect and is of black to brown-blackish colour. de Siegel and Valencia (1982) suggest that copper wad is amorphous since in diffractiongrams the lines of the Cu- and Mn-containing compound could not be detected.

To derive the chemical formula the following assumptions were made (de Siegel and Valencia, 1982):

- a) Si and Al are mechanically trapped, but only at isolated points in the copper wad samples;
- b) Ca, Co, Fe, P and K are present as impurities (in variable quantities);
- c) The only major copper wad components are CuO, MnO<sub>2</sub> and H<sub>2</sub>O.

### **3.6.2.- Climate: Optimal conditions for continuity, cessation and preservation of enriched deposits.**

Erosion of leached capping and lowering of base level in adjacent drainage channels during active weathering of a porphyry-copper system tend to encourage descent of the water table, causing leaching of previously formed enrichment zones and reprecipitation of supergene copper sulfides at progressively lower levels and augmenting copper grades and enrichment blanket thickness. Moreover, to continue the lateral migration (Ambrus, 1980; Titley, 1982; Brimhall et al., 1985; Alpers and Brimhall, 1989). Neither type of evolution, however, can proceed downward indefinitely, because vertical zoning of

hypogene alteration and mineralization must eventually expose a portion of system that is less favorable for leaching and enrichment. Some physical and chemical factors changing with depth that would cause cessation of enrichment are lower relative pyrite content, lower protore copper grade, lower permeability, and more reactive (acid-consuming) hypogene alteration assemblages. Dispersion of copper has already at Chilean porphyry copper deposits.

The preservation of the stratabound bodies and the ideal sequence of the mineralogy is related to the amount of pyrite from the porphyry copper mother deposit, which is the source of  $\text{FeSO}_4$  and  $\text{H}_2\text{SO}_4$ . The attack on the previously formed minerals previously formed is due to a new generation of acid. This attack can be intermittent or continuous, so the final result is an orebody of different dimensions and proportions of ore minerals which will occupy a major area, depositing these minerals for a significant distance from the main deposit or simply as a dispersion that is produced in such a way that the copper remains scattered so that its exploitation is not economical. The discoloured chrysocolla, looking like its copper content has been washed, is related to this continuous process.

The preservation of enrichment blanket and exotic deposits as a high-grade are thus due in large measure to the cessation of enrichment processes due climatic desiccation (Fig. 25 and 26) at a timely stage of the system's evolution, ceased prior to the earliest middle Miocene at about 14 Ma (Fig. 25 and 26) that can be represented by the youngest supergene alunite ( $14.7 \pm 0.6$  Ma; Alpers and Brimhall, 1989). Alpers and Brimhall (1989) postulate que local tectonic reasons for cessation of enrichment at a given deposit, the most likely mechanism for stopping the process of supergene copper sulfide leaching and enrichment at several localities in the region simultaneously is by widespread, severe climatic desiccation (Fig. 25).

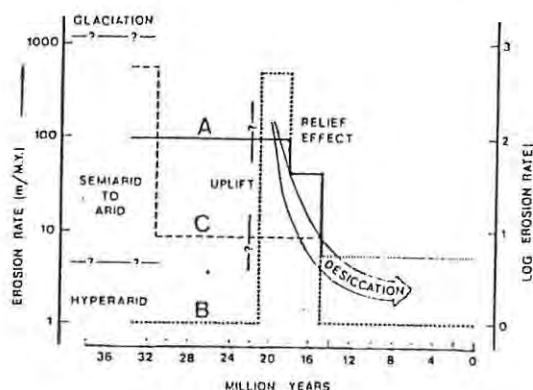


Figure 25. Possible interrelation of uplift, climatic change, and long-term erosion rates in northern Chile. After Alpers and Brimhall (1989).



### 3.7.- EXPLORATION

The exotic deposits are resources that are added to the main deposit, and they allow for the exploitation of low-grade porphyry copper deposits, for the lowering of mining costs and for deepening of the mine. In addition, an exotic deposit can be a good mining business by itself, as is shown in Chapter IV.

The exploration of the exotic deposits, is related to porphyry copper exploration. (fig. 23, 24, 25 and 26). Some past experiences are described below:

#### MINA SUR ex Exotica (Mortimer, et al., 1977).

Mina Sur (Fig.4) was discovered after attempts to recuperate copper-rich solutions derived from the lixiviation of the Chuquicamata waste dump: the solutions did not emerge at the foot of the tip but penetrated the underlying gravels. Boreholes were sunk to try to locate the possible sub-alluvial channel for such solutions, and in one of these holes, in October, 1957, "oxide" ores of copper were discovered. Exploration by churn and diamond drilling, and by geophysics, continued until 1968. Overburden removal was begun in September, 1967, and the first ore was extracted in July, 1969. The original reserves are 250 M ton with an average grade of 1.40% total Cu.

#### DAMIANA (Carrasco and Rojas, 1993; Rojas and Miller, 1994)

The exploration of Damiana started in July, 1992 with the hope of locating other deposits of the "exotic" type similar to Quebrada "M", after having calculated a mass balance among the primary copper, copper in the leached zone and the copper deposited in the secondary enrichment zone. This balance indicated that an important amount of copper was missing from the El Salvador porphyry copper deposit.

This last, concluded that 1,975,340 ton of copper had migrated laterally, and if it had been deposited as exotic chalcocite at Quebrada M, the average grade of this deposit should be of the order of 8.23%

total Cu. Because this did not happen, there existed a high probability of finding several deposits with tonnage and grade similar to Quebrada M (24 M with an average of 1.08% CuT). The first chosen target was Quebrada Riolita (Fig. 19 and 40), where a prominent east-west structure seemed to have the correct geological conditions to channelize and deposit exotic mineralization. From the first borehole drilling, mineralization was detected, totalling 150 M ton and 0.50% total Cu of leached ore minerals and 84 M ton and 0.17% Cu-phosphate minerals. It is probable that a second target will be located in the Quebrada Granito area.

**Summary.** For exploration of exotic deposits, a mass balance of the leached columns in the porphyry copper must be considered. Moreover, the lithology of the propylitic halo, permeability, drainage and palaeodrainage, major structures, fractures, joints, zonation of clay minerals are important. Geophysics should be undertaken to determine bedrock, major structures, thickness of the gravels, etc; geochemistry for copper, gold, uranium and mobil elements as for example: Zn, Mn, Pb and Ag. Uranium in these deposits ranges from very scarce to non existent. In practice, geophysics based on uranium is rarely done.

For example, Quebrada M (Fig. 40) presents a exotic mineralogy, related to the porphyry copper El Salvador, there exists an structural control of the mineralization, denoted by the existence of zones in which coincide as in the larger fault concentrations as in the mineralization. The geochemical analysis indicates that the mineralized zone presents major zinc concentrations and minor Molybdenum and gold values when comparing it with the enrichment zone of El Salvador porphyry copper (Palacios et. al., 1992). Zinc is a high mobility element in the supergene phenomena and that gold and molybdenum are generally stable in the lixiviation zones, it is considered as another criterion in exploration to define the economic mineralization of Quebrada M as transported character by the channels of N10-20°W direction (preferential direction of the structure), moreover, they are evidenced by the kaolin and montmorillonite associated to these channels (Palacios et. al., 1992).

## CHAPTER IV.- EVALUATION OF RESOURCES

The geological evaluation of the mineral resources is essentially based on the metallurgical and mining-economic concepts.

### 4.1.- Introduction

To fulfil the metallurgical and mining-economic objectives the geologist makes a programme of the geological activities from early stages of the exotic deposits discovery, besides he is advised by various professionals (it depends on the geologist requirements). Some of the programmed activities are:

- 1).- Reconnaissance of the borders of the deposit
- 2).- Mapping of: lithologic units, alteration, ore minerals, gangue minerals, top of sulphide, water table, measuring flow, top of calcite, bottom of supergene effects, zonation of clays.
- 3).- It is very important to delineate the different zones of mineralization-alteration, which will be useful as a base for the metallurgical tests. This is the mining business base, since it will indicate the possible copper recovery, in order to obtain the profit and gross profit.
- 4).- To obtain isopach maps of the overburden, mineralized zone, and clays. Isograde for Soluble Cu (CuS), Total Cu (CuT), pH, acid consumption.
- 5).- To carry out diamond drill hole and to make shafts with its respective exploration galleries in order to map the mineralization continuity, vertical and horizontal zonation of the mineralization, to collect samples for the metallurgical tests, geomechanics, etc.
- 6).- To carry out geostatistics studies in order to verify the mineralization continuity, essentially in perpendicular direction of structural control.
- 7).- To increase the maximum conceptual geological knowledge of the deposit.

8).- To use holistic criteria, that is to say, to go from general to particular, without establishing arbitrary limits; to determine the amount of suitable information to be planned in an optimal way; to do the best to obtain information on time, that means before fundamental decisions have been made; to use models based on meditated geological concepts; to use estimate methods of geostatistics respecting the geological models; and, to work in a multidisciplinary way considering several points of view.

#### 4.2.- METALLURGICAL CONSIDERATIONS

Some metallurgical data according to experiences in Mina Sur and Damiana are given below.

##### MINA SUR

In Mina Sur deposit the mineral reserves has been categorized according to three metallurgical type, numbered 1, 2, and 3. They are related to the chemical alteration grade ( argillization) of the rocks and mineralized gravel

Terrazas (1994) indicates that the present metallurgical knowledge permit to include new geological considerations which influence and control the metallurgical and economic results in the copper recovery which are contained in the orebody processed in an industrial scale in Mina Sur:

A) The **impermeability** of the percolable bed, attributed to the silica dissolution and/or to the material quality which can belong to the chemical alteration (N° 2 and 3 metallurgical types) or to the physics alteration controlled by the fine grain, clay type, which is characteristic of the gravel poorly consolidated and that is situated in the superior and lateral surrounding of the mineralized orebody.

B) The "copper wad" mineralogical specie is a refractory amorphous copper mixture, manganese and iron in variable amounts, which is presented in different percentages, respect to the other mineralogical species in the whole deposit, being relevant in the gravel with chemical and physical alteration as well and in the rock close to the contact gravel-rock.

C) The ore minerals' manner of **occurrence**, specially chrysocolla, which occurs as a cement in the matrix of the mineralized gravel and in fractures and impregnating feldspar of the fundamental rock. In this last the copper is difficult to be extracted.

D) The **granulometric characteristics** of the material show a minor or major surface exposed to the attack of leached flow. On the rock the mineralogical species are found locally and essentially in sealed fractures and in the fresh gravel as cement of the matrix so in this one the lixiviable surface is bigger, which increases even more due to the intrinsic porosity of the material.

Laboratory tests in percolator (idealized condition) were carried out in a pilot scale in four boreholes sunk in the south extension of Mina Sur. These tests showed successful metallurgical results, specially when the chrysocolla cements the matrix of the gravel and when it is scarce in the altered gravel contenting "copper wad" and atacamite in disseminated thin film (see Fig. 27)

## DAMIANA

Mina Sur from its earliest stages has had metallurgical problems. Several studies and metallurgical tests have been done. In Damiana a good use of these experiences have been made, in order to visualize the problem from its discovery to play an important role in the exploitation stage.





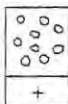
Metallurgical groups were formed according to ore minerals, gangue, and clay minerals starting from diamond drill hole, exploratory shaft and outcrop. The diamond drill and shaft were carried out in order to obtain the samples for metallurgical tests, besides to visualize the continuity of the mineralization, geomechanics (Laubscher type) and correlation of the essay.

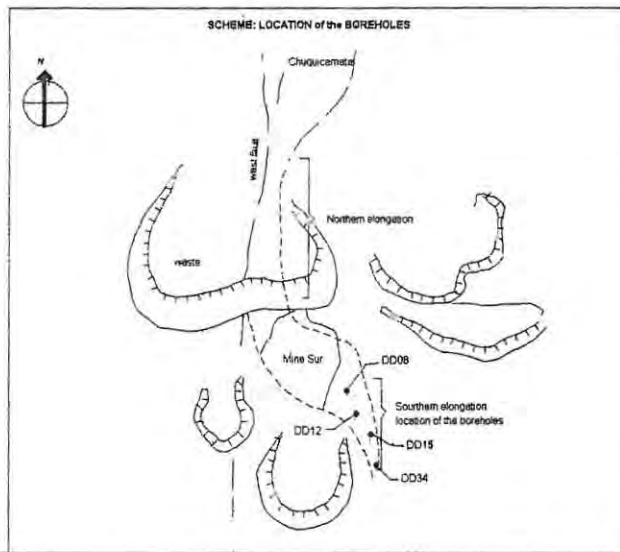
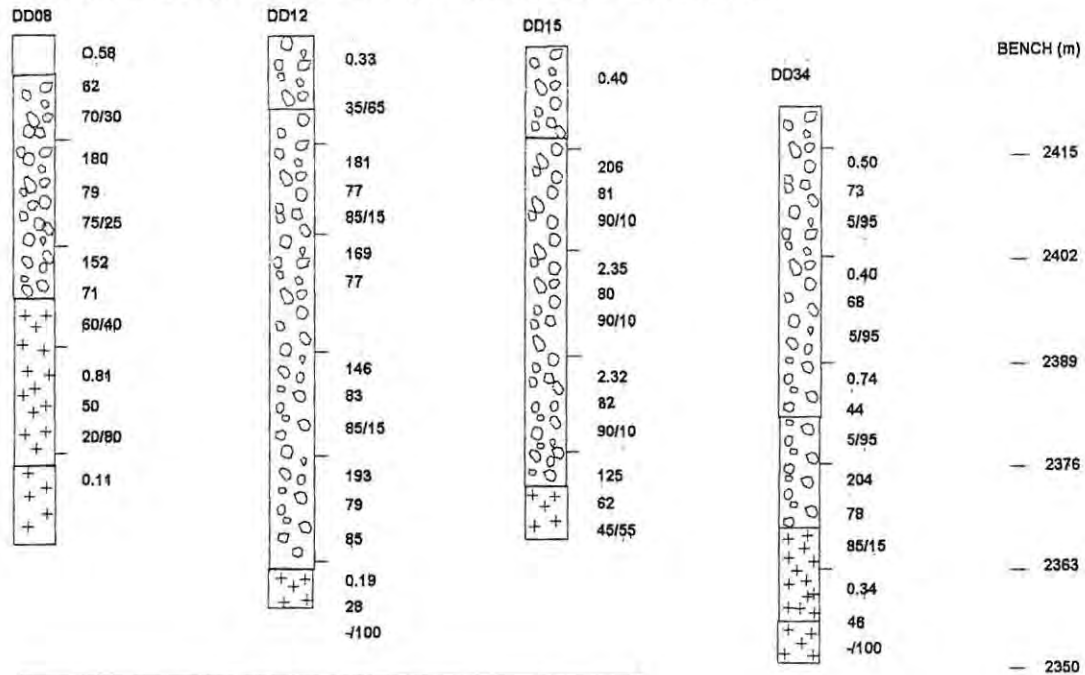
The metallurgical tests were carried out in pilot plants of the company and with contractor (CIMM, Centro de Investigaciones Mineras Metalurgicas) employing large box, columns and heaps.



FIG 27 GEOLOGICAL-METALLURGICAL DRILLING FEATURES, SOUTH EXTENSION of MINE SUR (Terrazas, 1994)

KEY

-  Orebody
-  GRAVEL
-  ROCK
-  GRAVEL/ROCK CONTACT
  
- 
  - % TOTAL COPPER
  - % COPPER RECOVERY
  - % CRYSOCOLLA- ATACAMITE/COPPER WAD
  
- DD08 Borehole



Chemical analysis by Total Cu, soluble Cu, Total Fe, sulphur, Co, SiO<sub>2</sub>, Mn and U, were carried out to each one of the samples and with three different method of dissolution: nitric acid, sulphuric acid and cyanide. Moreover, a standard swept by x ray fluorescence, microscopic analysis, chemical-granulometric analysis by fraction, pH and specific gravity

The initial metallurgical samples contemplated natural moisture, sulphuric acid consumption, maximum superficial water catchment and agglomeration/cured with sulphuric acid.

The conclusions indicate that the recovery varies between 60 and 92 %, however a previous cured is needed to lower the high acid consumptions in some samples. The kinetic of lixiviation shows that in 30 days the > 5 % (copper phosphated minerals) of the copper is recovered and that 170 days between 80% and 92% can be achieved (Carrasco and Rojas, 1993; CIMM,1994). See Table 2 and Fig. 28. Figure 28 was carried out employing averages of 38 Kg/ton and 75 Kg/ton of sulphuric acid consumption. Figure 29 shows that lower copper recovering are obtained from copper phosphated mineral ( $\pm 5\%$  in 60 days) and that the chalcocite needs 170 days to be extract 88.40% of total copper itself.

The samples with problems are those containing copper wad-clay minerals, malachite and calcite. The solution for the first group is to put more filters in the unit of solvent extraction, while for the malachite and calcite a previous cured will be carried out and it will be mixed up with chalcocite so the dissolution of this sulphur and the presence of bacteria (*Thiobacillus thiooxidans*; Jarube, 1987) will generate more sulphuric acid.

At the early stages of Mina Sur the problem was that the organic reactive were inhibited by the chrysocolla, at present this has been solved enhancing these reactives.

TABLE 2 - ANALYSIS AND VOLUMENS OF INPUT AND OUTPUT SOLUTIONS.  
 EXAMPLE COLUMNNE 24 CII-I. LIXIVIABLE UNIT - DAMIANA PROJECT (CIMM, 1994)

(DAYS)	INPUT SOLUTION						OUTPUT SOLUTION						L.S.
	Vol (l)	Cu (g/l)	Fe I (g/l)	Fe II (g/l)	HI (g/l)	pH	Vol (l)	Cu (g/l)	Fe I (g/l)	Fe II (g/l)	HI (g/l)	pH	
1													
3	15.47	0.00	0.00	0.00	9.49	1.04	10.16	0.10	0.37	0.13	1.00	2.15	732
5	14.53	0.00	0.00	0.00	9.49	1.01	13.40	2.00	0.02	0.01	0.00	2.59	734
7	14.74	0.00	0.00	0.00	9.49	1.01	13.00	1.70	0.01	0.03	0.00	2.64	737
9	14.22	0.00	0.00	0.00	9.49	1.01	14.86	1.10	0.03	0.05	0.00	2.58	741
11	13.70	0.00	0.00	0.00	9.49	1.01	13.10	0.73	0.12	0.00	0.00	2.43	742
13	15.04	0.00	0.00	0.00	9.49	1.01	14.60	0.50	0.35	0.00	0.00	2.32	742
15	15.50	0.00	0.00	0.00	9.49	1.01	15.50	0.32	1.10	0.00	0.00	2.20	742
17	15.50	0.00	0.00	0.00	10.03	1.00	15.20	0.36	0.61	0.00	1.16	2.12	832
19	14.52	0.00	0.00	0.00	10.03	1.00	13.05	0.25	1.10	0.00	1.29	2.09	837
21	15.30	0.00	0.00	0.00	10.03	1.00	15.40	0.20	1.00	0.00	1.49	2.10	837
23	15.50	0.00	0.00	0.00	10.03	1.00	14.90	0.19	1.10	0.00	1.46	2.04	852
25	14.60	0.00	0.00	0.00	10.03	1.00	13.30	0.19	0.91	0.00	1.53	2.02	854
30	20.10	0.00	0.52	0.00	10.20	1.14	33.50	0.19	1.70	0.00	1.97	2.02	854
35	20.25	0.00	1.30	0.00	10.20	1.14	34.10	0.15	1.50	0.00	1.74	2.02	856
40	20.25	0.00	1.30	0.00	10.20	1.14	31.31	0.12	1.90	0.00	2.01	2.01	859
45	20.25	0.00	1.30	0.00	9.34	1.10	32.21	0.10	2.10	0.00	2.52	1.81	873
50	20.25	0.00	1.60	0.10	9.19	1.10	30.30	0.00	2.10	0.00	2.41	1.80	876
55	20.25	0.00	2.00	0.03	8.45	1.13	37.74	0.07	2.40	0.00	3.01	1.76	857
60	20.25	0.00	1.90	0.03	9.24	1.21	37.62	0.00	2.90	0.00	3.02	1.81	861
65	20.25	0.00	2.40	0.00	9.07	1.22	37.96	0.06	2.00	0.00	4.10	1.72	861
70	20.25	0.00	2.40	0.00	9.00	1.18	35.00	0.06	3.20	0.00	3.04	1.76	864
75	20.25	0.00	2.80	0.00	9.29	1.19	37.00	0.06	3.50	0.00	3.51	1.76	852
80	20.25	0.00	3.00	0.00	8.77	1.21	37.80	0.05	3.30	0.00	4.10	1.72	860
85	20.25	0.00	2.80	0.00	9.07	1.22	35.60	0.05	3.40	0.00	4.67	1.67	865
90	20.25	0.00	3.30	0.00	9.10	1.22	36.54	0.05	3.40	0.00	4.64	1.64	863
95	20.25	0.00	2.90	0.00	8.60	1.25	37.00	0.04	3.70	0.00	4.95	1.66	850
100	20.25	0.00	3.40	0.00	9.07	1.25	38.00	0.01	3.70	0.00	5.42	1.61	850
105	20.25	0.00	3.30	0.00	8.07	1.24	37.00	0.04	3.70	0.00	4.90	1.61	857
110	20.25	0.00	3.50	0.00	9.57	1.20	37.50	0.03	4.00	0.00	5.06	1.58	810
115	20.25	0.00	3.60	0.00	9.10	1.24	38.10	0.04	3.90	0.00	5.51	1.56	809
120	20.25	0.00	3.80	0.00	11.10	1.10	28.40	0.03	4.70	0.00	5.13	1.53	796
125	20.25	0.00	3.90	0.00	11.10	1.10	34.90	0.03	4.50	0.00	6.20	1.51	754
130	20.25	0.00	4.10	0.00	9.31	1.24	35.60	0.01	4.60	0.00	5.34	1.53	762
135	20.25	0.00	4.30	0.00	10.25	1.16	35.65	0.03	4.90	0.00	5.72	1.53	758
140	20.25	0.00	4.50	0.00	9.07	1.17	38.50	0.02	5.00	0.00	6.48	1.45	750
145	20.25	0.00	4.60	0.00	9.44	1.20	37.40	0.02	4.50	0.12	6.41	1.48	748
150	20.25	0.00	4.80	0.00	9.75	1.17	36.60	0.02	5.30	0.10	6.40	1.44	759
155	20.25	0.00	4.70	0.00	9.30	1.18	37.50	0.02	5.40	0.12	6.43	1.43	676
160	20.25	0.00	4.80	0.00	9.89	1.17	36.90	0.02	5.10	0.15	6.42	1.37	713
165	20.25	0.00	4.80	0.10	10.14	1.16	35.70	0.03	5.30	0.16	5.90	1.43	665
169	20.25	0.00	5.00	0.10	10.05	1.15	32.00	0.02	5.00	0.15	6.05	1.33	704
171	0.60						2.00	0.02	5.90	0.17	5.95	1.30	725

Fig. 28.- EXPERIMENTAL SAMPLE OF KINETIC LIXIVIATION. DAMIANA PROYECT (Carrasco y Rojas, 1993)

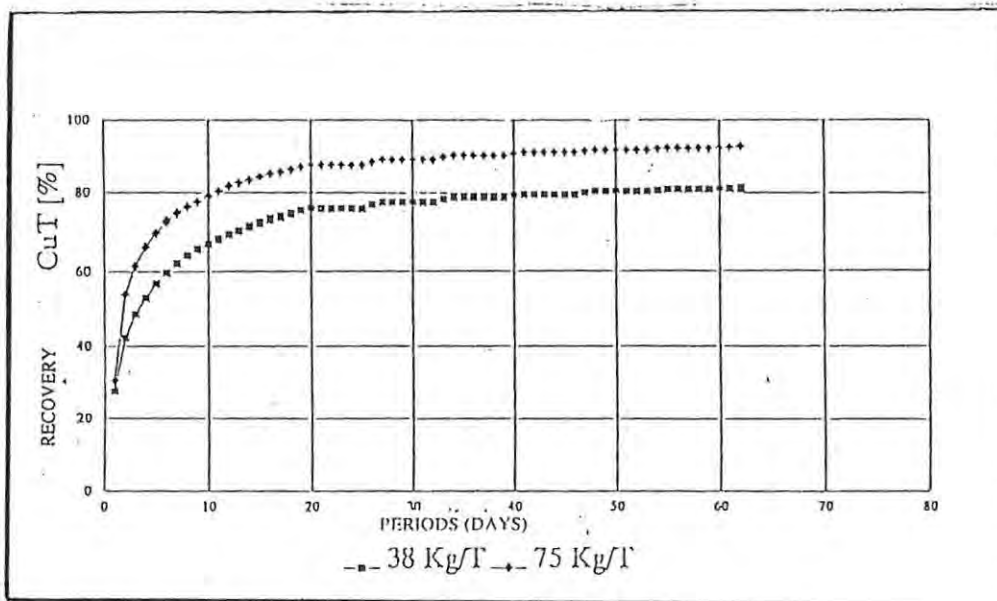
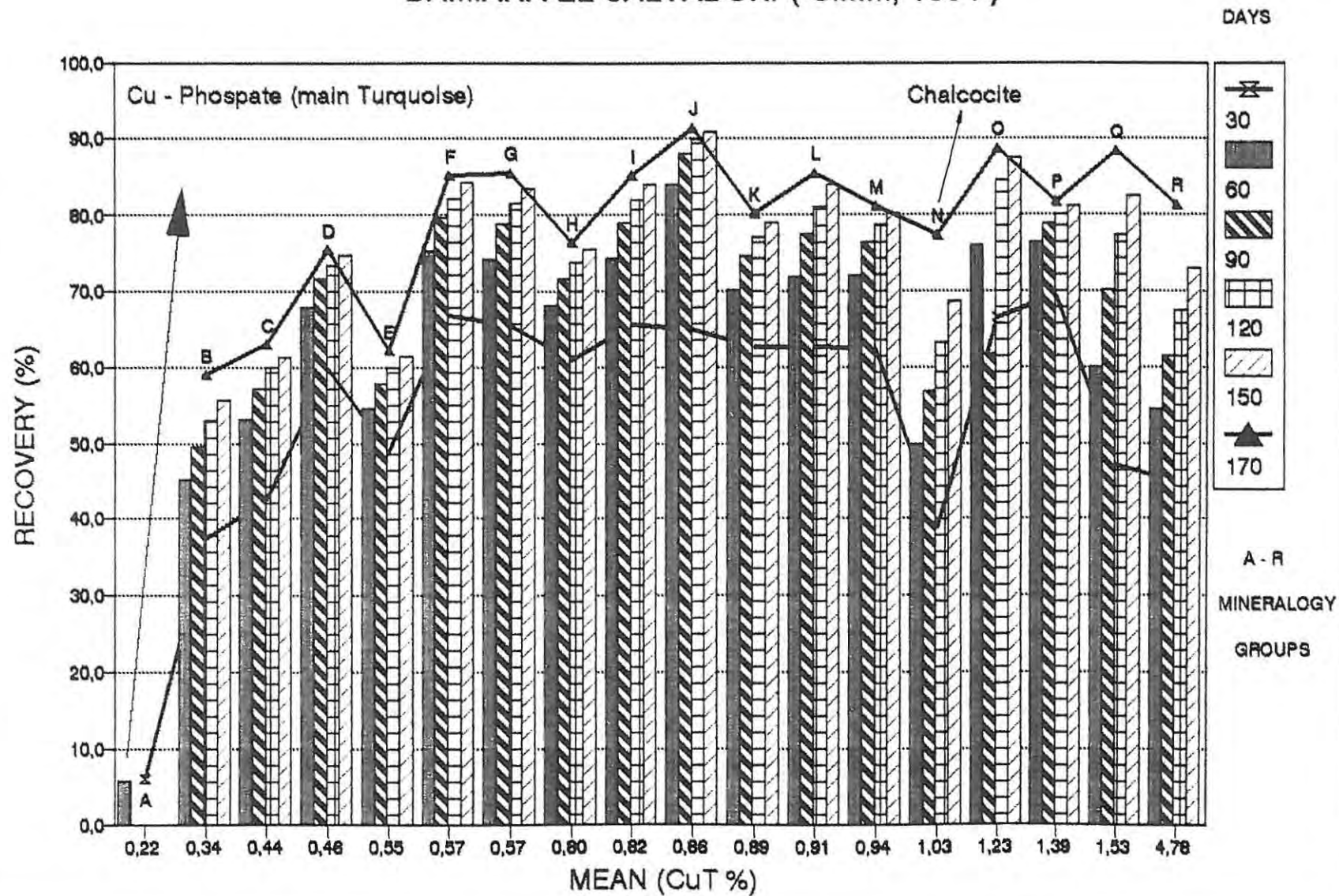


FIG.29 KINETIC AND METALLURGIC RECOVERY  
 ACCORDIG TO MINERALOGY GROUPS  
 DAMIANA EL SALVADOR. ( CIMM, 1994 )



#### 4.3.- SAMPLING AND ORE RESERVES ESTIMATION

In some deposits two important units are detected and they are: the Cu-phosphates and Cu-lixiviable units (to the sulphuric acid). Examples of these units are found in Damiana, while in Mina Sur, Sagasca and others only the second unit can be found. These units are two different geostatistical population, so they must be studied separately.

##### 4.3.1.- Sampling: method and errors.

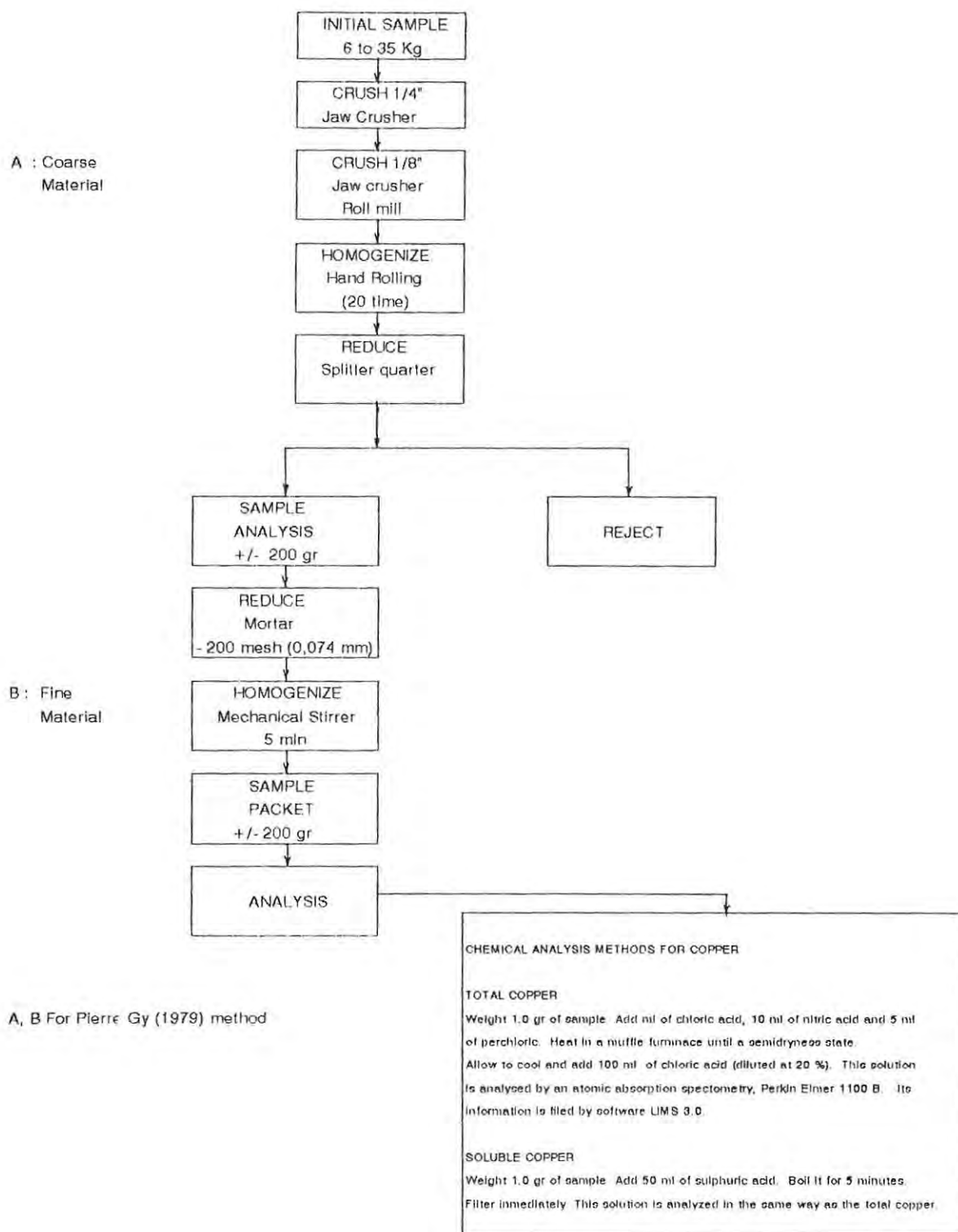
The figure 30 shows the diagram of the samples preparation and method of chemical analysis employed in Damiana-El Salvador. The aleatory errors generated are the following:

- a) To choose 200 grams at 100% minus 1", starting from 30 - 60 Kg.
- b) To choose 1 gram at 100% minus 200 mesh for analysis starting, from 200 grams.
- c) Analysis errors

In order to know the total error and the possible skew 31 samples were duplicated which more and less represents the distribution of the grade at 3432 samples of the lixiviable unit (UL). The results are shown in Table 3.

Table 3 indicates that the skew is not likely to exist since the middle error is not significantly different to zero; the contribution of the errors of the sampling and analysis to the nugget effect is very low, in other words the sampling and analysis procedures have not modified the final results of the cut off. Moreover, it indicates that the relative error of sampling is inferior to 10% . This is quite acceptable.

FIG. 30.- FLOWSHEET PREPARATION OF SAMPLES FOR ANALYSIS. GEOLOGY LABORATORY - EL SALVADOR.



Another way to obtain or verify the sampling errors is to employ the Pierre Gy method (Gy, 1979). Table 4 shows the results for the turquoise unit (UT).

**TABLE 3.- Statistics of the sampling and analysis Duplication Lixiviable Unit. (Carrasco and Rojas, 1993).**

	Duplicated N° 1	Duplicated N° 2	Error (1-2)
MEAN	0,489	0,469	0,203
VARIANCE	0,171	0,134	0,00415
Contribution to the NUGGET EFFECT			1,36 %
ERROR related to the SAMPLING			9,84 %
STUDENS TEST for the MEAN			1,75 %

**TABLE 4.- Errors of sampling for the Turquoise Unit, employing the Pierre Gy method (Carrasco and Rojas, 1993).**

STAGE	SAMPLING RATIO (g-1)	FORM FACTOR	MINERAL FACTOR (g/cm <sup>3</sup> )	LIBERATION FACTOR	GRANULOMETRIC FACTOR	TOP SIZE (cm)	SAMPLING ERROR (%)
A	5 * 10	0,2	1224	1	0,25	0,3175	9,85
B	0,995	0,5	1224	1	0,25	0,0074	0,79
TOTAL (A + B)	-	-	-	-	-	-	9,88

A: Coarse material;

B: Fine material

**TABLE 5.- Experimental Nugget effects for the Turquoise and Lixiviable units (Carrasco and Rojas 1993).**

UNIT	TOTAL VARIANCE	NUGETT EFFECT	COEFFICIENT OF CHAOS	MAXIMUM Relative ERROR
TURQUOISE	0,006	0,001	16,7 %	18,6 %
LIXIVIALE	0,099	0,019	19,2 %	28,7 %

From table 4 it is deduced that the total error of the sampling is acceptable for the turquoise unit. It can also be concluded that the stage A (coarse material) of the preparation flowsheet is the most important in the generation of errors. Stage B (fine material) generates a very low error.

The maximum errors are inferior to 29% and 18.6% for the lixiviable and turquoise units respectively (see table 5) this indicates that the sampling and analysis procedures are adequate. From the estimation point of view such nugget effect does not generate relevant errors since decisions are not made with only one sample. For example, estimating a block with 16 samples, the relative error contributed by the nugget effect is reduced to 7.2% in the lixiviable unit and to 4.7% in the turquoise unit.

#### 4.3.2.- Statistic Analysis

With the purpose to study the grade distribution of CuT (Fig. 31), histogram and lognormal distribution for both units are plotted. Figures 32 to 35 and table 6 show the obtained results.

**TABLE 6.- Statistics characteristics of Total Cu (Carrasco and Rojas 1993)**

UNIT	MEAN	STANDARD DEVIATION	COEFFICIENT VARIATION	MINIMUM	MAXIMUM	N
TURQUOISE	0.170	0.099	58.31	0,01	1.11	1836
LIVIVABLE	0,476	0,492	103,34	0,01	11,30	3416

The statistics of table 5 shows the significative existent geological differences between both units. From the statistic point of view this is reflected in a coefficient of variation almost twice major. The lixiviable unit, shows a higher mineralogical diversity than the turquoise unit.

The quality of the lixiviable unit is fairly better than the turquoise unit, it might be noted that the total copper in the turquoise is only 8% CuT while the minerals of the lixiviable unit (chrysocolla, brochantita, chalcocite, etc) is fairly higher.



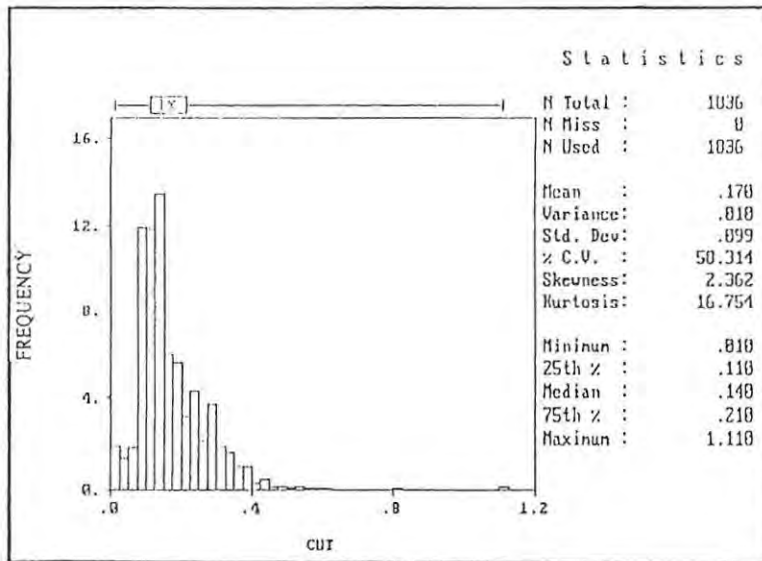


Fig.32 .- HISTOGRAM CUT FOR TOTAL POPULATION, TURQUOISE UNIT DAMIANA (Carrasco and Rojas, 1993)

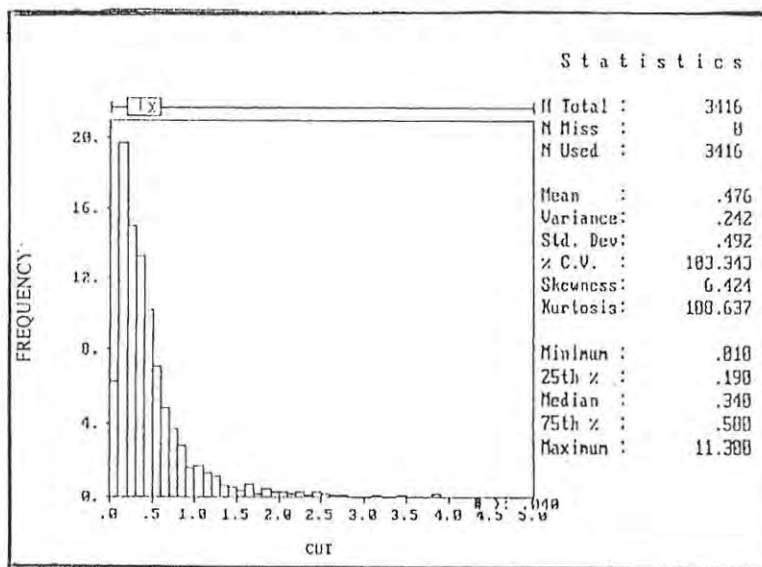
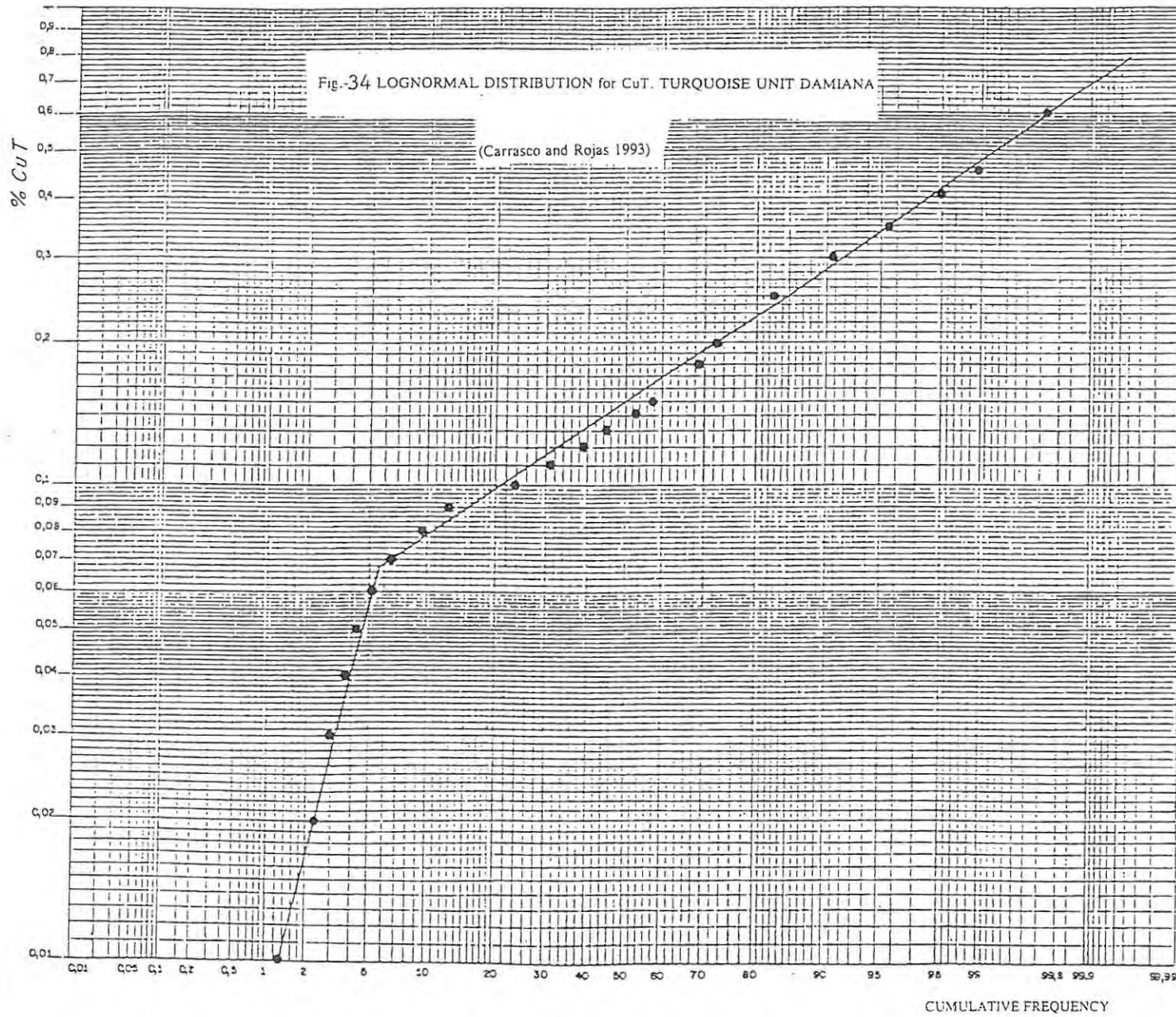


Fig.33 .- HISTOGRAM CUT FOR TOTAL POPULATION LIXIVIALE UNIT DAMIANA (Carrasco and Rojas, 1993)



de  
e

The distribution of both units is asymmetric and approximated to a lognormal distribution. However, in the detail two populations in the turquoise unit and three population in the lixiviable unit can be distinguished. The first population in the UT. represents 5% of the population and belongs to very low grades ( $CuT < 0.07\%$ ); the rest of the Turquoise Unit is represented by a lognormal family of grades which do not exceed 1%

The first one of the Lixiviable family represents 2% of the population and correspond to a barren material intra mineral. The second population comprises 94% of the unit and includes grades between 0.07% and 2% of CuT. The third population represents high grade of ore minerals, probably high concentration of chalcocite veinlets.

The UL evaluation is more complicated than the enrichment zones of a normal porphyry copper, which hardly presents coefficient of variation superior to 60% and less complicated than epithermal of Au/Ag which present coefficient of variation superior to 150%.

Fig 36 and 37 show the distribution of accumulative frequency of the Units' thickness. The data from Table 7 indicate that the UL present major thickness than the UT, but less variable. It is necessary to emphasize that both coefficient of variation are high for a variable like the thickness, fact that indicates that the morphology of the mineralized stratabound is intricate.

**TABLE 7.- Statistics characteristics of the Units' thickness (Carrasco and Rojas 1993)**

UNIT	MEAN (m)	STANDARD DEVIATION (m)	COEFFICIENTE VARIATION (%)	MINIMUM (m)	MEDIAN (m)	MAXIMUM (m)	N
TURQUOISE	19,69	18,36	93,25	2,0	6,0	92,0	172
LIVIVABLE	23,67	16,71	70,62	2,0	12,0	78,0	249

The UT is composed by two lognormal families. One of thickness below 12 m which represents 46% of the thickness populations. The second family represents major thickness and 54% of the total population.

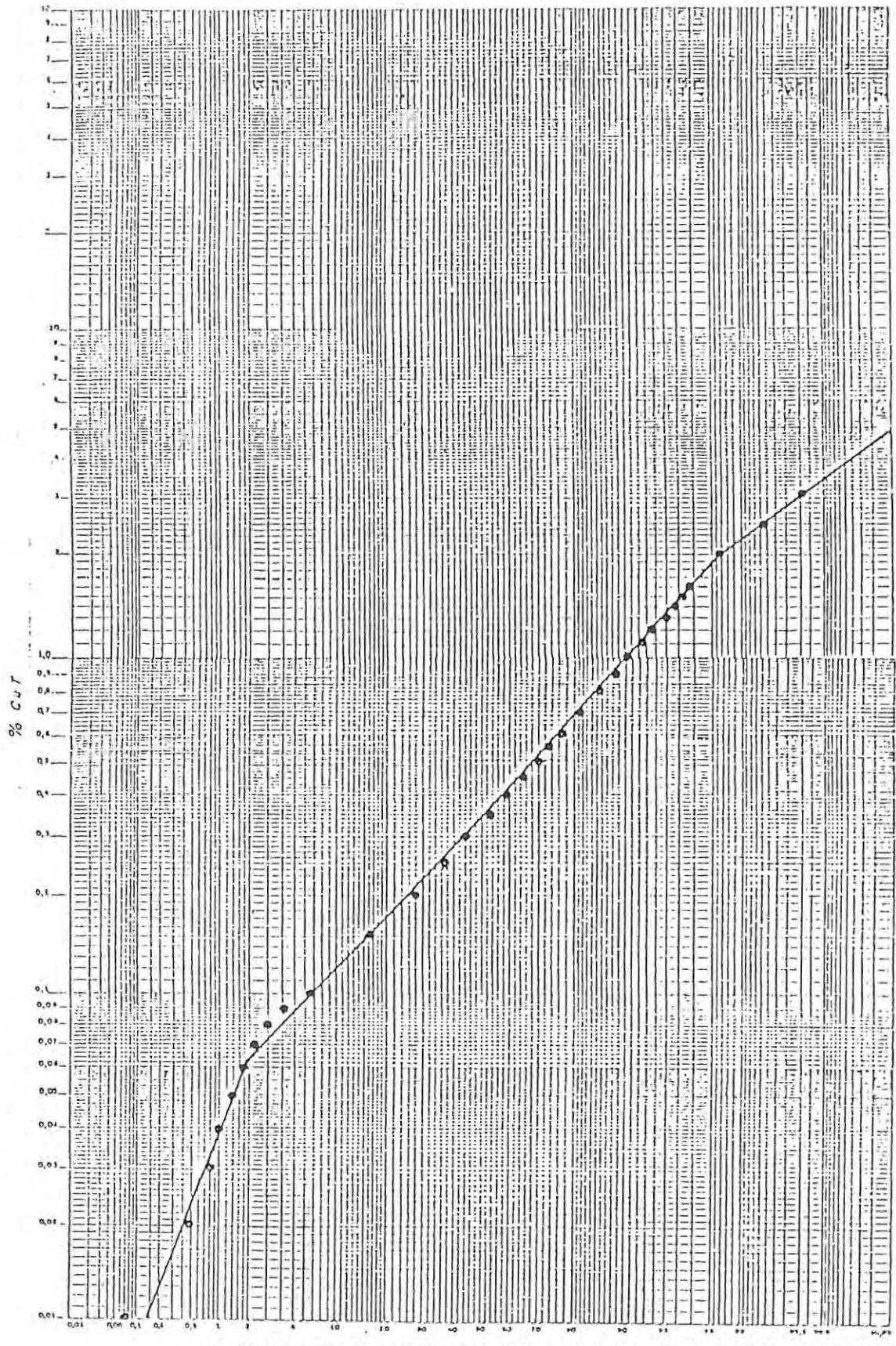


Fig.-35 LOGNORMAL DISTRIBUTION for CuT. LIXIVIABLE UNIT, DAMIANA

(Carrasco and Rojas 1993)

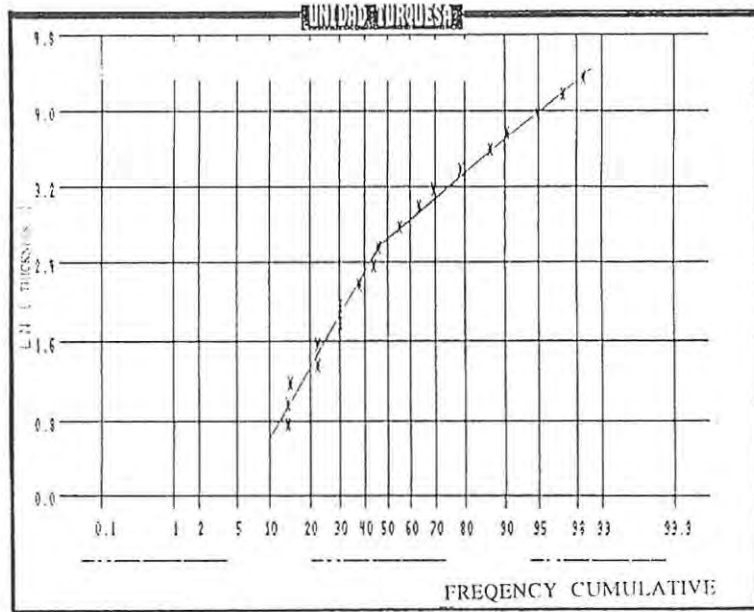


Fig.36 .- CUMULATIVE DISTRIBUTION OF LN (THICKNESS) TURQUOISE UNIT DAMIANA (Carrasco and Rojas, 1993)

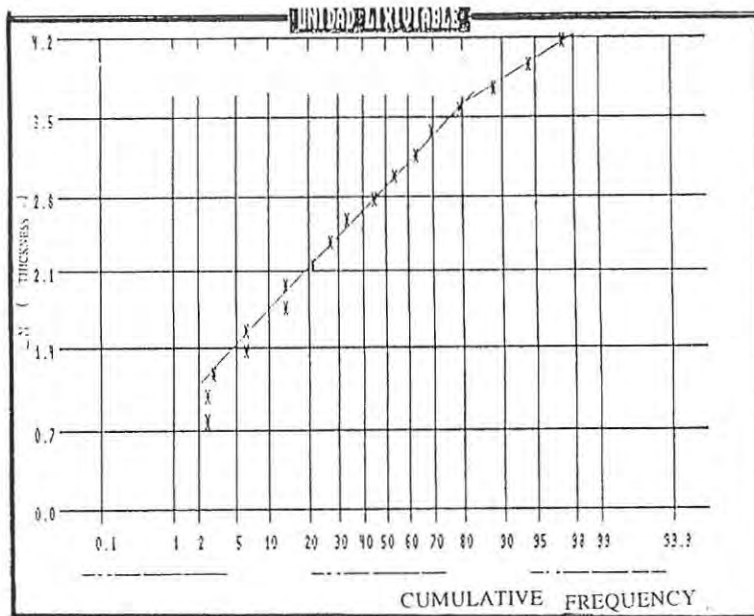


Fig.37 .- CUMULATIVE DISTRIBUTION OF LN (THICKNESS) LIXIVIALE UNIT DAMIANA (Carrasco and Rojas, 1993)

The UL also represents two lognormal families of thickness. The first is the most important representing 80% of the population and thickness minor than 37 m.

#### 4.3.3 .- Geostatistic Analysis

In order to evaluate the continuity of the thickness (Fig. 38) and the grade of the mineralized units a variographic study was carried out. Table 8 indicate the variographic characteristics of the thickness.

**Table 8.- Variographic characteristics of the Thickness (Carrasco and Rojas 1993)**

UNIT	NUGGET EFFECT	SILL	RANGE	COEFFICIENT OF CHAOS
TURQUOISE	40,0	134,8	136,0	-
TURQUOISE	-	150,0	946,0	12,3 %
LIXIVABLE	60,0	230,7	362,0	20,6 %

The semivariograms indicate that the UT remains stationarily, that is to say that there is not increment or systematic descent of thickness in any direction. In general there are three variability scale for the UT:

A) the first belongs to the nugget effect and it is not a very important one since it represents only 12% of the total variability nevertheless indicate that a local scale there are thickness variation non detected by the present drillhole grid.

B) The second structure represents 41.0% of the total variability and shows mineralized bodies of range average of 136 m, which would be nested in major bodies of range average of 946 m, which are suggested by.



C) the third variability structure and it is the most important because it represents 47% of the total variability. So it is a mineralization morphologically continue, but very variable. This indicates that the morphology and the chemical characteristics of the tuff that control the emplacement of the mineralization are intricate and variables.

The UL semivariography indicate that the morphology of the mineralization is generally less variable. There exists a semi stationarity of a domini of more and less 500 m but, later a radial derivative is manifested, as a product of a systematic diminution of the thickness towards the borders of the deposit.

At local level the thickness variations are more important and impossible to be detected with the present drillhole grid. In general it is a unit morphologically continued, but with important local variations. Finally it is necessary to emphasize that to determine the morphology of the mineralization in both units the present drillhole grid is enough.

The local thickness variation will be defined only by the different stages of production. For the UT the horizontal the major axe of the anisotropy ellipse is more and less EW and the minor axe is NS. The hole effect indicates that there are barren intercalations in the vertical as well as in the NS. The previously implies that besides a lithologic control, the mineralization presents a strong structural control. The average dimension of the orebody is the order of 133 m in the EW, less than 25 m in the NS and 7 m in the vertical (Carrasco and Rojas, 1993)

The semivariogram of CuT for the UL are quite similar in the horizontal to the previously described for the UT. However, due to a bigger amount of data the anisotropy direction has been better determinated. They are in N65W and N25E direction. It is necessary to mention that the direction of the major axe coincides with the strike of the Reidel structures which control the mineralization in Quebrada M deposit. The vertical semivariogram permit to recognize two variability structures nes-ted in such direction. In summary the orebodies should have averages of dimensions 150 metres long along the strike of N65°E and 40 metres long along the strike N25°E and 40 metres in the vertical (Carrasco and Rojas, 1993).

The high grade orebodies represented by the first structure of vertical variability will be of smaller dimensions. Therefore it is necessary to emphasize that the mineralization is controlled by the same structures in both units and that the present grid is not able to delimit properly the variability of the mineralization in the NNE direction neither the distribution of the high grade bodies.

To control the previously mentioned vertical semivariograms have been carried out, in the direction NNE for the low grade ( $CuT < 0.33\%$ ) and for high grade ( $CuT > 0.33\%$ ). The high grade distribution is difficult to determine because even the vertical semivariogram is pure nugget effect. The low grade mineralization is more continue despite that at local level it present important variations. Nevertheless the present grid permit to delineate the low grade bodies but not those of high grade. This implies that the variability and perhaps the median of the deposit would be underestimated which implies that the economic value would be underestimated. This is quite important from the economic point of view because the indicators are very sensitive to the variance of the mineralization.

#### **4.3.4.- Evaluation of Resources**

In order to calculate the total tonnage of the turquoise (UT) and lixiviable (UL) units, an common or simple Krigage in blocks 25 x 25 m which was carried out in the interior of the delimited space by the drillhole grid to avoid extrapolation. The grades distribution was calculated globally. Local estimation has not been carried out because the grid does not permit it in the NNE direction. The variance of the unit dispersion of selection of different sizes was calculated based on the model of semivariogram of CuT

It has been considered that a size of SMU's of 5x5x5 is adequated for this estimation, so a lognormal grade has been adjusted a lognormal grade of median identic to the previously calculated based on the variance drilling corresponding to the unit of chosen selection for both units (see table 9). The results are shown in tables 9 and 10.

**TABLE 9.- Tonnage-Average-Cut off, for the Lixiviable Unit (Carrasco and Rojas 1993)**

CUT OFF	TONAGGE (M ton)	AVERAGE (% Cut)
0,0	148,6	0,48
0,1	145,3	0,49
0,2	123,0	0,55
0,3	94,2	0,64
0,4	69,4	0,74
0,5	50,6	0,85
0,6	36,8	0,96
0,7	26,9	1,08
0,8	19,8	1,20
0,9	14,6	1,33
1,0	10,9	1,47

**TABLE 10.- Tonnage-Average-Cut off, for the Turquoise Unit (Carrasco and Rojas 1993)**

CUT OFF (% Cut)	TONNAGE (M ton)	AVERAGE (% Cut)
0,0	83,8	0,17
0,1	71,9	0,19
0,2	23,0	0,27
0,3	4,6	0,38
0,4	0,8	0,52

It is necessary to emphasize that these resources suppose a capacity of adequated selection, that is to say, that the operator can physically select blocks of 5 x 5 x 5 and that the quality control in the moment to make the decision to send the block to the Plant or waste deposit permit to estimate the grade of the block with great precision.

#### 4.3.5.- Categorization of the Resources

The resources have been classified according to the existent certainty in the tonnage and also to the grade of CuT. The criterion used to categorize is based on the concept of slope between estimators and reality. The reconnaissance of the resource will be better if the slope close to the unit.

The criterion adopted consists in calling measured to those resources that presents a slope major to 0.9, indicated when the slope is comprised between 0.8 and 0.9 and inferred in other case. Table 11 shows the results for the tonnage.

**Table 11.- USGS classification (Carrasco and Rojas 1993)**

UNIT	MEASURED	INDICATED	INFERRED
TURQUOISE	28,5 M TON	18,4 M TON	36,9 M TON
LIXIVIABLE	80, M TON	43,1 M TON	25,3 M TON

The major proportion of the demonstrated resources in the lixiviable unit (measured+indicated) is explained for the major continuity of thickness. Table 12 shows the results for a grade of CuT.

**TABLE 12.- Classification of In Situ resources for SMU's 5 x 5 x 5, according to the Cut Off in the Lixiviable Unit. (Carrasco and Rojas 1993)**

GRID	TONNAGE ( M ton)	MEASURED (M ton)	INDICATED (Mton)	INFERRED( Mton)
50 X 50	29,70	10,70	5,30	13,70
100 X 100	77,30	15,50	7,70	54,10
200 x 200	41,60	4,20	2,10	35,30
TOTAL	148,6	30,40	15,16	103,10

**TABLE 13.- Classification of Resources In Situ for SMU's 5 x 5 x 5 according to Cut Off in the Turquoise Unit. (Carrasco and Rojas 1993)**

TONNAGE (M ton)	MEASURED (M ton)	INDICATED (M ton)	INFERRED (M ton)
83,8	17,20	8,50	58,10

From tables 11, 12 and 13 it can be concluded:

- The uncertainty in the grade is fairly major than the tonnage.
- Only 30% of the resources belongs to the demonstrated category.

Therefore the present geological knowledge does not permit to carry out detailed studies of exploitation. Only global studies or in other words prefeasibility studies.

#### 4.3.6.- Preliminar Economic Analysis

In order to have an idea of the economic value of the deposit, it has been determined the cut off and exploitation rhythm with which the net present value (NPV) can be obtained, applying the methodology according to the following expression:

$B_i = [ V(m) - P(t) ] * t [(1 - e^{-iN})/i] - I(t)$ , where

$B(z)$  = Actualized benefit to cut off  $z$      $V(m)$  = Profit per ton for average grade  $m$

$P(t)$  = Total cost/ton en funcion del ritmo  $t$      $t$  = Rhythm of annual exploitation

$i$  = Rate of actualization

$N$  = mine life     $I(t)$  = Capital cost (inversion) in function of the rhythm  $t$

The input data for this study are the following:

a) Plant recovery

According to metallurgical tests of variable columns between 15 kg and 2 tonnage the metallurgist engineers of the Lixiviation Project, have given the following model of metallurgical behave for the oxides ore minerals:

$Rec = 0.8171 - 0.6918^{(-1.463*m)}$ , where  $m$  is the average grade of Cut

b) Total cost per ton v\ s Rhythm of treatment. The costs and rhythms of exploitation of the annual lixiviation plan have given the following model:

$$P(t) = 11.671 - 1.696 * \text{ton} \quad \text{si ton} < 3 \text{ MT/year}$$

$$P(t) = 0.8778 + 17.22/\text{ton} \quad \text{si ton} > 3 \text{ MT/year}$$

c) Investment versus rhythm of exploitation

It has been considered the investment of the lixiviation plan, that is to say 60 MUS\$ for a mill of 5MT annual to determine the slope and the relation, lineal supposed, between Inversions and Rhythm de exploitation.

d) The tonnages and average grades have been calculated for each Cut off according to the lognormal probabilities of the CuT for SMU's 5 x 5 x 5 m.

**TABLE 14.- Optimum technic-economic characteristics for the Lixiviable Unit. (Carrasco and Rojas 1993)  $i = 12\%$**

PRICE (US\$/lb)	Cut Off (% CuT)	Rhythm of exploration (MT/year)	Tonnage (M ton)	Average grade (% CuT)	Mine Life (year)	NPV (M US\$)	Capital Cost (M US\$)	IVAN
0,7	0,575	9	40	0,93	4,4	90	108	0,83
0,8	0,525	10	47	0,88	4,7	132	120	1,10
0,9	0,500	11	51	0,85	4,6	176	132	1,33
1,0	0,475	12	55	0,85	4,6	222	144	1,54

For the Turquoise unit the same cost parameters have been proposed, but at a less metallurgical recovery:

$$\text{Rec} = 0.30 * m$$

Even when supposing that this unit does not need investment and employing a rate of nulli actualization and a high price (1 US\$/lb) this unit is far from being economic.

#### SUMMARY

According to the previously mentioned it can be suggested:

A) Being realistic the supposed employed in the analysis, it can be say that the Lixivable Unit is a good business.

B) Probably the indicators will be best when recognizing the deposit better, since as it has been previously explained the probability of finding high grade zones is high as well as the probability that the deposit variability increase. The following table show the sensibility of the economic indicators respect to the variability of the deposit.

**TABLE 15.- Economic Indicators versus variability (Carrasco and Rojas 1993)**

$$i = 12\% \quad p = 0.8 \text{ US\$/lb}$$

VARIANCE	NPV (M US\$)	IVAN
0,05	60	0,455
0,10	108	0,900
0,15	143	1,192
0,20	171	1,425

This table 15 implies that the best efforts to know the geology of the deposit must be done, which necessarily mean an acceptable estimation of the mineralization variability.

On the other hand, if it is considered that the borders of the deposit are unknown it is also likely that the tonnage increases. Table 16 shows the tonnage sensibility to the economic parameters:

**TABLE 16.- Sensibility of Economic Indicators versus tonnage (Carrasco and Rojas 1993)**

$$i = 12\% \quad p = 0.8 \text{ US\$/lb}$$

TONNAGE (M ton)	NPV (M US\$)	IVAN
200	199	1,27
300	331	1,45
400	464	1,55

The table 16 indicate that it is quite important to delimitate correctly the deposit.

C) It is very important zoning the different units of mineralization- alteration because they determine the metallurgical behaviour. Table 17 shows the sensibility of the economic indicators before variations of metallurgical recovery.

**TABLE 17.- Recovery versus economic indicators (Carrasco and Rojas 1993)**

$$i = 12\% \quad p = 0.8 \text{ US\$/lb}$$

Recovery Variation (%)	NPV (M US\$)	IVAN
+ 15	185	1,28
+ 10	167	1,26
+ 5	149	1,13
0	132	1,10
- 5	115	0,96
- 10	98	0,91
-15	82	0,76

Table 17 corroborates the essential character that has the mineralogical and metallurgical systematic knowledge of the deposit.

## CHAPTER V.- MINING, METALLURGICAL PROJECT AND ENVIRONMENT IMPACT

The projects are for the exploitation of reserves by open pit methods. The projects plan to extract and to crush copper oxide ore which will be pre-treated with concentrated sulphuric acid prior to heap leaching, solvent extraction and electrowinning. The copper output varies between 10000 to 50000 ton per year of cathode copper. The total investment varies between 20 to 100 millions dollars (Reghezza,1993).

### 5.1.- MINE

Based on the geological information a number of design parameters have been selected for pit planning:

NOTE: These parameters are based on the literature (Domic, 1989) and visits to mining sites.

- a).- Ore density 2.0 (gravel) to 2.7 (rock) ton/m<sup>3</sup> in situ, 1.6 to 1.8 ton/m<sup>3</sup> loose;
- b).- Pit slope angles, according to circumstances, from 0° to 20° (outcrop, 0.5 - 2.0 thickness) and 45° to 60°;
- c).- Bench height of 10 m is common; and, 0 m is unusual;
- d).- Cut-off grade of 0.15 to 0.55% CuT;
- e).- Estimated dilution at 5%;
- f).- Maximum grade of carbonate (gangue:calcite, etc.) is 3%;
- g).- pre-development between 0 and 1 year (pre-striping, haul roads.

Main items of equipment in the mine will be the following:

- Truck-mounted 165 mm (64) DTH drills;      - 9.9 m<sup>3</sup> (13 yd<sup>3</sup>) front-end loaders;
- 5.3 m<sup>3</sup> (7 yd<sup>3</sup>) front-end loaders,                      - trucks;                      - 300 hp tracked dozers;
- wheel dozer;    - 150 hp motor grader;      - service trucks

Mining operations are being planned on the basis of working three 8 h shifts/day for 25 days/month. The typical truck haulage distance to the primary crusher will be 850 m.

Pit planning has been carried out using diverse software on the basis of 5 x 5 x 5 and 10 x 10 x 10 block models and evaluated using a kriging package built into the program, giving an overall waste/ore ratio (including pre-stripping) of 0:1 in outcrop to 3:1.

## 5.2.- METALLURGY AND PLANT

Recovering copper from solutions via solvent extraction (SX) and electrowinning (EW) has had a great commercial development all over the world since Ranchers Exploration Company started its Bluebird project in Arizona in 1968 (Reghezza, 1993).

The leaching technology, SX-EW, has been adopted separately and at different times during the history of metallurgy in Chile which has reached an advanced stage of development and maturity.

In the leaching field, its origin dates from the beginning of the century in Chuquicamata, vat leaching followed by a direct electrowinning. Later, in the 1970s, low profile leach heaps have increased, the Lo Aguirre Project was the first step in adapting the Holmes and Narver technology of "Thin layer leaching" (TL) (Domic, 1989).

In 1987 the "Proyectos Ripios de Chuquicamata" reached its developed stage. The studies had been started at the beginning of 1970. The studies resulted in a complex development based on the irrigation of "parcels" of variable height between 80 and 120 m, with all the hydraulic problems associated with the project (directionality, running off and catchment of the solutions).

In the area of SX, the first experiments were conducted at Chuquicamata, at the beginning of 1970, based on the operations of its SX Plants of 1 and 50 GPM. At the end of 1980 the SX industrial Plant of Minera Pudahuel was started (Domic, 1989; Reghezza, 1993)

Between 1984 and 1987 the SX-EW Plants were installed: a.- El Teniente for the mines water treatment; b.- The secondary leaching SX-EW Plant of Lo Aguirre; c.- Minera Tocopilla Plant; d.- Minera La

Florida Plant, and e.- the great SX-EW Industrial Plant of Chuquicamata for a nominal production of <sup>78</sup> 250 tpd Cu.

Apart from the above mentioned features, the hydrometallurgy process presents other advantages such as the following;

- The process requires low investment
- The process is clean and does not interfere with the environment
- It is more flexible in terms of the variation of the price of copper
- The production costs are low.
- Large sulphuric acid quantities are consumed.
- Water resources are not consumed excessively. Moreover, sea water has been successfully utilized in these processes.
- The development of building materials has resulted in a decrease of investment required.
- The development of the chemical technologies has diminished the eventual monopoly of the supplier market.
- It has substantial flexibility and it can be applied to various materials of different contents and mineralogy in copper and virtually, in all sorts of sizes.
- The process is fairly versatile, thus it can be implemented in various technological units.

### 5.2.1.- LEACHING TECHNIQUES

The leaching methods can be divided into four categories.

- a) "In situ", Dump and heap leaching
- b) Vat leaching
- c) Agitation leaching
- d) Pressure leaching

The present lixiviation processes for copper bearing minerals are employed or being considered by the

mining companies for using in their feasibility studies. These are mentioned in a) and described below.

#### 5.2.1.1.- In situ, Dump and heap leaching

In situ, Dump and heap leaching are basically the same techniques. The material is fractured and the leaching solutions are added. The main requirements for these three methods is an impermeable base (natural or artificial) where the leaching solution can be recovered.

In **in situ leaching** there is no material removal and the technique can be applied to low grade deposits or to underground mines which have reached their end of exploitation. Andacollo (Concha et al, 1991) and Quetena in Chile are examples of this sort of operation.

**Dump leaching** is applied to low grade minerals that are left aside in the normal mine operations, generally in open pit methods. Huge profile leach heaps are built (millions of tons) and the leachate flow is periodically distributed over the surface and left to run off through the pile for a long time.

The **heap leaching** is similar to the dump leaching except that it is applied with major planning, technology and economic advantages. The minerals are piled in heaps of 1000 to 500000 tons with a smaller grading than the dump leaching. The lixiviation is continuous and substantially faster. The copper recovery of sulphured minerals present in the material is low because leach time is relatively low (100 - 180 days).

In the In-situ leaching, the impermeable base for the solution recovery is natural, e.g. clay strata which impedes drainage of the solutions. In the other two techniques, (dump and heap leaching), the impermeable base is artificial this constitutes a fundamental difference in the implementation. Therefore the economics of the process depend mostly on the total recovery of the leachate flow. Several materials can be considered for the construction of the impermeable base: polyethylene (0.25 to 0.5 mm thickness), rubber butilico (1/32' to 1/16" thickness) a mixture of waste, pebbles and lime or asphalt. Normally the base has a slope of 5° to facilitate the flow and the collection of the solutions.

### 5.2.1.2.- Heap leaching. General description

The Plant project considers the treatment of copper oxidized minerals, chalcocite, and scarce primary minerals of copper using any kind of water through the following stage of processes:

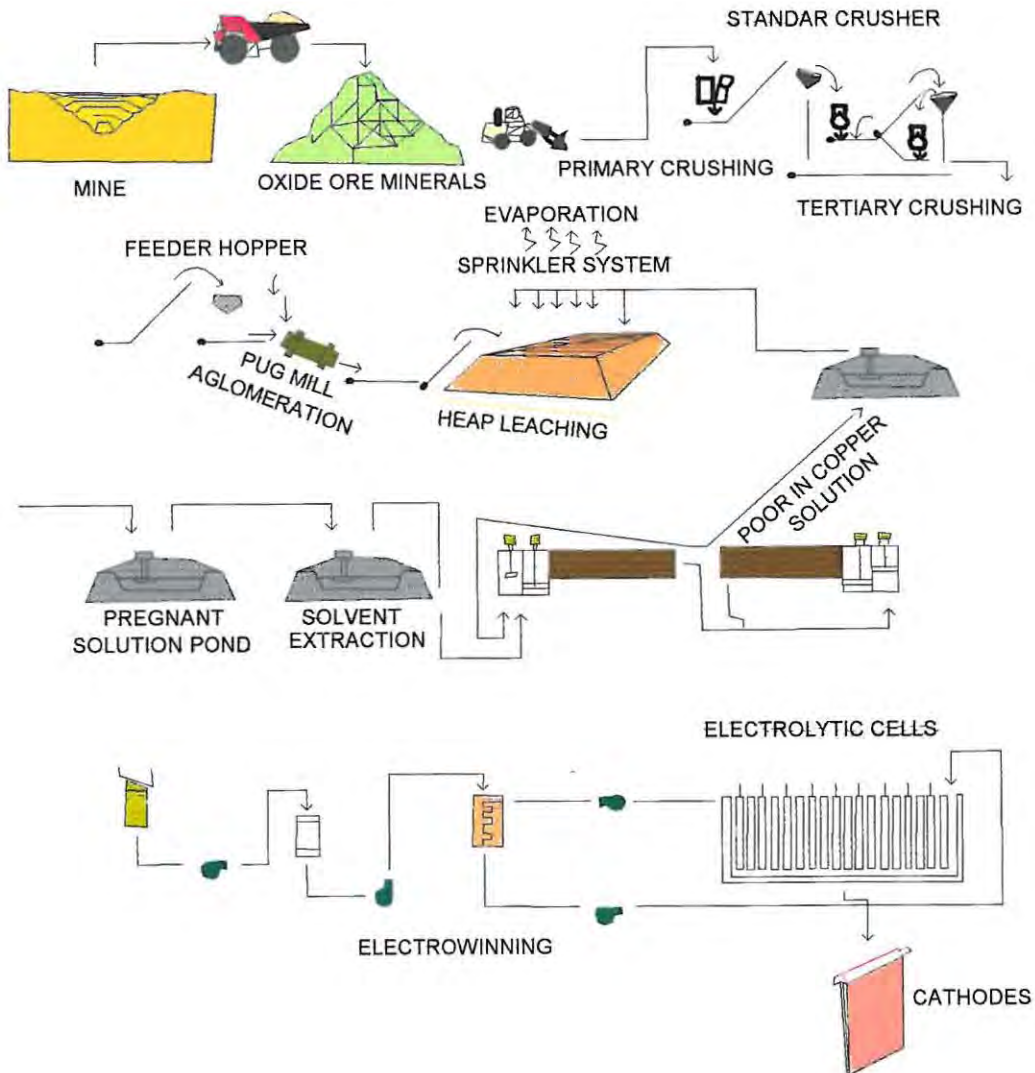
- reception of the minerals in a hopper
- three stages of crushing, the third stage operating in a closed circuit.
- leaching occurs through preconditioning (curing) the ore with concentrated sulphuric acid in agglomeration or "T.L." process, followed by a conventional heap leaching with diluted acid solutions;
- SX to extract the copper selectively, from the leachate flow through an organic phase, diluted acid solutions are returned to such circuit, and the copper is delivered to a strong electrolyte later.
- Electrowinning of the copper contained in the already mentioned electrolyte to produce high purity cathodes.

These stages are in general described according to Domic (1989, 1990), Chadwick (1994), Araya (1995). The mentioned metallurgical process is represented in the General Process Diagram. (Fig. 37).

In general, the results are summarized in overall recoveries higher than 85% from the oxidized mineralogical species and in acid consumption, because of the gangue, of the order of 35 to 37 kg/ton (discounting the acid consumed by the copper). The necessary operation time for the results is the function of the preconditioning (cured), heaps height and the regularity of the spraying (irrigation rate).

For project calculations, an estimated 65% - 82% of copper recovery and 37 - 40 kg/ton can be used as net acid consumption due to the ore. The leaching time is estimated as 30 to 45 days for heaps of 4,5 to 30 metres high. As a result of this, the plant capacity is determined by an annual equivalent of 10.000 to 25.000 ton Cu per year. (Reghezza, 1993; table 1)

FIG. 39.- ORE TREATMENT PLANT FLOWSHEET



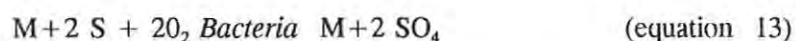
### 5.2.2.- Biometallurgy

*Thiobacillus ferrooxidans*, a bacterial species for the attack on the sulphur minerals was isolated and described by A.R. Colmer and M.E. Hinkle (1947) in Jarufe, (1987) late intensively studied throughout the world in order to be successfully utilized in industry.

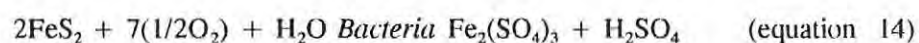
The biometallurgical processes are extremely important from the economic point of view. It is estimated that the biometallurgical extraction contributes nearly 8% to the world copper production annually (Jarufe, 1987). Another metal that is obtained by metallurgical degradation on an industrial scale is uranium. Both metals are lixiviated mainly from low grade sulphured minerals and minerals which are found close to the cut off.

#### Mechanisms of the bacterial oxidation of metallic sulphide (Jarube, 1987)

The microbiological lixiviation is an oxidation process in which the insoluble metallic sulphide is oxidized to soluble sulphate in an aqueous environment. So it is dissolution process (lixiviation) of the metal according to the following simplified equation:

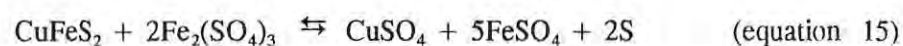


Where M is a divalent metal. For example, the present ferrous iron in the sulphur substratum is oxidized by the microorganism to ferric iron. It was shown that oxidation of the pyrite occurs in the following manner:

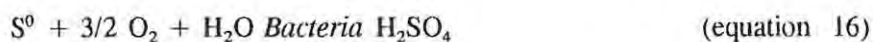


The ferric sulphate produced in this way is an oxidizing agent which contributes to the chemical lixiviation processes of sulphide minerals. Chalcopyrite oxidation occurs as follows:

For the chalcopyrite:



The elemental sulphur formed in the equations (15) is oxidized by the microorganism, like *Thiobacillus thiooxidans*, producing sulphuric acid in the following form:



The oxidizing bacteria of the iron and sulphur are known to be resistant or can adapt themselves to high metallic ion and acid concentrations (55 g/l of Cu). The optimum pH for certain bacteria vary between 1 and 3.5.

### 5.3.- INFRASTRUCTURE AND SERVICES

The Plant requires several infrastructure elements and support operation services. Major ones are briefly discussed below.

#### 5.3.1.- Water

The brackish water can be a resource of process water for the lixiviation with average requirement of 0.40 m<sup>3</sup> per ton of ore minerals. It is possible to employ brackish water just up to the stages prior to electrolysis. The water will be lost by 12 to 14% in the residual moisture in the final waste and 25 to 30% through filtration and evaporation. Some water occurring as moisture in the residual material in the leach heaps (12% to 14%) and 25% to 30% of the circulating can be lost through evaporation

Fresh water is very difficult to get (for supply) and is used to obtain the electrolyte for the SX stage of cleanliness; (the water will be used to wash the organic reagent). Thus it is possible to stop the transfer of chlorine from the leachate flow to the electrolyte which at the same time presents a maximum tolerance of between 30 to 100 ppm of total chlorine. Fresh water consumption requirements are  $\pm$  180 m<sup>3</sup> per day.

In order to get fresh water, an installation of a desalinating unit by reverse osmosis or vacuum distillation can be seen as a good alternative.

### 5.3.2.- Sulphuric acid supply

In the Plants sulphuric acid requirements are variable, depending on the ore minerals, gangue and copper grades. However, the acid average consumption has been estimated between 30 and 40 kg/ton, that is to say  $\pm 170$  ton acid per day. The minimum which must be stored is the quantity required for a month's operation, ( $\pm 5100$  ton). It will be transported by trucks to tank of reception and storage.

Table 18 (Fortin, 1991) shows potential supply and demand and indicates the existence of large projects of acid sulphuric consumption in Chile according to the political divisions of the country. If all the projects are developed, beginning in 1994, an important deficit of sulphuric acid by the years 1995-1996 will occur. Sulphuric acid is formed of sulphur (57%), melting gas (24%) and pyrite (19%).

The exotic Codelco deposits (Mina Sur and Damiana) can obtain sulphuric acid from Chuquicamata Smelting. It is being planned to build a sulphuric acid plant in El Salvador due to the environmental restrictions.

Sulphuric acid prices in Chile vary according to the location of the producing source, e.g.

	US\$/Ton
Tocopilla -Chuquicamata	70-90
Fundicion H.V. Lira	40-65
Fundicion Ventanas-Chagres	60-120

An importation price put in Tocopilla, Michilla, and San Antonio ranges between 80 to 100 US\$/Ton including duties, shipping charges, and storage.

### 5.3.3.- Electrical energy

It is quite usual for most of the mining projects to obtain electrical energy from the northern energy system (Sistema Interconectado del Norte Grande, SING). Connection will be made at the unique national red, from which comes all the substations, that serves all the demands of the northern zone of

TABLE 18- POTENTIAL SUPPLY AND DEMAND OF SULPHURIC ACID CONSUMPTION (x 1000 TON)  
IN CHILE, ACCORDING TO THE POLITICAL DIVISIONS (Fortin, 1991).

YEAR	1991	1992	1993	1994	1995	1996	1997	1998/2000
I REGION								
SUPPLY	113	113	113	113	113	8	8	8
DEMAND	124	117	143	174	174	104	164	164
SURPLUS - DEFICIT	-11	-4	-30	-61	-61	-96	-156	-156
II REGION								
SUPPLY	695	770	890	890	1090	1600	1840	1840
DEMAND	779	841	920	1213	1485	1475	1055	1955
SURPLUS - DEFICIT	-84	-71	-30	-323	-395	215	-115	-115
III REGION								
SUPPLY	47	44	75	86	86	166	166	166
DEMAND	63	63	119	145	193	193	193	193
SURPLUS - DEFICIT	-16	-19	-44	-59	-107	-27	-27	-27
IV REGION								
SUPPLY	0	0	0	0	0	0	0	0
DEMAND	20	21	20	60	60	60	60	60
EXCEDENTE-DEFICIT	-20	-21	-20	-60	-60	-60	-60	-60
V REGION								
SUPPLY	223	277	372	372	542	542	542	542
DEMAND	13	18	55	72	82	282	282	282
SURPLUS - DEFICIT	210	259	317	300	460	260	260	260
REGION METROPOLITANA								
SUPPLY	0	0	10	30	30	30	30	30
DEMAND	86	87	100	100	100	55	55	55
SURPLUS - DEFICIT	-86	-87	-90	-70	-70	-25	-25	-25
VI REGION								
SUPPLY	27	30	30	30	230	480	480	480
DEMAND	58	60	60	100	100	100	100	100
SURPLUS - DEFICIT	-31	-30	-30	-70	130	380	380	380
VII - VIII REGIONES								
SUPPLY	0	0	0	0	0	0	0	0
DEMAND	24	37	37	37	37	137	137	137
SURPLUS - DEFICIT	-24	-37	-37	-37	-37	-137	-137	-137
TOTAL SUPPLY	1105	1234	1490	1521	2091	2916	3066	3066
TOTAL DEMAND	1167	1244	1454	1901	2231	2406	2946	2946
SURPLUS - DEFICIT COUNTRY	-62	-10	36	-380	-140	510	120	120

Chile. Generally 110 kV, 10000 kW power line can be built for the projects.

#### 5.3.4.- Camp, access and auxiliary installations

The location of the mine and plant sites are associated with the porphyry copper deposit in production, and established facilities can be used for this. Thus there is no need to build a new mine camp or access to one. In some deposits e.g. Damiana, the existing access roads have been modified since they were in the centre and borders of the exotic deposit.

For the services of the mine and the plant, the following facilities have been considered: an administrative office, dining halls, metallurgical and assay laboratory, warehouse, workshops. Most of these installations are located in the Plant site and they are properly equipped.

#### 5.4.- ENVIRONMENTAL IMPACT

The study of the environmental impact is summarized in environmental variables of physical, biological and socio-cultural characteristics related with the zona of work using the frame work of the **BASE LINE** study and the **IMPACT EVALUATION** derived from the Construction and Project Operation phases. The conclusions and recommendations will diminish, mitigate and/or eliminate impact which results from the specific activities.

**BASE LINE** : The base line is divided into two zones, which are differentiated according to the intensity of the demand on the environmental variables: **A).- Area of Direct Influence (ADI)**: Is the area that is directly influenced by the engineering infrastructure, mine-plant and the process exploitation-metallurgic during the mine life. **B).- Area of Indirect Influence (AII)**: It has been considered to estimate the significance of the starting of the Project about the variables of a regional character, which have to deal as with the labor demand, infrastructure and services demand.

To carry out an enviromental study the elemental parameters are: **Climate, Fauna, Flora and hydrogeology** (underground, superficial continental and sea water).

**IMPACT EVALUATION:** At this point the measurements and evaluation of the variables that would cause some disturbance in the different operations which the project will include will be considered. These variables are: **Direction and Speed of the wind; Seismic activity; Inundations; Acid Solutions; Combustible and acids; Catchment of sea water; Abandonment Plan**

#### 5.4.1.- Specific actions.

The projects comprise four big areas of daily work which must be operable during the whole useful life of the mine, so specific actions are necessary in order to improve the labor conditions, restore the environment and thus regenerate the vegetation and animal species.

**A).- Opencast :** during the mine exploitation, studies of the slope stabilities and rock mechanic will be permanently carried out in order to keep or to enhance the stability levels in the walls of the excavation. Thus in the abandonment phase, the final slopes will be secure.

**B).- Heap leaching and waste:** the chutes built to collect the solutions will be fitted in such a way that they could last longer for collecting rain water. The berm built in the superior perimeter of the heap will be used in order to prevent rain water running off over the slope and eroding them. Thus, the rain water will run off in a controlled way and the rain water that remains in the surface will tend to evaporate.

**C).- Plant :** It is proposed to take structures and additional element off from the buildings and plant installation removing the interior ways which are not going to be used as future access. In relation to machinery, pipes, tanks and structures, there will be taken away from the place, leaving the surface in such a condition to permit the regeneration of vegetation and animal species that usually live in the area.

**D).- Drainage of solutions and storage:** the solutions which will keep on drainig for a estimated period of 1 to 2 years will be left connected to the pool of rich solution which will be properly protected and from where the solution will evaporate thus impeding its free running off.

## CONCLUSIONS

The genesis of the Chilean exotic deposits, described in this dissertation, are considered to be dependent upon the existence of the cal-alkaline porphyry mother deposits, originated by the lateral migration of the solutions that overflowed during the secondary enrichment process.

The climatic necessities for the leaching and transportation of copper minerals seem to have been ubiquitous in northern Chile during much of the Cenozoic, prior to the present regime of non-leaching in an extremely arid situation which permitted the conservation of exotic deposits.

The narrow relationship of host rocks of exotic deposit, described above, supports the idea that the formation of such deposits in the Central Andes is directly related to the compressive tectonic that was produced by the Andes Mountain range in the Oligocene Superior-Miocene Inferior (Mortimer, 1977; Makshev and Zentilli, 1994; Munchmeyer, 1994). A product of the denudation generated by this upheaval includes the gravel of Atacama, Calama Formation, and the sedimentary members of the Formation Altos de Pica (Munchmeyer, 1994). The resulting erosion controlled the formation of palaeorelief and caused the subterranean water to fluctuate, favouring the formation of the enriched horizons and the subsequent exotic deposits as a result of the lateral migration of acid solutions rich in copper.

These conditions predominated in the northern part of the Chilean territory and in the south of Peru, approximately between latitudes 15° and 27° south. According to present knowledge, it is estimated that the period of supergene enrichment of the porphyry copper occurred approximately between 23 and 14 Ma (Mortimer, 1977; Arias, 1985; Makshev and Zentilli, 1994; Munchmeyer, 1994). In parts of the territory, this period overlaps (between the 16.5 and 8.0 Ma) with the accumulation of large horizontal layers of gravel that fill the frontal tectonic basins. This was terminated locally by the deposition of extensive levels of ignimbrites which sealed the supergene activity.

The lateral copper transport in acid solutions originated from the lixiviation in the primary sources of copper sulphide drain by structures (faults, discordance, fractures), porosity, permeability, changes in

the pH of the rock, and in many examples is helped by the topographic slope. As a result of the lateral migration of the copper-bearing solutions, the exotic deposits show a zonation, alteration and mineralization whose characteristics depend, among other factors, on the reactivity of the bedrock and the Cu/S ratio of the mother deposit. In these deposits three zones can be recognized: Proximal (0 to 2 km), Intermediate (2 to 3) and Distal (3 to 8-14) with palaeodrainage control.

In all the well-known examples of exotic deposits, the mineralization of oxide of copper minerals occurs by cementing alluvial gravels and less often recovering the layers of fractures of the bedrock where this gravel is lying.

The underlying, lateral or distal disposition down water of the fresh rocks and those mineralized with chrysocolla respect to the kaolinized and mineralized span with "copper wad" nearer to the resource is consequent with the fact that the silica has been previously leached from the kaolinized rocks, facilitating the incorporation of silica to the solution, so later it can be deposited as chrysocolla and in minor grade associated to copper pitch and locally atacamite and malachite, in increasing conditions of pH and in an environment predominately alkaline.

The geomorphologic conditions and the reactivity of the bedrock determine the form of the resulting exotic deposits, which may be grouped into three distinctive types.

The first group is constituted by the formed deposits along palaeochannels such as: Sagasca, Quebrada Blanca, Huinquintipa, Ujina, Lagarto and Mina Sur. What is determined in these cases is the notable control of the mineralization for the palaeodrainage, in such a way that the final results are tabular bodies, of reduced size in section but that usually ranges from hundreds of metres up to about eight kilometres long.

The second differentiated types for its morphology are the fan-shaped deposits which are formed in the skirts of the topographic elevation which content the mother deposits. Damiana and El Tesoro are important examples of this group. The orebodies cover a great areal extension, of the order of square kilometres and relatively reduced thickness of the order of ten of metres.

Finally, the third group is formed by irregular deposits, of which a typical case is the Ichuno deposit, associated with the porphyry copper of El Abra, which occurs in part of its extension strongly controlled by subhorizontal structures, so that it conforms a lens whose three dimensions, of the order of hundreds of metres, is very similar.

The size of the "exotic" deposits varies considerably. Thirteen deposits are now recognized which range from those of very small size (100 to 10.000-ton Cu), medium size (160.000 to 400.000-ton Cu) and to the bigger deposits (1.200.000 to 3.500.000-ton Cu). The total amount of reserves plus production that is known is of about eight million tons of fine Cu. If these ranges of reserves are compared with the porphyry copper, it may be concluded that the big exotic deposits are comparable to the reserves of a deposit of medium size of porphyry copper type.

Usually, the propylitic halo of the porphyries copper are superimposed to a low grade metamorphism, which is fundamental for the copper fixation, when existing a bigger amount of calcite (carbonates).

Metallurgical groups were formed according to ore minerals, gangue, and clay minerals. The initial metallurgical samples contemplated natural moisture, sulphuric acid consumption, maximum superficial water catchment and agglomeration/cured with sulphuric acid.

Laboratory tests in a pilot scale showed successful metallurgical results, specially when the chrysocolla cements the matrix of the gravel and when it is scarce in the altered gravel contenting "copper wad" and atacamite in disseminated thin film. The conclusions indicate that the recovery varies between 60 and 92%, however a previous cured is needed to lower the high acid consumptions in some samples. The kinetic of lixiviation shows that in 20 days the > 65% of the copper is recovered and that 170 days between 80% and 92% can be achieved (Carrasco and Rojas, 1993; CIMM,1994). The samples with problems are those containing copper wad-clay minerals, malachite and calcite.

In some deposits two important units are detected and they are: the Cu-phosphates and Cu-lixiviable units (to the sulphuric acid). Examples of these units are found in Damiana. These units are two different geostatistical population, so they must be studied separately.

The Cu-lixivable units evaluation is more complicated than the enrichment zones of a normal porphyry copper, which hardly presents coefficient of variation superior to 60% and less complicated than epithermal of Au/Ag which present coefficient of variation superior to 150%.

Being realistic the supposed employed in the economic analysis, it can be say that the Lixivable Unit is a good business. The Cu-phosphates, even when supposing that this unit does not need investment and employing a rate of nulli actualization and a high price (1 US\$/lb) this unit is far from being economic

For an exploration of exotic deposits, a mass balance of the leached columns and the size de las alteraciones phyllic and potassic in the porphyry copper must be considered. Moreover, lithology of the propylitic halo, permeability, drainage and palaeodrainage, major structures, fractures, joints, zonation of clay minerals. Geophysics to determine bedrock, major structures, thickness of the gravels, etc; geochemistry for copper, gold, uranium and mobil elements as for example: Zn, Mn, Pb and Ag. The uranium in this deposits ranges from very scarce to non existent. In practice, geophysic based on uranium is rarely done.

The projects are for the exploitation of reserves by open pit methods. The projects plan to extract, to crush copper oxide ore which will be pre-treated with concentrated sulphuric acid prior to heap leaching, solvent extraction and electrowinning. The copper output varies between 10000 to 50000 ton per year of cathode copper. The total investment varies between 20 to 100 millions dollars with a variable cost between 0.43 and 0.60 US\$/lb (Reghezza,1993) and sulphuric acid prices between 40 and 120 US\$/ton.

The location of the mine and plant sites are associated with the porphyry copper in production, and already installed facilitates can be used for this.

The environment impact is summarized relating to the characterization of the physical, biological and socio-cultural effects, using the framework of the Base Line study and the Impact evaluation derived from the construction and project operation phases. The conclusions and recommendations will diminish, mitigate and/or eliminate impact derived from the specific activities.

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## APPENDIX 1 .- RELEVANT EXAMPLES OF EXOTIC DEPOSITS

### Larger Deposits

#### Mina Sur (Figs. 1, 23, 27 and 40)

There are various descriptions and detailed geological surveys of this deposit, such as Newberg (1967), Munchmeyer and Urqueta (1974), Mortimer, et al (1977), Fam (1979) and Munchmeyer (1995). This study includes only a summary of exotic deposit and age of the geological events that took part in the formation of the deposit are emphasized.

This lenticular mineralized area begins at the head of a paleodrainage located at the divide over the central portion of the Chuquicamata mine and extends southwards with a slope of 3 to 7 degrees for about 6 to 7 km. Its northern end outcrops within the Chuquicamata mine and its southern end is under 200 metres of barren gravels ( Fig. 40). This relationship and other considerations indicate the Chuquicamata porphyry copper deposit as source for copper in the Mina Sur deposit.

The bedrock in the deposit corresponds to a complex of Paleozoic metamorphic rocks (Renzetti, 1957) in contact with a sequence of Mesozoic stratified volcanic rocks by the West Fault. The metamorphic rocks are propylitically altered to an assemblage with calcite, chlorite, epidote and pyrite. Erosion formed a paleochannel whose first 3 km are tightly confined and situated adjacent to the West Fault. Between 3 and 5 km the paleochannel curves and had gentler slopes, again becoming narrowly confined over the last 2 km, possibly following the course of a fault running parallel to the West Fault.

The gravel cover consists of two interlayered units that corresponds to slope talis and mud flows. a K-Ar date of volcanic ash deposited on sedimentary unit indicates a minimum age of 8.4 Ma. (Munchmeyer and Urqueta, 1974).

The copper mineralization is deposited in the basal part of the gravels and conforms to the palaeochannel, forming a lenticular sinusoidal body with a maximum width of 1.2 km and a maximum thickness of 110 m. with the cross section presenting a horizontal, upper surface and a lower irregular, concave surface conforming to the channel base.

The copper minerals that form the ore in increasing order of abundance chrysocolla, copper wad and atacamite. Their distribution is intimately related to the clay alteration of the host rocks and is

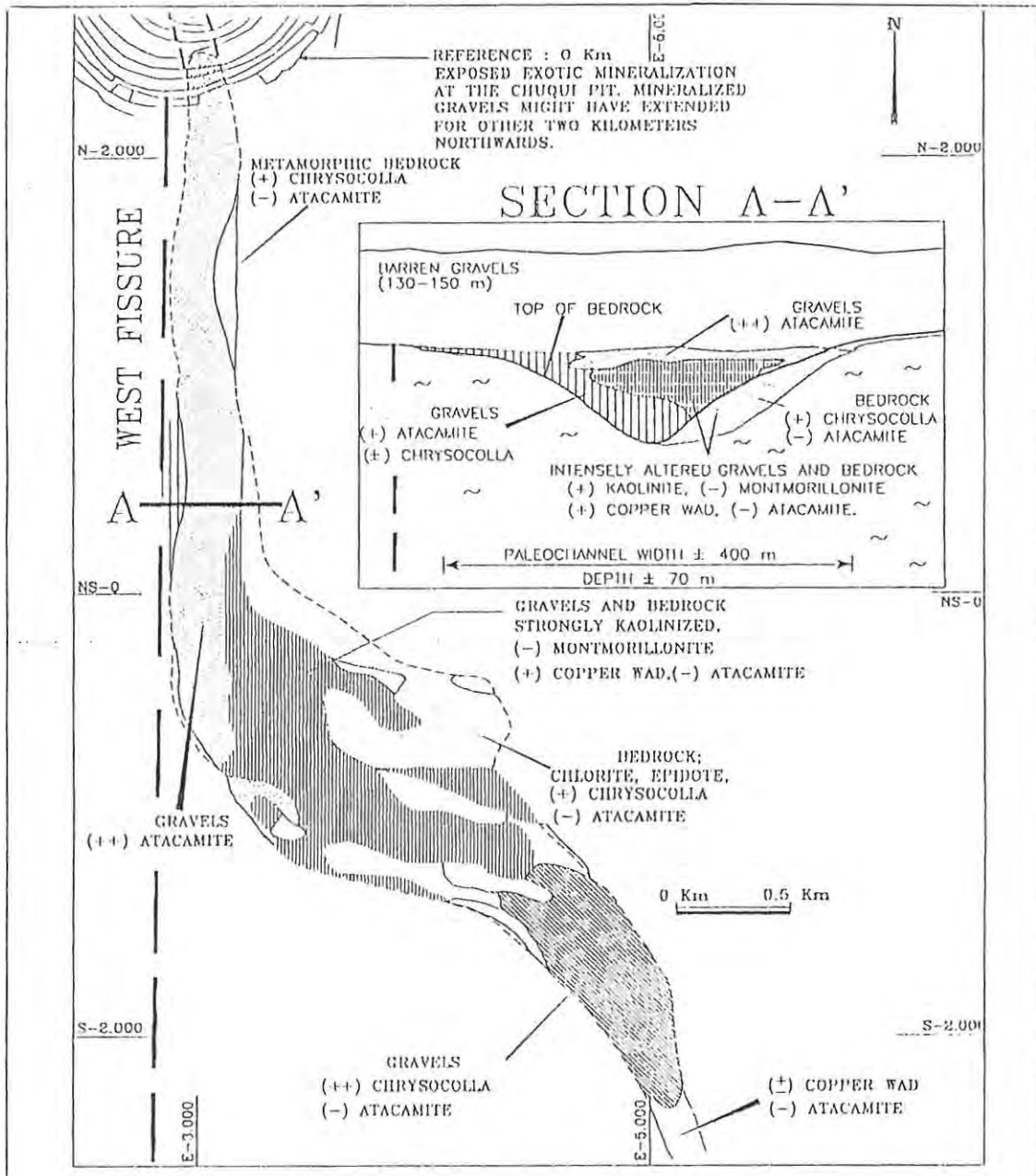


Fig. 40.- Sketch of the Mina Sur showing a) From Chuquicamata the mineralization extends continuously for 6.5 Km; b) The important mineralization in the mine rocks ends at 5 km but occurs in lesser amounts 1,5 km in the gravel channels; c) Two thirds of the ore occurs in the curvature and area of widening of the paleochannel; d) In the gravels atacamite predominates up to 4.5 km from source and then chrysocollas predominates up to 6.5 km; e) The gravels in the deposit are partially altered to kaolin and mineralized with copper wad between 0 and 5 km; f) The fresh rock mineralized with chrysocolla extends from 0 to 5 km. (Munchmeyer, 1995).

characterized by kaolin and montmorillonite. In fresh rocks there is a predominance of chrysocolla over atacamite and copper wad, in contrast with the strongly kaolinized rocks where chrysocolla is absent and copper wad and atacamite were deposited. As shown in figure 2, the association of alteration/mineralization is well defined and makes it possible to relate their occurrence with distance from the Chuquicamata deposit.

Radomiro Tomic (Munchmeyer, 1995) (Figs. 1 and 41)

As can be seen from figure 41, the Chuquicamata deposit coincides with the topographic divide that controls the deposition of host gravels of Mina Sur to the south.

The Radomiro Tomic mega-deposit extends at least 7.5 km to the north from Chuquicamata, has width up to 1.5 km, a zone of oxidation up to 300 m thick and a secondary enrichment 50 to 200 m thick overlaying primary sulphides.

The host gravels fill a palaeochannel, along the extent of which there is a continuous gravel cover containing exotic copper mineralization that is to 30 m thick up to 300 wide and has been traced over a distance of 2.5 km north-south direction.

Apart from the exotic copper in the gravels there is evidence that the copper in the oxidized zone overlaying the primary and secondary sulphides is largely transported. Four to six degrees of general inclination due north of the copper oxide orebody indicates that transport has been mainly lateral, of the type found in exotic deposits. The copper source may be an earlier secondary blanket or a combination of the original secondary blanket and the copper originating from a redissolution of the enrichment and/or oxide zone of the Chuquicamata deposit which migrated northward and precipitated at least as the oxidized part of the R. Tomic copper deposit

The R. Tomic copper mineralogy consists of atacamite, clay with atacamite, chrysocolla, copper wad and turquoise, all minerals that normally characterize exotic mineralization. The clay alteration associated with copper is in turn a common feature of exotic deposit. In this particular case clay mineralogy on the basis of XRD studies consists of smectite with lesser amounts of kaolinite.

The lateral flow of solutions in the palaeodrainage produced simultaneous formation of mineralization in gravels in the Chuquicamata area, with the formation of the Mina Sur deposit and at least part of the R. Tomic oxidized zone. The exogene mineralization contrast with the above because of the

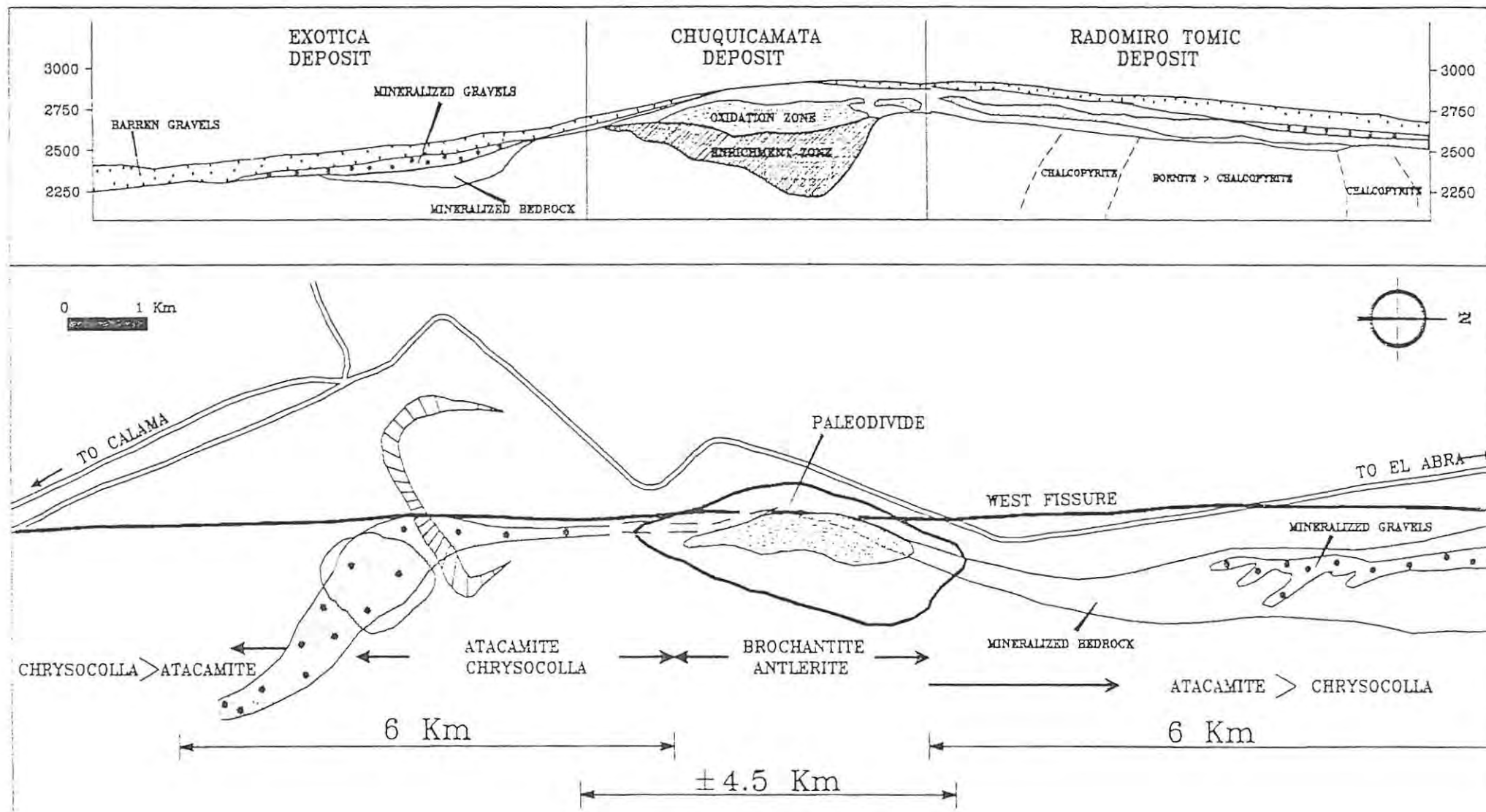


Fig. 41.- Longitudinal schematic profile of approximately 15 Km, North-South section which displays the relationship between Mina Sur/ Chuquicamata/ Radomiro Tomic deposits. The Chuquicamata deposit occupies the site of the paleodivide to the south Chuquicamata, the accumulation of gravels and the exogene mineralization of Mina Sur and to the north, the gravels and mineralization the Radomiro Tomic zone. On a district scale the copper mineralization displays the zoning indicated. (Munchmeyer, 1995).

predominant content of atacamite versus copper sulphates, like antlerite and brochantite.

Damiana and Quebrada M (Carrasco and Rojas, 1993; Rojas and Muller, 1994) (Figs. 19, 20, 21 and 42)

Damiana is an exotic deposit which occurs in the area immediately west of the cerro Indio Muerto at the El Salvador mine and underlies the plain between the camp and the mine. It forms a layer slightly inclined to the west which has a surface area of 3.4 x 2.2 km. It has an average thickness of 23 metres with an overburden of 20 metres. (Fig. 42)

According to Carrasco and Rojas (1993), the Damiana deposit is situated mainly in andesite volcanoclastic rocks of the lower Cretaceous Llanta Formation. A smaller part of the mineralization occurs in nearby cineritic flows the Domo del Indio Muerto of palaeocene-lower Eocene age and in gravels that fill the palaeochannels cutting a Miocene peneplain which formed on the Cretaceous andesites. The deposit is partially covered by unconsolidated Quaternary deposits.

In a nearby area to the El Salvador porphyry copper deposit, thin films of chalcocite mineralization of an exotic nature has been described associated with pyrite (Carrasco and Rojas op.cit.). In this occurrence, turquoise mineralization is associated with lenticular bodies of kaolinized volcanic tuffs. The predominant copper minerals are principally chrysocolla with lesser amount of copper wad, occurring in the propylitized andesites and in the gravel fields in the paleochannels.

As can be seen from Fig. 42 there was a lateral flow of solution to the north of the zone with secondary enrichment, producing the Quebrada M exotic deposit. Its origin is interpreted to be from solutions from one of the El Salvador deposit centers being preferentially controlled by a structural system. The resulting mineralization is ochreous material and pyritic on which thin films of chalcocite have been deposited.

El Tesoro (Munchmeyer, 1995) (Figs. 1 and 43)

El Tesoro is an exotic type deposit hosted in Tertiary gravels. The copper mineralization extends over an area of 5 x 2.5 km ( Fig. 43). The area is situated adjacent to a series of alteration zones which occur along tens of km in a north-south direction. The gravels containing the exotic mineralization are partially covered by barren gravels and a layer of volcanic ash. An age of 10 Ma. has been obtained in these hosts which provided a minimum age for the adjacent mineralized gravels (Munchmeyer, 1995).

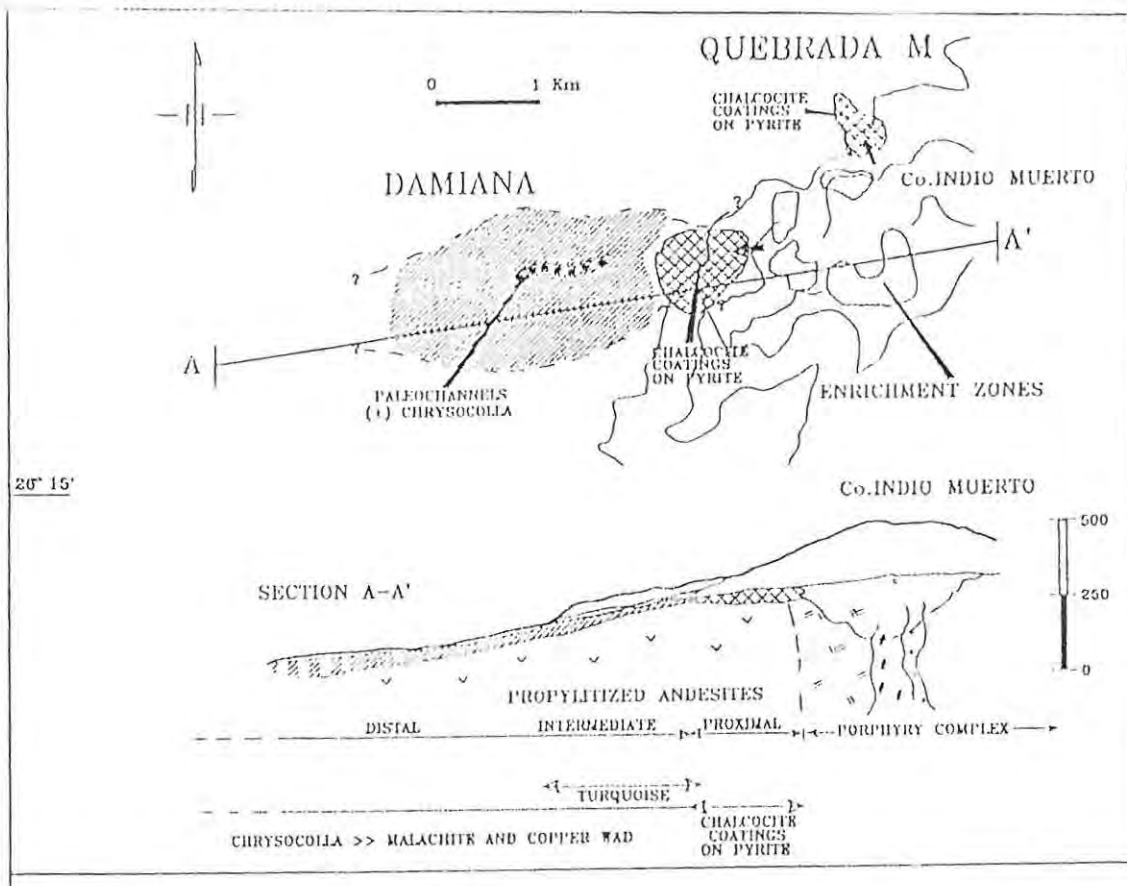


Fig. 42.- Sketch of the Damiana deposits and its relationship with the El Salvador copper porphyry (Cerro Indio Muerto) showing the large areal extent occupied by the exotic deposit. The surface area is approximately 3.4 x 2.2 Km. In the immediate area of the porphyry deposit chalcocite precipitation as films on pyrite of the porphyry halo (Munchmeyer, 1995).

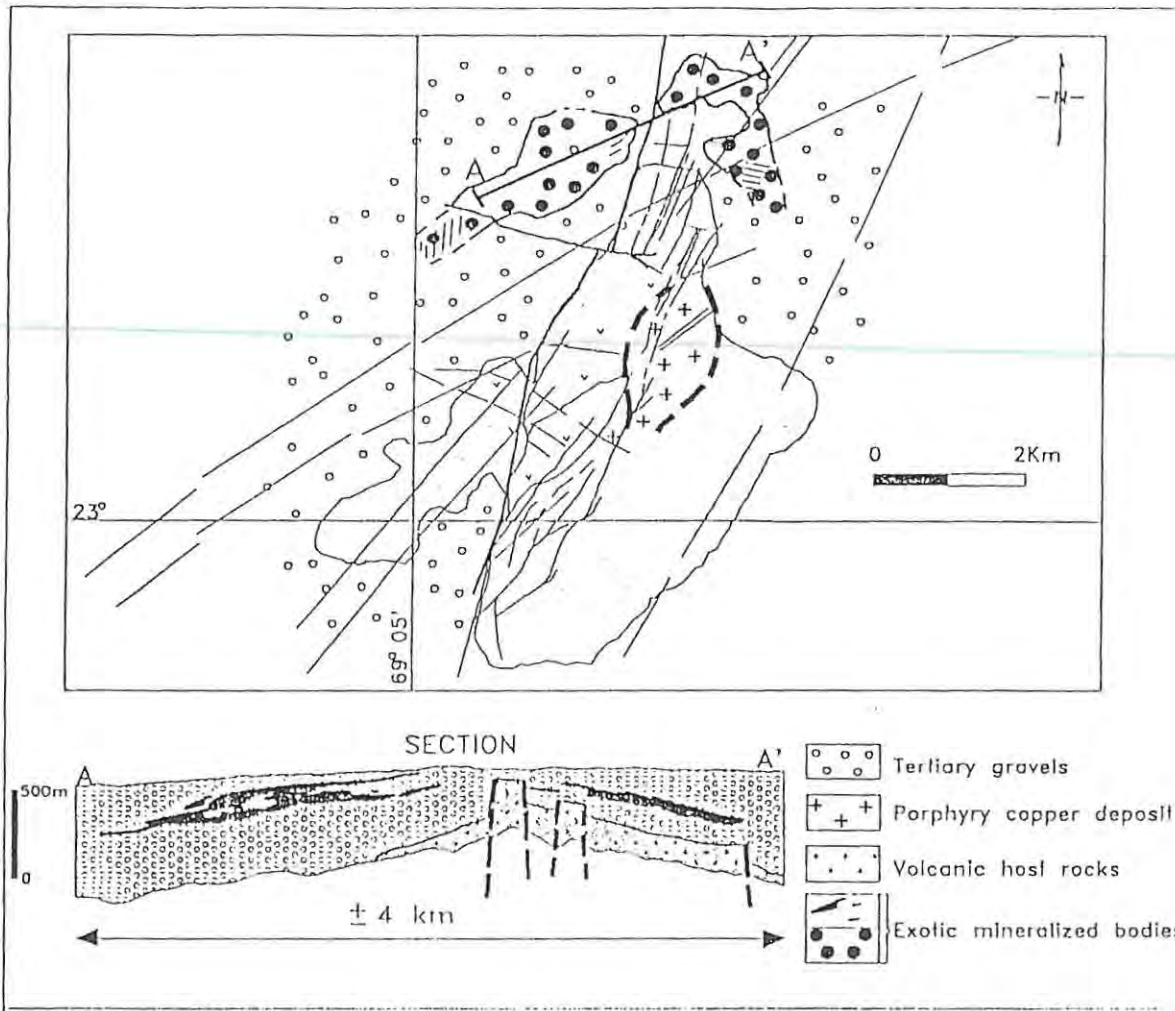


Fig. 43.- Sketch of the El Tesoro deposit, modified from Muhr and Mora (in prep.), showing the semi-circular layout of the exotic coverings around the northern and of the paleotopographical high wich is of tectonic origin. The extension covered by the zone mineralized with exotic copper and the presence of the porphyry copper mineralization in the district must be noted. (Munchmeyer, 1995).

In the area of the El Tesoro mine there is a buried paleorelif covered by 350 to 800 metres of gravels. The accumulation of conglomerates and arenite correspond to what has been interpreted as an extensive fan conglomerate distributed around the apex of paleotopographical high.

The deposit consists of several mineralized occurrences 10 to 50 m thick, contained within sediments which are locally up to hundreds of meters thick and contain iron oxides and copper impregnations. The tabular occurrences have a dip between 10 to 20 degrees and apparently conform to the semiconcentric nature of a debris zones (Muhr and Mora, 1995 in Munchmeyer, 1995).

The mineralogy consists principally of chrysocolla and atacamite as impregnations in the conglomerate matrix. It is common that the mineralized conglomerate contains fragments and rounded clasts of sericitized quartz porphyry, belonging to the assumed porphyry copper source.

The deposit is affected by block tectonics which generated the paleotopographical high referred. Locally, the andesitic rocks exposed at the surface are biotitized, implying proximity to a porphyry copper deposit. These altered rocks appear to represent remnants of a porphyry system displaced by faulting.

The fact that these source deposits display extensive zones of potassic alteration, sparse development of late veins zones, telescoped sericitization, hydrothermal breccias and other characteristics of mineralization, suggest that they have been subjected to deep erosion as these characteristics corresponds to the deep, more central zones of porphyry systems.

### **Medium Deposits**

Sagasca (Munchmeyer, 1995) (Figs. 1 and 44)

The lenticular, mineralized, sub-horizontal body of Sagasca is approximately 4 km long, up to 400 m wide and 70 m thick. It is located some 200 m beneath an extensive pediplain of Miocene age. The deposit is exposed near the base of the Sagasca valley as a result of the deep erosion. The erosion exposes andesites along 3.5 km, which are overlain by discordant sedimentary and volcanic cover of the Altos de Pica Formation (Fig. 44). The andesite rocks correspond to the Cerro Empexa Formation of Paleocene age. The ignimbrite of the Altos de Pica Formation have been locally dated at 17.4 Ma. (Vergara et. al., 1986), which indicates a minimum age for the underlying conglomerates that conforms the host rock of the copper mineralization.

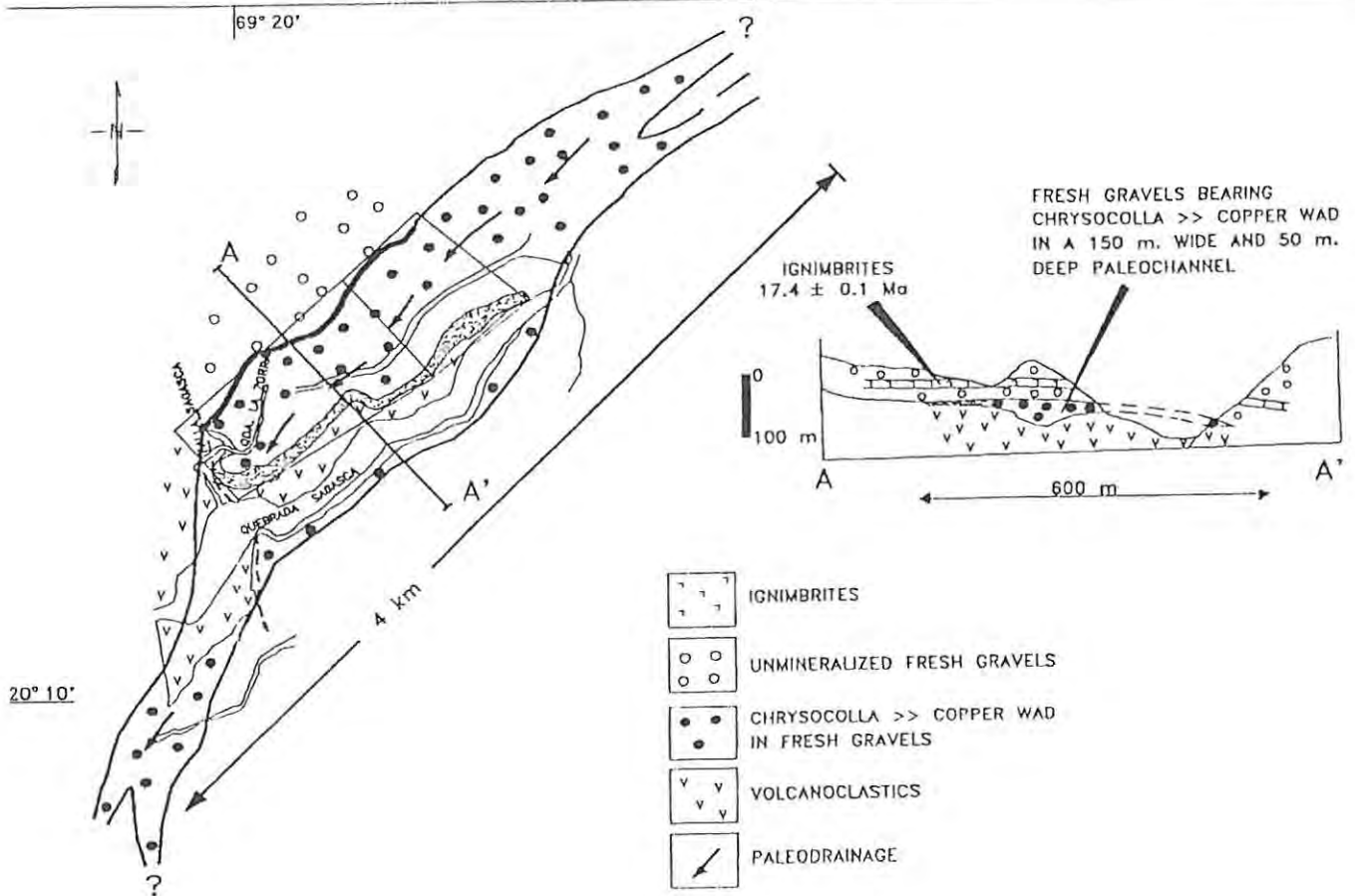


Fig. 44.- Geological sketch of the Sagasca deposit for which the source of the copper has not been located. Along 4 Km the copper mineralization consists of chrysocolla, lesser amounts of copper wad contained in fresh gravels or gravels with sparse clay alteration, suggesting and intermediate to distal location with respect to the source (Munchmeyer, 1995).

The deposit consists of a stratified body immediately above the bedrock. There is no significant mineralization in the andesitic debrocks. The location of the body is controlled by a paleochannel sloping gently to the southwest and ranges between 100 and 150 m wide and 20 to 50 m deep. The predominate copper mineral is chrysoicolla, which occurs in the matrix of the conglomerate, accompanied by copper wad and gypsum. The conglomerate is predominantly of andesitic composition and contains occasional leached, altered, white fragments. These fragments may correspond to a quartz porphyry of the source deposit.

The mineralized conglomerates have copper mineralization deposited in bedding planes which are locally eroded and truncated which results in angular discordance with the immediately overlaying, barren conglomerate. This indicates a close contemporaneity between the host gravels deposition and the copper precipitation from solutions as chrysocolla.

Huinquintipa (Munchmeyer, 1995) (Fig. 1, 22 and 45)

In the Collahuasi district remnants of gravels filling paleochannels and small basins are present, corresponding to the paleosurface developed during the Miocene period. The paleodrainage was from east to west with gravel being transported from the east. In intervals of these paleochannels, the gravels are impregnated with copper mineralization producing exotic copper deposits, originally continuous, but subsequently interrupted by the erosion from present drainage (Munchmeyer, 1984) (Fig. 22, 23 and 45).

The remnants with exotic copper, whether in gravels or in what was the bedrock of the paleochannels, can be reconstructed along 6 km upstream to the Rosario copper porphyry deposit. A second branch of the paleodrainage leads to the area known as San Nicolas, where recognized mineralization is related to important structural systems. Mineralization consists of associated enargite, tennantite, bornite, chalcopyrite, and pyrite with minerals of secondary enrichment origins. As shown in Figure 45, the two paleochannels coalesce in the channel called Huinquintipa and produce the widest and best mineralized area of the paleochannels.

The mineralized body of Huinquintipa is situated approximately 6 km in a straight line to the west of the Rosario copper porphyry deposit. The mineralized layer of Huinquintipa is one km long 150m wide and about 10 m in average thickness.

In the Collahuasi district there is an excellent opportunity to observe a zoning of alteration and mineralization as the paleodrainage runs 6 km from the copper source. The solutions percolated

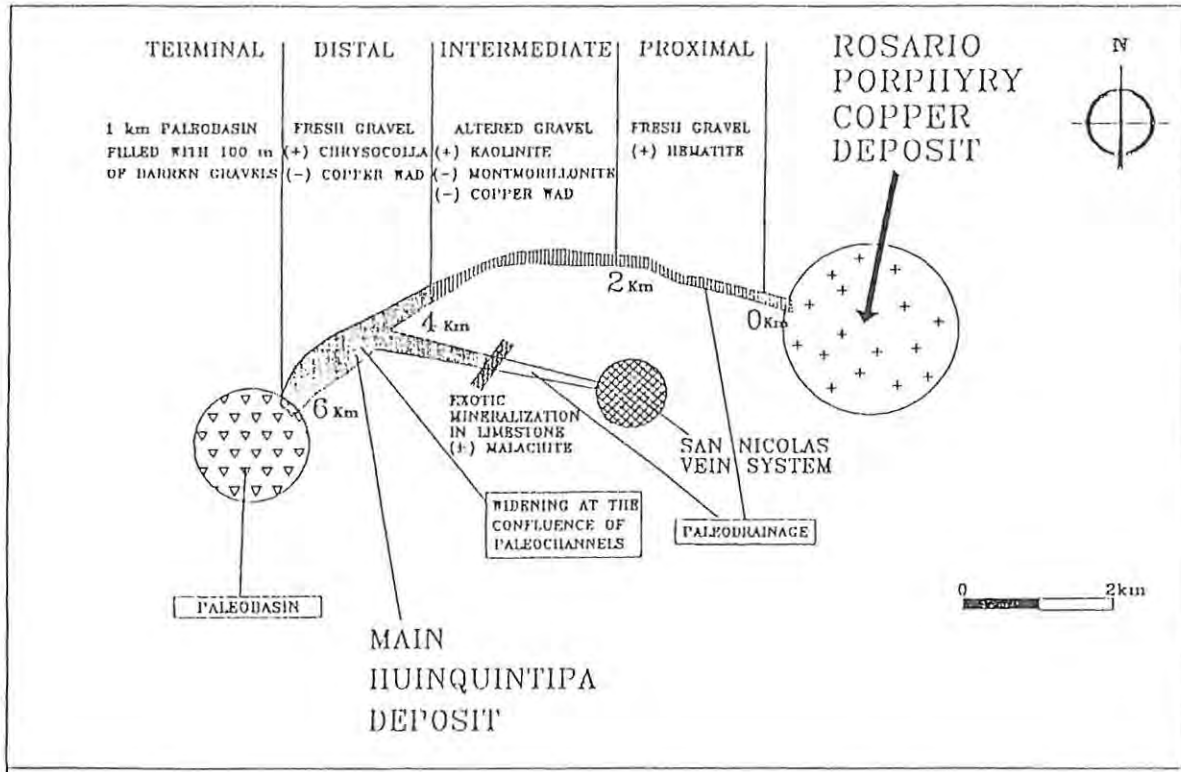


Fig. 45.- Geological sketch of Huinquentipa showing a) The reconstitution of the paleodrainage which makes it possible to trace the exotic mineralization and related alteration upstream to the Rosario porphyry copper, an overall length of 6 km; b) The zoning of mineralization and alteration along its course; c) The precipitation of copper minerals in places where the paleochannel crosses reactive calcareous layers and d) The end of the exotic deposits coinciding with the entry of the channel into a paleobasin (Munchmeyer, 1995).

westward, making use of the permeability of the gravels and the fracturing in the bedrock underlying the pelecannels. The percolation of solutions occurred through a homogeneous medium, consisting of gravels with slightly reactive rhyolitic fragments. It is assumed that the mineralization and alteration characteristics were basically controlled by the passage of the solutions and/or their mixing with meteoric waters.

The deposition of copper minerals from the solutions was accompanied by a decrease in pH as they percolated downstream in the valley. A proximal zone is noted, approximately 2 km long and beginning at the porphyry copper deposit, in which the gravels appear fresh and contain abundant iron oxides in the matrix. An intermediate zone is present between 2 and 4 km and is characterized by an intense kaolinization of the gravel and mineralization by copper wad. The wad coexists locally with layers of fresh gravel mineralized chrysocolla. The third zone, distal stretches from 4 to 6 km and is represented by the mineralization and alteration that characterize the Huinquentipa deposit itself. The kaolinization of the gravel decreases or becomes nonexistent and the mineralization consists of chrysocolla and subordinate copper wad. Drilling has indicated that despite the continuation of the palaeodrainage and gravel filling beyond km 6, the chrysocolla mineralization decreases abruptly and disappears completely beyond a distance of 6 km from its source.

It should be noted that this determination of the exogene mineralization coincides with the change of the palaeodrainage from channeled drainage to one that is represented by a palaeobasin of approximately 1.5 km<sup>2</sup> and 100 m deep. It is highly probable that the solutions with copper were diluted on flowing into the palaeobasin environment without precipitating copper from the solutions resulting from the porphyry copper system.

The bedrock in the palaeochannel contains weak mineralization as veinlets in the rhyolitic rocks and impregnations are relatively abundant in andesitic arenite. Small deposits with abundant malachite occur when the palaeochannel intercepts small lenticular layers of reactive calcareous rock.

Ichuno and Lagarto (Munchmeyer, 1995) (Fig. 1 and 46)

The Ichuno exotic deposit extends for four km of the El Abra porphyry copper deposit (Ambrus, 1977). Its location coincides with the eastwards wedging of the Atacama Miocene gravels pediplane. Characteristic exotic type of alteration and mineralization occurs at the base of the gravels and also in

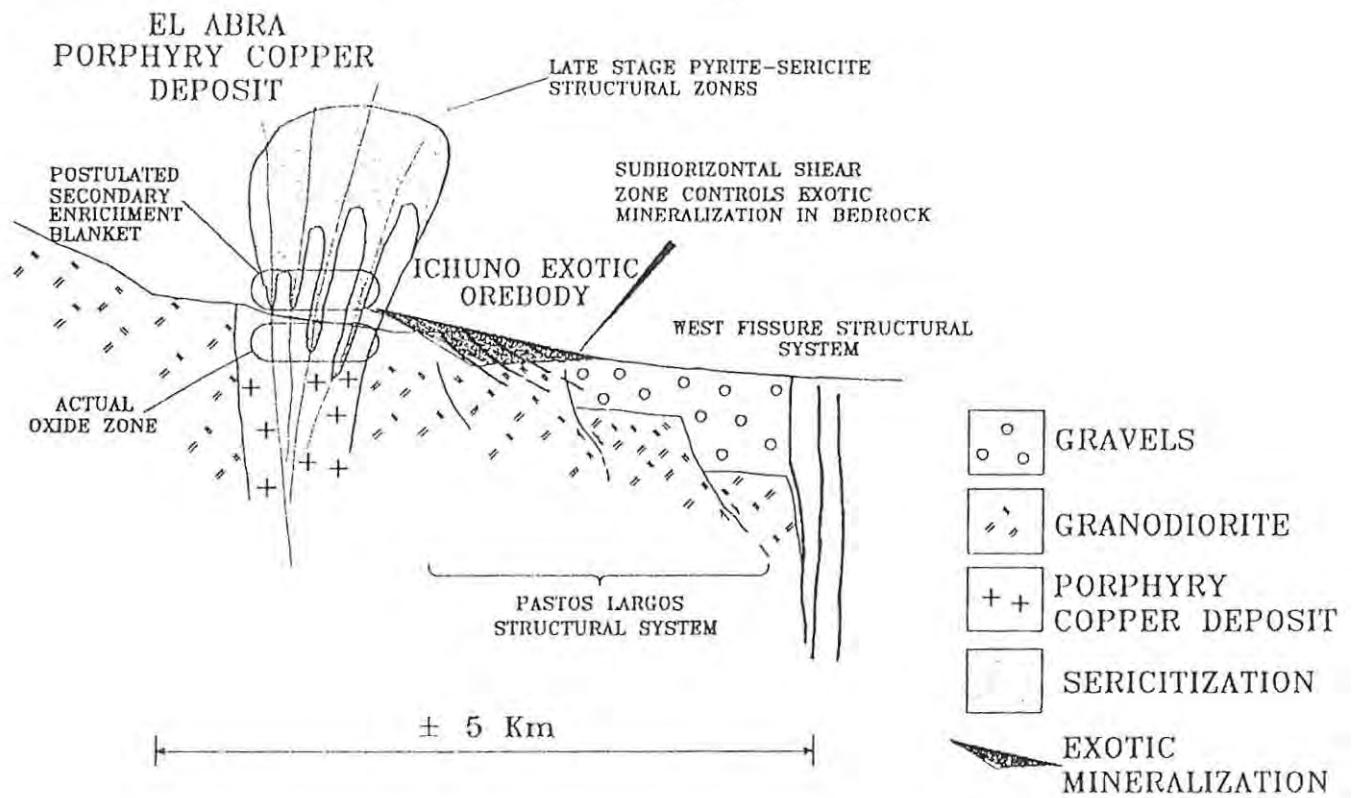


Fig. 46.- Sketched profile of the Ichuno deposit connected to El Abra. The central part of the mineralized body of El Abra contains small amounts of pyrite and the host rock is reactive, which makes conditions unfavorable for exotic generation. It is possible that El Abra was a telescoped system and that the exotic deposit was related to sericitic zone enriched in copper and subsequently eroded. (Munchmeyer, 1995).

the granodioritic basement.

In prolytized marginal rocks of the El abra porphyry copper deposit, the exotic mineralization occurs as chalcocite coating on pyrite. Equivalent rocks of the upper leached zone commonly presents turquoise in fractures. A palaeochannel develops downslope and an alteration and mineral zonation consisting of iron and manganese oxides in the proximal part changes to chrysocolla and atacamite further down of the course. In an intermediate zone the bedrock is affected by strong kaolinization associated with copper wad. In a distal zone, about 3 km from El Abra low angle shearing and intense faulting and fracturing made possible the percolation of solutions hundreds of meters downwards through granodiorite, depositing chrysocolla in fractures in a fresh primarily unmineralized granodiorite. In this interval an exotic orebody was formed in the tectonically controlled reservoir (Fig. 46)

It is probable that the copper wad derived from a layer of secondary enrichment in the El Abra porphyry copper deposit which occurred above erosion level. The areal extent of the sericitic alteration of the El Abra deposit would have broadened upwards. This alteration would render the host non-reactive and produced an environment permissive to the development of supergene enrichment. This situation contrasts with the present level of erosion at El Abra, where the rocks with central zone potassic alterations are predominantly reactive causing the local fixation of copper.

About 4 km east from the El Abra deposit there is a second deposit of exotic copper in gravels exposed by the Lagarto valley from which it takes its name. This mineralization dominated by copper wad and subordinate chrysocolla in the matrix of the gravels filling a paleochannel tens of meters wide and at a maximum, 10 m deep.

### **Smaller Deposits**

Various cases of small sized exotic deposits are known, among which the exotic mineralization at Mocha, La Planada, Quebrada Blanca and Ujina are worthy of mention. There is also evidence of exotic mineralization related to La Escondida porphyry copper deposit and the Mansa Mina porphyry copper deposit (nearby area to Chuquicamata porphyry copper deposit). In some of these cases it is possible to assume that these are remnants left by the selective erosion of the mineralized paleochannels.