

Oxide Mineralization at the Radomiro Tomic Porphyry Copper Deposit, Northern Chile

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Abstract

The main copper oxide minerals in the Radomiro Tomic deposit are atacamite, copper clays, chrysocolla, and copper wad. Their relative abundance provides the basis for dividing the oxide zone into two major geologic units: the Upper Oxide unit and the Lower Oxide unit. Furthermore, the study of mineral abundances in the oxide zones allowed the definition of an oxide mineral zonation that consists of five mineral assemblages, based on the relative proportion of the three main copper oxide components: atacamite, copper clays, and chrysocolla. These classifications allow both an understanding of the distribution of copper minerals throughout the zone and an interpretation of the supergene processes that formed it.

The Upper Oxide unit is mineralogically heterogeneous. The copper content is furnished, on average, by 40 vol percent atacamite, 31 vol percent copper clays with minor chrysocolla and copper wad. The Lower Oxide unit is more homogeneous. Atacamite accounts for 70 vol percent of the copper ore minerals with minor amounts of copper clays and chrysocolla. Copper and chlorine concentrations and porosity are greater in the Upper Oxide unit, whereas hematite, chalcocite, and molybdenite concentrations and specific gravity are greater in the Lower Oxide unit.

The vertical distribution of the Cl/Cu ratio shows a chlorine-deficient zone located between elevations of 2,780 and 2,870 m. Between these elevations, the proportion of atacamite is lower and the proportion of copper clays, chrysocolla, and copper wad is higher than in other portions of either the Upper Oxide or Lower Oxide units.

The oxide zone at Radomiro Tomic was originated through the *in situ* oxidation of a preexisting secondary sulfide enrichment blanket. Oxidation produced an extensive zone of atacamite, accompanied by weakly developed argillic alteration. The upper part of the deposit was further enriched by lateral migration of copper-rich solutions to the north and east, where copper precipitated as chrysocolla, copper wad, and copper in clays. In these areas, strong argillic alteration, characterized by the presence of montmorillonite, was developed. This second alteration phase impacted only the uppermost portion of the oxide zone and the base of overlying gravels.

Introduction

THE RADOMIRO TOMIC porphyry copper deposit is located beneath a flat desert valley about 5 km north of the Chuquicamata mine and 40 km north of the town of Calama in the Antofagasta region of northern Chile (Fig. 1), at an elevation of 3,000 m above sea level.

The deposit was discovered in 1952 during the course of an exploration program undertaken by the Chile Exploration Company, which sought the extension of low-grade oxide minerals to the north of the Chuquicamata deposit, in the so-called Pampa Norte area. The first churn drill hole (CD-273) that cut interesting oxide mineralization was so encouraging that the campaign was prolonged until 1960. Inclined diamond drill holes, surface mapping, magnetic surveys, and mineralogical studies of the core samples were included in the extended program. The latter work revealed a major change in the oxide mineralogy compared to Chuquicamata; the most abundant oxide mineral was atacamite rather than brochantite. The results obtained are registered in extensive correspondence between the resident geologists Glenn Waterman and R. L. Hamilton and company management C. M. Brinkerhoff, Vincent Perry, and William Swayne, between 1952 and 1959.

Following the discovery of a high-grade exotic copper deposit south of Chuquicamata, known today as Mina Sur, the exploration work at Pampa Norte was completely stopped in 1960. In 1971, Codelco-Chile became owner of the property

and further exploration was carried out discontinuously during the ensuing years. This work consisted of several drilling campaigns, geologic mapping, geophysical surveys, and the excavation of more than 3,000 m of underground workings for direct observation and metallurgical testing. The geologic model that supported the mine project included all the information generated during this 40-yr period (Cuadra et al., 1994; Cuadra, 1997).

Operations began on April 1, 1996, and now the mine is in full production, at an optimized capacity of 180,000 metric tons (t) of copper cathode per year. Through 1998, more than 257,000 m of drilling (mostly diamond drill holes) were completed, constituting the database for geologic modeling and resource estimation.

The study of oxide mineralization presented here is based on a statistical analysis of the information from the 1996 campaign, consisting of 12,545 m of diamond drill holes located in the central part of the deposit, between the local coordinates 10,400 N and 11,100 N (Fig. 1) and the previous drill hole data. The data were obtained from 216 diamond drill holes and consisted of assays (total copper, soluble copper, iron, and molybdenum by atomic absorption and chlorine by volumetric methods) on 3-m-long core samples and core logging parameters (44 in total), which refer to lithology, mineralization zones, ore mineralogy, alteration mineralogy, and limonites. The core logging system is a modified semiquantitative and coded version of the Anaconda method. This mineralogical approach is based on visual identification of ore and alteration minerals, validated with some X-ray diffraction and microprobe

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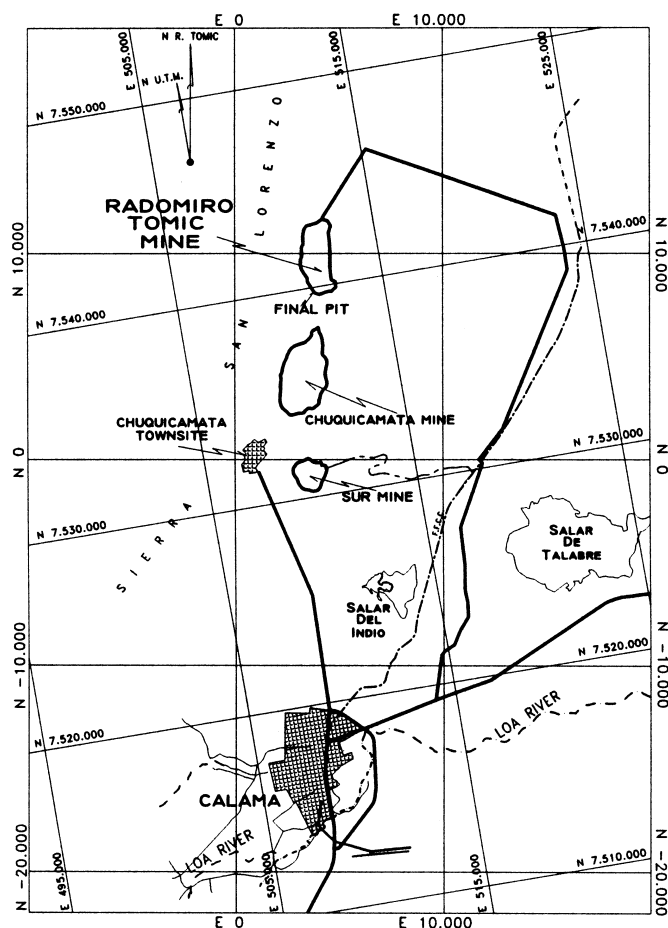


FIG. 1. Location map of the Radomiro Tomic deposit.

analyses of selected samples. In the studied area there are 27,369 m of drill holes in oxide units. Specific gravity and porosity were determined on 1.5-m-long interval samples from six selected drill holes in the area. The existing data from geologic core logging and assays was stored in a database and then studied statistically. The geologic interpretations were made on 1:2,000-scale cross sections with a 50-m spacing and on horizontal plans each spaced 15 m.

Geology of the Deposit

The Radomiro Tomic porphyry copper deposit is located along the West Fissure structural domain, one of the main strands of the Domeyko fault zone (Cuadra and Camus, 1998). The orebody is 1 km wide, elongated north-south, and is completely buried by 30 to 150 m of Tertiary to Quaternary alluvial gravels, below which a thick oxidation zone was developed on granitic bedrock during a semiarid regime (Fig. 2).

Lithologies

The host rock of copper mineralization at Radomiro Tomic is the Chuqui Porphyry, the youngest intrusion emplaced on the eastern side of a Tertiary intrusive sequence. To the east the Chuqui Porphyry is in contact with a coarse-grained granodioritic intrusion, the Elena Granodiorite, and to the west

with the Fortuna Granodiorite Complex (Fig. 2). The latter is a north-northeast-elongated intrusion 22 km long by 5 km wide that comprises five intrusive bodies of fine- to medium-grained hornblende-biotite granodiorite. This complex, dated 39 to 37 Ma (Dilles et al., 1997) intruded Triassic to early Tertiary andesitic volcanics. Contact relationships between the Chuqui Porphyry and its host rocks are not well defined because information is based only on a few existing drill holes along the margins of the deposit.

The hypogene alteration and mineralization processes are restricted almost entirely to the Chuqui Porphyry, a granodioritic to monzonitic intrusion with medium- to coarse-grained phenocrysts set in a fine groundmass, and they were originated within the West Fissure fault zone. Recent $^{40}\text{Ar}/^{39}\text{Ar}$ dating on the Chuqui Porphyry at Radomiro Tomic gives an average age of 32.7 Ma for the K silicate late-magmatic phase and an age of 31.8 ± 0.3 Ma for the sericitic alteration (Cuadra et al., 1997). These ages define a slightly different hydrothermal timing compared to Chuquicamata (33.4 and 31.1 Ma, respectively; Zentilli et al., 1995). At Radomiro Tomic, potassic alteration is younger and the quartz-sericitic event is older than at Chuquicamata, so the time duration of alteration is shorter at Radomiro Tomic than at Chuquicamata.

The mineralized intrusion is buried beneath Tertiary to Quaternary alluvial gravels, with a thickness ranging from 30 m on the east side to 150 m on the west side. As a result the bedrock surface has a relatively gentle slope to the west, with some abrupt changes indicating possible faults, but this is not well-defined yet. The gravels are composed of angular andesitic fragments, 1 to 10 cm in diameter, in a sandy and poorly to moderately cemented matrix. This unit is in direct contact with the underlying leached or oxide zones of the deposit. Locally, the gravel is mineralized with exotic copper reaching thicknesses of tens of meters, mainly along north-west-trending paleochannels according to the paleotopography. A tuff intercalated in the gravels, 2 m below the current surface, was dated in biotite by the K-Ar method at 9.7 ± 0.7 Ma (Cuadra et al., 1997).

Structure

During late Eocene to early Oligocene the Chuquicamata district (including the Chuquicamata and Radomiro Tomic orebodies) was affected by a compressional deformation cycle that favored the tectonic inversion and uplift of the Cordillera Domeyko through the reactivation of older extensional basement faults (Mpodozis and Ramos, 1990). The resulting structures controlled the intrusion of the Chuqui Porphyry and the associated hydrothermal alteration and copper mineralization (Fig. 2).

Dextral displacements along the West Fissure generated most of the structural elements recognized in the district (Fig. 2). They include the main north-south faults, associated east-northeast- and north-northeast-striking structures and, particularly, the prominent northeast-striking tensional fractures along which vertical quartz-pyrite-chalcopyrite veins were emplaced. These structures also controlled the circulation of later ground waters, resulting in leached zones in the oxide zones and downward projections of the secondary sulfides into the primary zone.

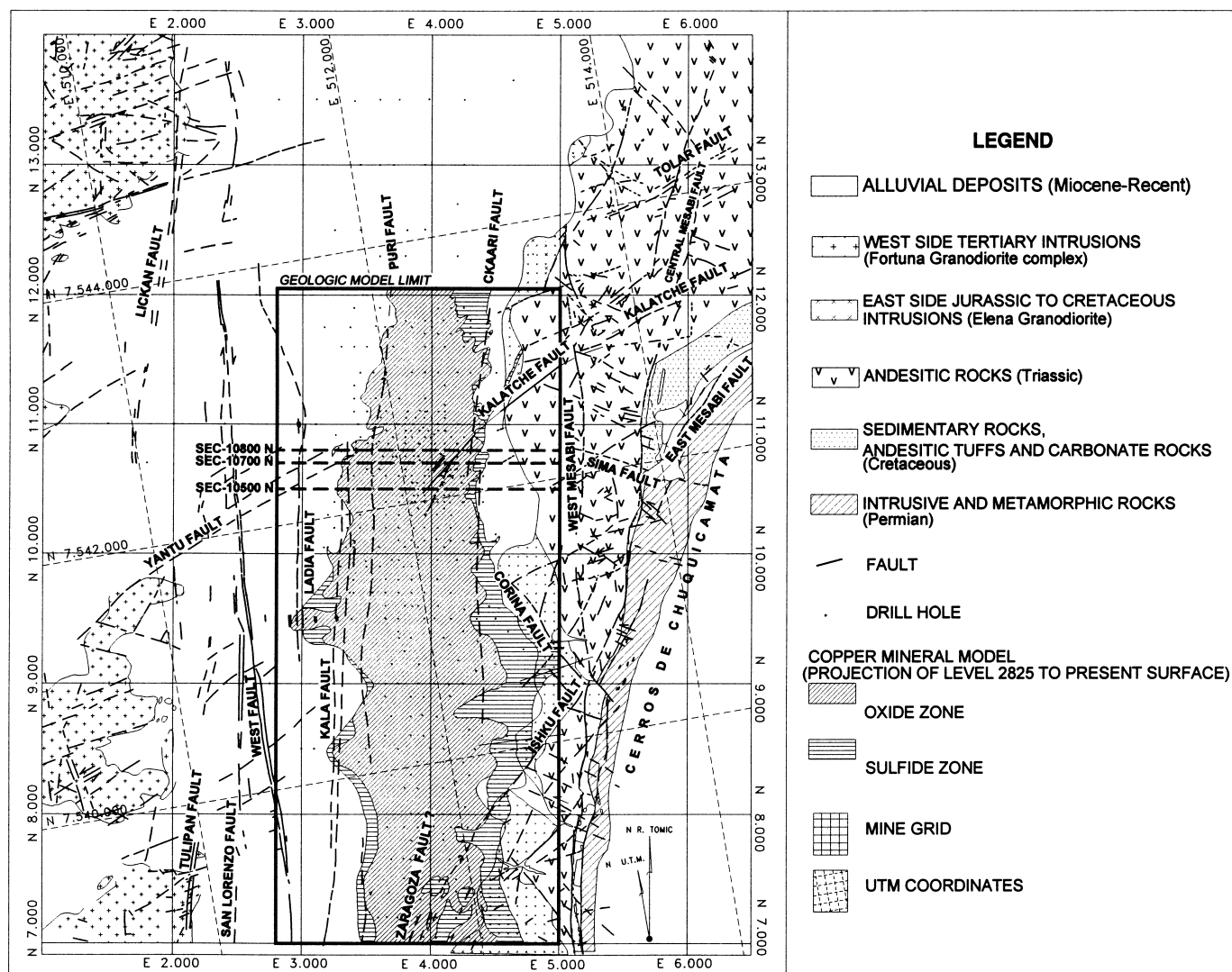


Fig. 2. Surface geology of the Radomiro Tomic area. The shaded area represents the subsurface geologic projection of the orebody at level 2,825 m.

Alteration

K silicate alteration is developed pervasively throughout the entire Radomiro Tomic deposit, with the highest intensity found in the area between coordinates 10,000 N and 11,000 N (Fig. 2). It is represented typically by quartz-K feldspar veinlets and biotitization of hornblende phenocrysts.

Quartz-sericitic alteration is less abundant and is clearly controlled by northeast- and north-south-striking subvertical structures. These structures are marked by quartz-pyrite-chalcopyrite D-type veins, with quartz-sericite halos. In the upper part of the oxidation zone supergene argillic alteration is defined by montmorillonite and kaolinite in fractures and as replacement of feldspars.

Hypogene mineralization

Hypogene mineralization follows a concentric distribution of inner bornite-chalcopyrite, intermediate chalcopyrite > pyrite, and outer pyrite > chalcopyrite zones centered around the coordinates 9,700 N and 11,000 N (Fig. 2) and averaging

0.5 wt percent total copper. Minor molybdenite mineralization is present alone or associated with chalcopyrite and pyrite in quartz veins and veinlets striking north and dipping subvertically. Arsenic minerals such as enargite are absent in significant contrast to the Chuquicamata orebody. This difference may indicate a greater degree of erosion for the Radomiro Tomic orebody. Hypogene mineralization continues to at least 400 m below the top of sulfides (Fig. 3).

Supergene mineralization

Supergene oxidation and leaching processes affected the hypogene mineralization to an average depth of about 200 m beneath the gravel-bedrock contact (Fig. 3). Supergene mineralization is present immediately below the gravels with a typical vertical distribution of leached oxide zones, a mixed (oxide sulfide) zone, and a secondary sulfide zone. Locally, along quartz-sericite-faulted veins enrichment has reached depths of up to 800 m. The description of the different zones follows.

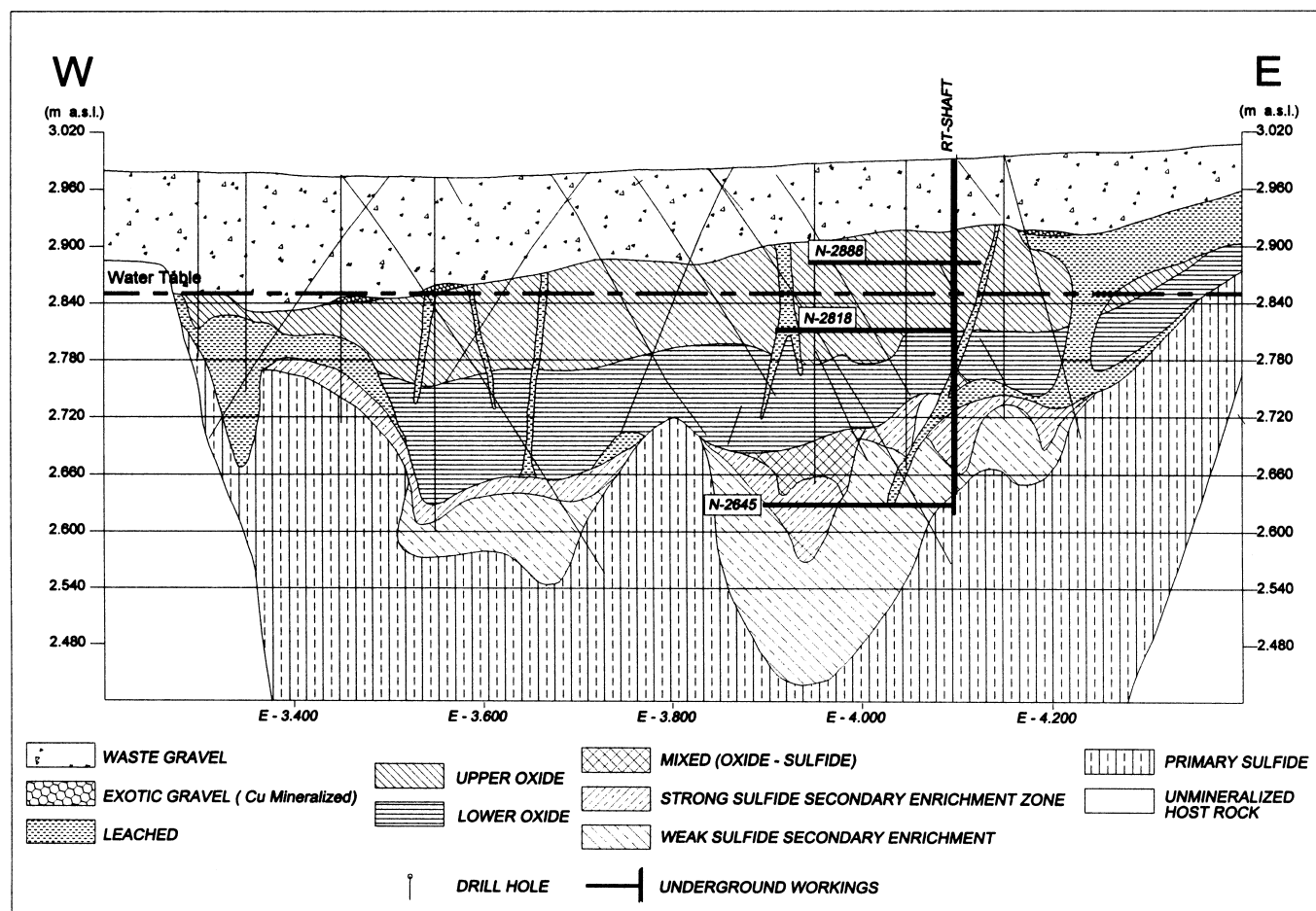


FIG. 3. Geologic cross section 10,700 N, showing distribution of the different geologic units defined at Radomiro Tomic.

Leached zone: Leached zones are narrow and structurally controlled by subvertical structures (originally quartz-pyrite D-type veins) that cut the oxide zone down to the top of sulfides, constituting internal dilution of ore. Along the east side of the deposit there is a more massive leached zone, possibly developed from a pyrite-rich marginal zone (Fig. 3). In general, leached zones contains less than 0.2 wt percent total copper.

Oxide zone: A thick blanket of oxide copper mineralization is present immediately below the contact with gravels. It is characterized by the presence of atacamite and subordinate copper clays, chrysocolla, and copper wad, in association with supergene alteration minerals (mainly kaolinite and montmorillonite). This blanket has a thickness of 150 to 200 m in the central part of the deposit and thins to the north and south.

The distribution of copper oxide minerals is strongly controlled by northeast-striking structures. Generally a sharp contact with the underlying secondary sulfides is observed; however, a gradation through small bodies (5–30 m thick) of mixed ore occurs in some locations. The copper oxide minerals occur both along structures (fractures, faults, and veins) and as disseminations associated with selective sericitic-argillic alteration of plagioclase feldspars.

Exotic high-grade mineralization, consisting of chrysocolla, atacamite, copper wad, and gypsum, was deposited locally in

the colluvial sediments that characterize the base of the gravels, mainly in the northwest- to east-west-trending channels, representing a paleodrainage system with a flow direction to the north located approximately on coordinate 3,400 E. The oxide mineralization cements the gravels, which are composed of rounded to subangular fragments of intrusions, volcanic rocks, and sedimentary rocks in a sandy matrix. This type of mineralization shows some continuity to the bedrock, where a correlated zone of intense montmorillonite alteration is found near the contact.

The oxide zone at Radomiro Tomic represents a total geologic resource of approximately 1,000 million tons (Mt) that average 0.55 wt percent total copper.

Secondary enrichment zone: The supergene copper sulfide enrichment zone is a continuous but irregular (20–150 m thick) blanketlike deposit underlying the oxide zone (Fig. 3). The northeast- or north-south-trending structures in the deposit localized extensions of supergene sulfides well down into the hypogene zone. The upper part of the enrichment zone, immediately below the top of the sulfides, is characterized by the highest grades and is defined by the presence of >80 vol percent hypogene sulfides coated by chalcocite (strong zone, Fig. 3). In contrast, the lower part has less chalcocite and the main secondary sulfide is covellite, with minor amounts of chalcocite (weak zone, Fig. 3).

The supergene sulfide mineralization represents an overall geologic resource of 350 Mt with a grade of 0.83 wt percent total copper in the upper part and 0.53 wt percent total copper in the lower part. Lying between the oxide and sulfide zones is a mixed zone of oxides and secondary sulfides of 30 Mt with an average grade of 0.81 wt percent total copper (Fig. 3).

Ground water

Based on drill hole data and underground workings, ground waters are characterized by high content of chlorides, sulfates, nitrates, sodium, and minor calcium and magnesium, and a neutral to slightly acid pH (see Table 1). Drill hole data have defined the elevation of the water table at near 2,847 m above sea level. Local variations from this level are controlled by structures extending into the bedrock and the semipermeable gravels on the west side of the deposit. At present, this ground water is draining into the pit from benches below the mentioned elevation. Recent hydrogeologic modeling indicates that ground water flows generally from south to north and in the pit area flows along a northeast direction (Urzuza, 1999).

Detailed Characterization of the Oxide Zone

As mentioned previously, copper in the oxide zone is present mainly as atacamite, copper clays, chrysocolla, and copper wad. They occur in the proportions shown in Figure 4. Other minerals such as brochantite, pseudomalachite, sampleite, libethenite, azurite, cuprite, and native copper are present in minor amounts. The spatial distribution of the four main oxide minerals (copper clays and copper wad are not minerals in the strict sense) shows a heterogeneity in the vertical direction that allows separation of the oxide zone into two large units: Upper Oxide unit and Lower Oxide unit. The interface is almost flat and located approximately at elevations of 2,780 to 2,820 m above sea level. There is a sharp contrast in alteration, because montmorillonite is more abundant in the Upper Oxide unit. Additionally, in the Upper Oxide unit the rock is physically more heterogeneous, showing higher porosity and lower specific gravity on average than in the lower unit (see Figs. 5 and 6).

TABLE 1. Chemical Analysis of Underground Water at Radomiro Tomic

Samples		1	2	3	4	5
Calcium	mg/l	647	605	465	446	456
Cadmium	mg/l	527	483	360	339	327
Iron	g/l	6.31	5.69	2.95	2.87	2.75
Magnesium	mg/l	57.5	82	42	38	35
Sodium	mg/l	128	225	69	71	45
Potassium	g/l	4.88	5.0	1.91	2.07	2.0
Bicarbonates	mg/l		0.28	0.20	0.20	<0.05
Chlorides	g/l	7.17	7.22	1.68	5.77	1.78
Fluorides	g/l	3.33	3.75	1.60	1.50	1.42
Sulfates	mg/l	<0.50	<0.25	<0.25	<0.25	<0.25
Nitrates	mg/l		<0.03	<0.03	<0.03	<0.03
Aluminum	mg/l	0.047	<0.01	<0.01	0.01	0.01
Arsenic	mg/l	0.08	0.09	0.24	<0.05	0.11
Copper	mg/l	1.24	0.28	2.3	2.66	1.7
Zinc	mg/l	1.12	0.19	0.26	0.19	0.23
Manganese	mg/l	1.17	0.83	0.06	0.24	<0.05
Molybdenum	mg/l	1.36	4.0	0.57	0.81	0.69
pH		7.34		6.57	6.58	6.89

Notes: Samples 1 and 2 collected from water circulating through rock and samples 3, 4 and 5 from water circulating through gravels in the west wall of the pit

¹ Taken from water level at 200-m depth in exploration shaft (1994); analyzed at Isotope Geosciences Laboratory, British Geological Survey

² Taken from the open pit at 2810 bench (1998); analyzed at CIMM laboratory, Calama

^{3, 4, 5} Taken from the open pit at 2840 bench (1998); analyzed at CIMM laboratory, Calama

Upper Oxide unit

The ore mineralogy in the Upper Oxide unit is very heterogeneous and varies widely in a vertical direction. Atacamite is most abundant in the upper part of the unit and copper clays are most abundant in the lower part (Fig. 6). Moderate chrysocolla and lesser amounts of copper wad are also present (Figs. 4 and 6). The alteration is predominantly argillic of supergene origin (kaolinite and montmorillonite), superimposed on the hypogene sericitic and potassic alterations. Goethite is the main iron oxide mineral, and the molybdenum content is low.

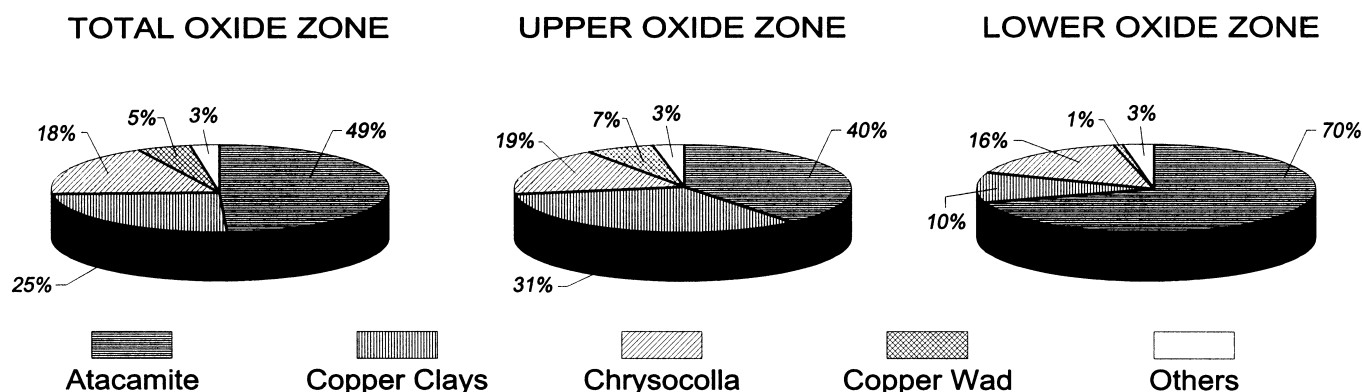


FIG. 4. Average distribution of copper minerals in weight percent of total Cu contained in the oxide zone of Radomiro Tomic.

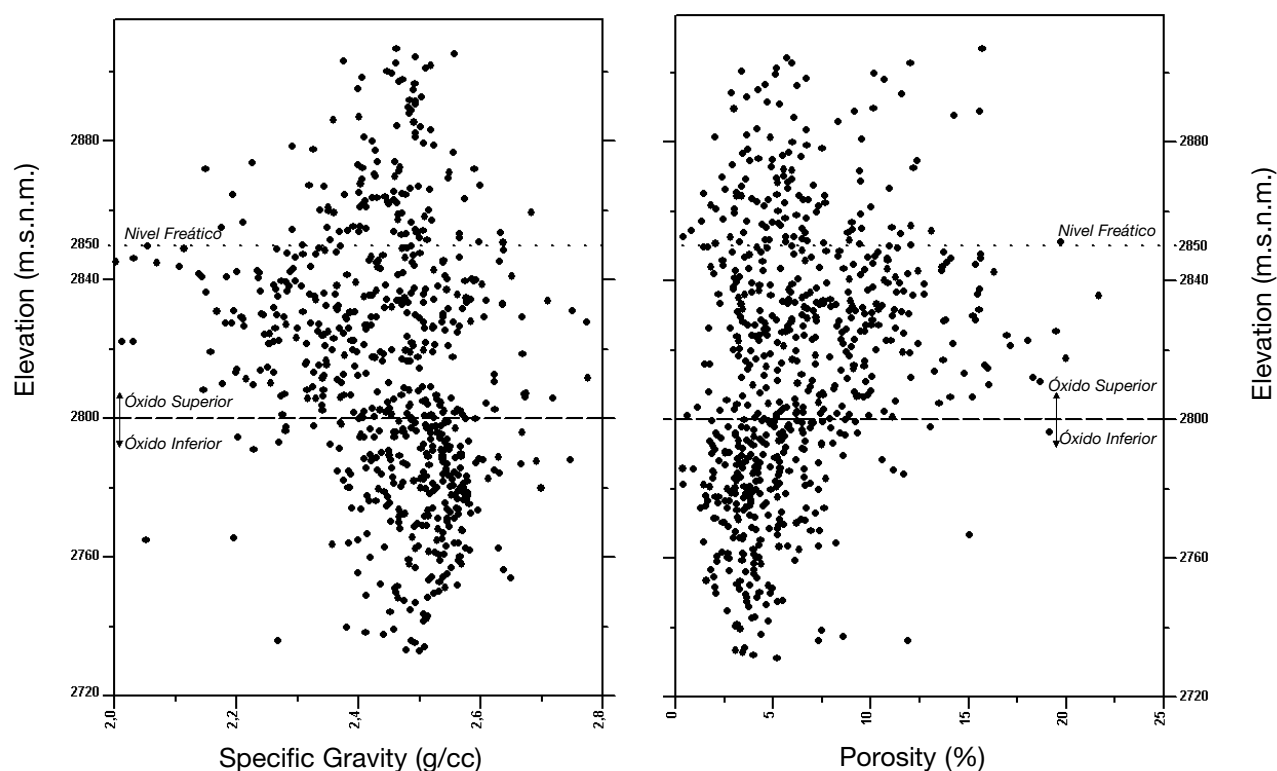


FIG. 5. Vertical distribution of specific gravity and porosity through the Upper and Lower Oxide units.

Lower Oxide unit

In contrast to the Upper Oxide unit, this unit is more homogeneous in ore mineralogy, with atacamite predominating over chrysocolla and copper clays. Copper was present only in trace amounts (Fig. 4). Supergene argillization is less intense than in the Upper Oxide unit, reflected mainly in the low montmorillonite content, leaving a higher abundance of preexisting sericitic and potassic alteration. Hematite is the predominant iron oxide. Going downward, chalcocite (remnant of the preexisting secondary enrichment) and atacamite coexist, showing a gradual increase of the former toward the top of the sulfides. The molybdenum content is significantly higher than in the Upper Oxide unit.

The principal chemical, mineralogical, and physical differences between the Upper Oxide and Lower Oxide units are presented in the form of ratios in Table 2.

In order to understand and model the distribution of the main mineralogical associations present at RadomiroTomic, a statistical and spatial distribution study of most relevant copper minerals in the oxide zone was completed (Fig. 6).

Atacamite ($\text{Cu}_4\text{Cl}_2(\text{OH})_6$): The vertical distribution of atacamite shows the presence of two distinct horizons (Fig. 6). Between elevations of 2,780 and 2,870 m there is a subhorizontal intermediate zone where atacamite is scarce. Above and below this zone, atacamite is present in moderate to abundant amounts. In both the intermediate and upper zones

(i.e., Upper Oxide unit), atacamite is often well-crystallized in fractures, coatings, and cavities filling. It always covers preexisting copper minerals or fills fractures within the zones. In the lower zone (i.e., Lower Oxide unit) atacamite is found in veins and, subordinately, is disseminated, frequently together with sericite and commonly with hematite.

Copper clays: Copper clays are considered as ore minerals because they make a significant contribution to the total copper content of the system. These clays include smectites, belonging to the montmorillonite subgroup, where copper is included in the clay structure in an octahedral position (Levi, 1997; Brimhall et al., 2001). The clays also include bluish- to greenish-colored kaolinite and/or sericite, where copper is due to ultrafine-submicroscopic inclusions of chrysocolla or atacamite (Baum, 1998). A study of some selected fracture filling of montmorillonite type showed that the copper content of these clays is not due to microscopic inclusions of atacamite or chrysocolla, because there was no correlation between copper and chlorine and the correlation with silica is inverse (Levi, 1997; Brimhall et al., 2001). On the other hand, the colored kaolinite-sericite is found in fractures and as a selective alteration of feldspars, mainly plagioclases. A semiquantitative scanning electron microscopy (SEM)-energy dispersive spectroscopy (EDS) analysis of a partially argillized-sericitized chrysocolla-impregnated feldspar gave a 14.6 wt percent copper content (Baum, 1998).

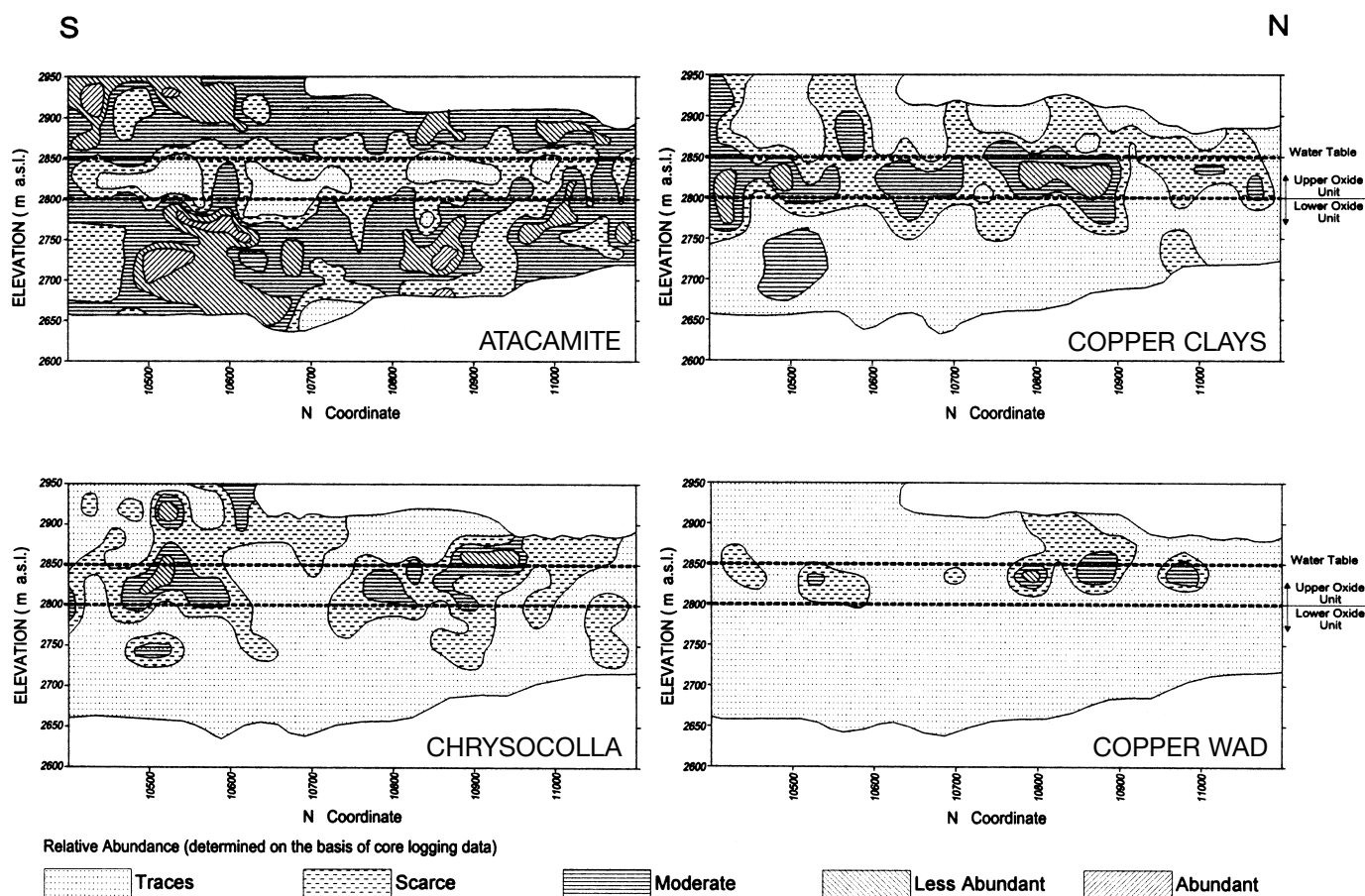


FIG. 6. Longitudinal north-south composite section (all data projected to a central section with the main features), showing the vertical and horizontal distribution of the main oxide copper minerals along the Radomiro Tomic deposit.

TABLE 2. Principal Chemical, Mineralogical, and Physical Characteristics of the Upper Oxide and Lower Oxide Units (number indicates Upper/Lower ratio)

Grades		Ore minerals	
Total copper	1.22	Atacamite	0.83
Soluble copper	1.25	Copper clays	4.51
Soluble/total copper	1.02	Chrysocolla,	1.72
Total iron	1.12	Copper wad	9.88
Total molybdenum	0.51		
Chlorine	0.93		
		Limonites	
		Hematite	0.16
Alteration minerals		Physical parameters	
Kaolinite	1.23	Specific gravity	0.97
Montmorillonite	1.54	Porosity	1.58
Sericite	0.78		

Notes: Original data are in weight percent for grades and in volumetric proportions for mineralogy; specific gravity is in g/cc and porosity in percent; number of samples considered are 2,917 for grades, 9,123 for mineralogy, and 702 for specific gravity and porosity

Although much of the copper content of altered feldspars is due to copper clays, in many cases the copper appears to have originated as submicroscopic inclusions or veinlets of chrysocolla or atacamite in plagioclase or potassium feldspar (Brimhall and Tidy, 1997; Baum, 1999; Brimhall et al., 2001).

Copper clays are most abundant between elevations of 2,780 and 2,870 m, where they occur as a subhorizontal zone. Above this zone their abundance is moderate to scarce, and below this zone they occur in only trace amounts. Their presence defines the boundary between the Upper and Lower Oxide units (Fig. 6).

Chrysocolla: Chrysocolla is more abundant in the lower part of the Upper Oxide unit, above the 2,780-m elevation. Below, it is remarkably scarce (Fig. 6). Although an upper limit for this zone cannot be delineated clearly, chrysocolla principally occurs at a one-depth interval, thus a horizontal trend for mineralization control can be suggested.

Chrysocolla is found mainly in fractures, coatings, and as plagioclase replacement and impregnations. In the deposit, it is typically greenish blue to blue and also black in color. Black chrysocolla is found with copper wad or as coatings and interdepositional layers in regular chrysocolla (Baum, 1998).

Copper wad: Copper wad is found as an irregular horizontal blanket between elevations of 2,800 and 2,850 m (Fig. 6). Above and below this zone copper wad is scarce to absent.

Copper wad occurs as thin coatings and specks in fractures, deposited over copper clays and chrysocolla, generally where copper clays are the predominant ore minerals deposited over copper clays and chrysocolla. When atacamite is present, copper wad also can occur as coatings on it.

Most of the copper wad is X-ray amorphous, but some selected X-ray analyses and microscopic studies indicate characteristics of cryptomelane and crednerite (Cu-Mn oxides; Baum, 1999).

Cl/Cu_(total) ratio: The distribution of the Cl/Cu_(total) ratio (wt ratio of chlorine/total copper) constitutes an adequate index of atacamite relative to other copper oxide minerals, because atacamite (Cl/Cu_(total) = 0.28 approx) is the predominant copper oxide mineral containing chlorine in its crystalline structure. A composite north-south longitudinal section illustrates the distribution of Cl/Cu_(total) ratios (Fig. 7). The range of Cl/Cu_(total) ratios from 0.22 to 0.32 is of particular interest as this is the stoichiometric range corresponding to atacamite as estimated from mine production data. The most remarkable feature is the existence of a zone located between elevations of 2,780 and 2,870 m, where there is a chlorine deficit (Cl/Cu_(total) < 0.10). This zone coincides with the low atacamite and high copper clays-chrysocolla-copper wad zone described previously. Above this chlorine-deficient zone, chlorine increases gradually relative to copper until the stoichiometric range of atacamite is exceeded. This indicates an excess of chlorine relative to atacamite, which is probably due to the presence of soluble salts coming from the overlying gravels. In the Lower Oxide unit, the Cl/Cu_(total) ratio is very similar to the atacamite stoichiometric ratio (Fig. 7).

Mineral zonation: Composite sections of the ore minerals and Cl/Cu_(total) ratios (Figs. 6 and 7) were constructed in order to define the most relevant features and conceptual guidelines to do a detailed mineralogical model. From the examination of the distribution of minerals and other variables the following conclusions can be made: (1) each of the oxide ore

minerals shows a particular distribution, (2) oxide ore minerals and Cl/Cu_(total) ratios have contrasting variations in a vertical direction, and (3) there is an antithetic distribution of atacamite with respect to the other oxide minerals. Where atacamite is abundant, copper clays, chrysocolla, and copper wad are scarce and vice versa. This is reflected in the distribution of Cl/Cu_(total) ratios. Although the highest content of copper clays, chrysocolla, and copper wad coincides roughly with elevations between 2,780 and 2,870 m, the boundaries of each mineralogical domain are not coincident, reflecting the complexity of the Upper Oxide zone. The vertical changes in the mineral proportions and the predominance or absence of them in some areas represent the different depositional physicochemical conditions that occurred within the supergene environment.

In order to get a complete representation of mineral zoning within the oxide zone and the two oxide units, all the copper minerals were grouped into five minerals associations (Table 3) that represent mappable units depicting mineralogical changes. These associations were defined by a statistical analysis of the distribution of all the combinations of oxide ore mineral relative abundances determined from core logging. Two east to west sections illustrating the distribution of these mineral associations are presented in Figure 8.

The most distinctive feature observed in these sections is the subhorizontal disposition of association 5 (Cu clay dominant) between elevations of 2,780 and 2,870 m, closely related with association 4 (chrysocolla dominant) and the presence of copper wad, grading upward and downward to associations where atacamite predominates. Association 1 (atacamite dominant) is located both near the top of the sulfides and below the contact with the gravels, that is to say near the boundaries of the oxide zone.

The heterogeneity of the Upper Oxide unit and, by contrast, the homogeneity of the Lower Oxide unit are evident from the distribution and proportions of ore minerals (Fig. 8).

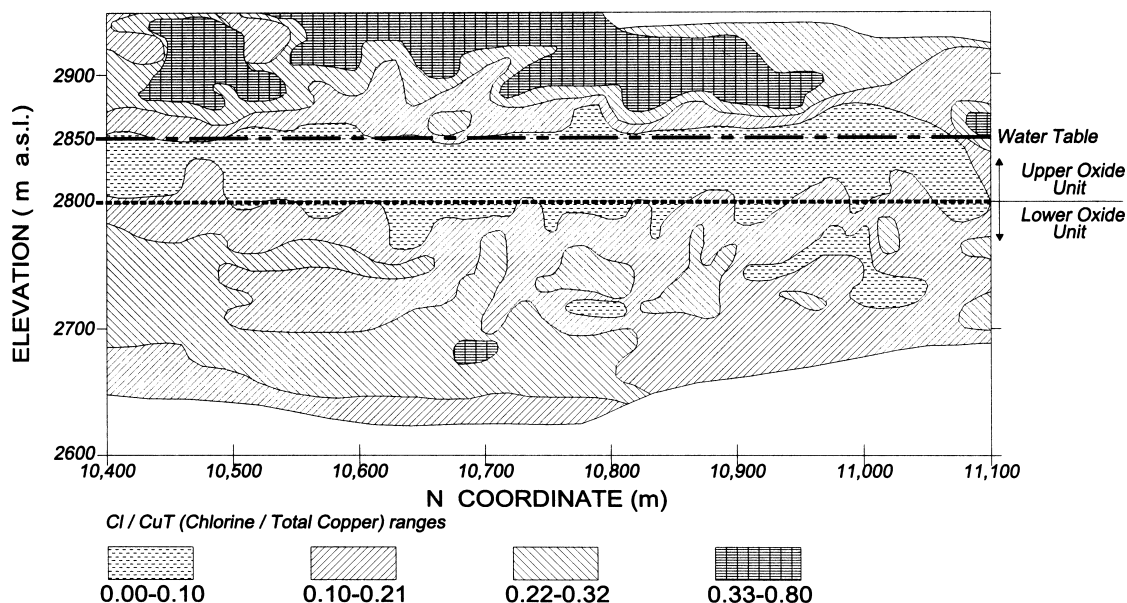


FIG. 7. Longitudinal north-south composite section (all data projected to a central section with the main features), showing the vertical and horizontal distribution of the Cl/Cu_(total) weight ratios along the Radomiro Tomic deposit.

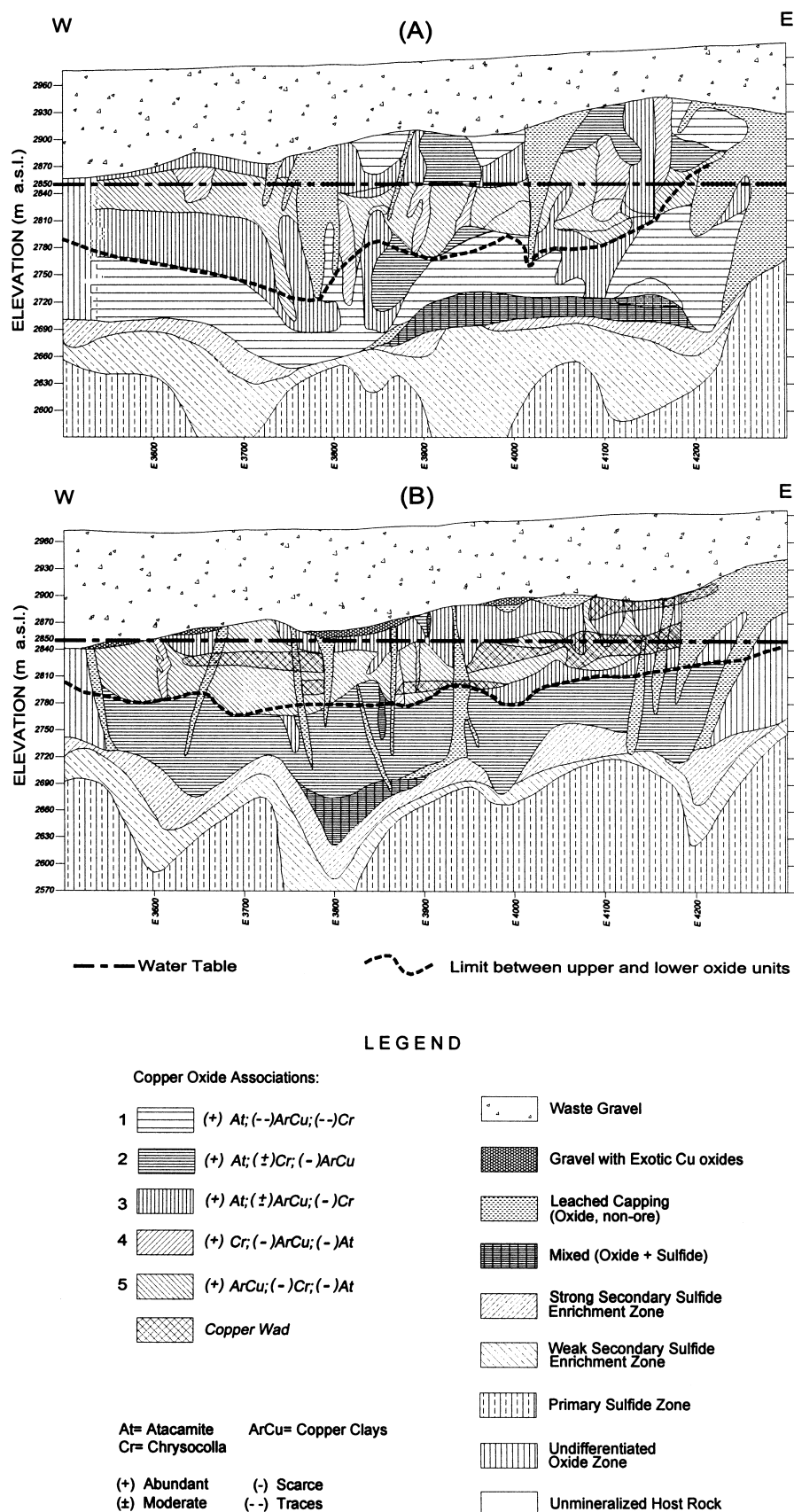


FIG. 8. Geologic cross sections 10,500 N (A) and 10,800 N (B), showing distribution of principal oxide copper mineral associations within the oxidation zone. The limit between Upper and Lower oxide units is also shown.

TABLE 3. Oxide Mineral Associations at the Radomiro Tomic Deposit¹

Mineral association	Abundant (++)	Moderate (+)	Scarce (-)	Traces (=)
1	Atacamite			Copper clays Chrysocolla
2	Atacarnite	Chrysocolla	Copper clays	
3	Atacarnite	Copper clays	Chrysocolla	
4	Chrysocolla		Atacamite	
5	Copper clays		Copper clays Atacamite Chrysocolla	

¹Proportions determined from the analysis of core logging data

On the other hand, the ore mineralogy distribution suggests a phreatic control together with the morphology of the top of the bedrock, which is reflected in a proportional increase of

atacamite toward the contact with the gravels (Figs. 8 and 9).

Based on the observed relationships among the different copper ore minerals a schematic paragenesis has been drawn in Figure 10. Atacamite is thought to have formed by at least two processes: in situ and remobilized. In the latter, atacamite is present together with copper clays in a phase of intermediate age and, in a final phase, in cracks in copper clays and over chrysocolla and copper wad.

Origin of the Oxide Zone

The analysis of drill core data and the current pit exposures indicate that the oxide zone is the result of two complex processes. The first is an in situ oxidation of a secondary sulfide zone, represented now by the Lower Oxide unit. The second is a shallow process involving migration of copper-bearing ground water to redeposit copper in the upper part of the porphyry deposit (Upper Oxide unit) and in some places

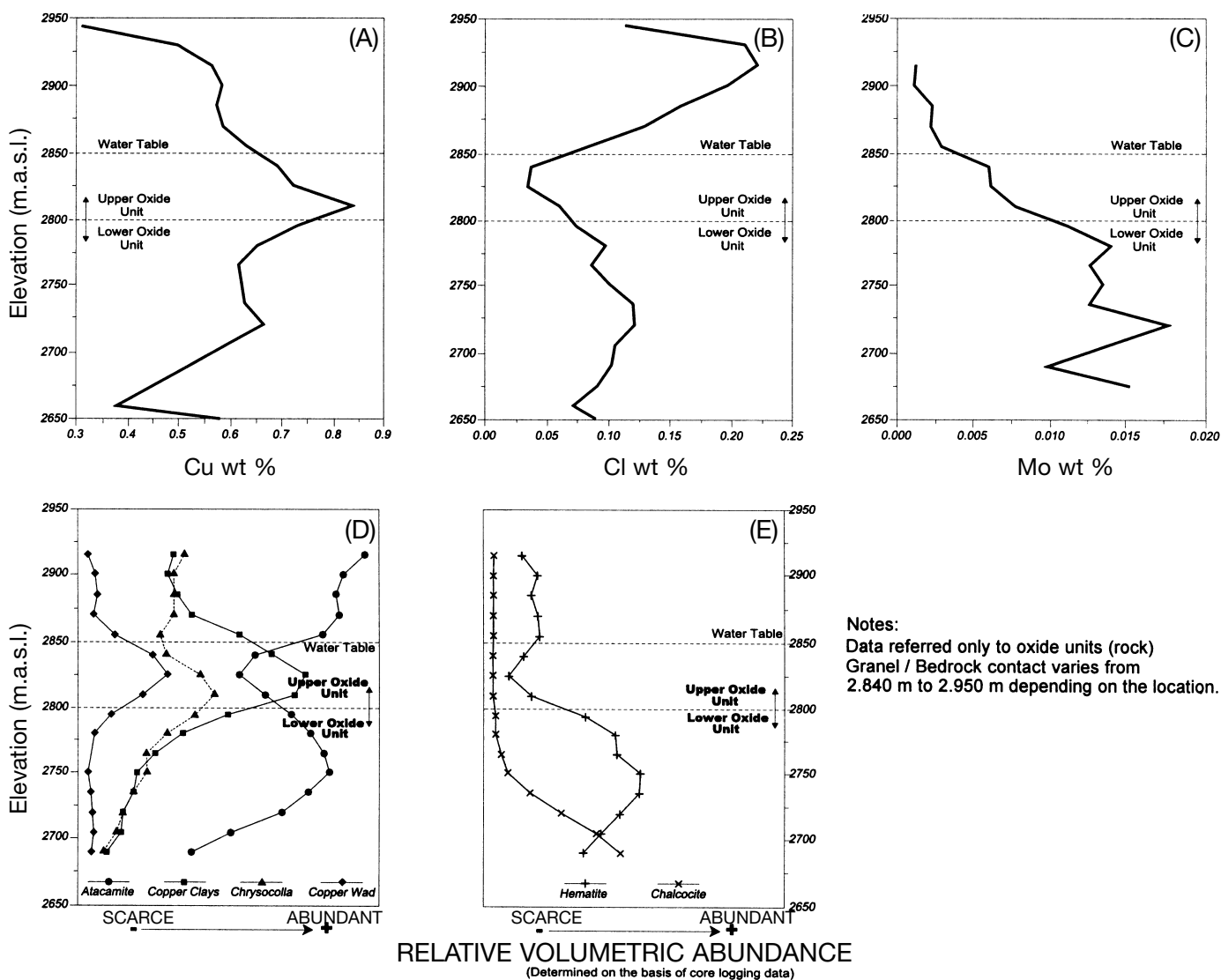


FIG. 9. Vertical distribution of assays of total Cu, Cl, Mo by assay, copper oxide minerals, hematite, and secondary chalcocite, based on visual estimates of several drill core intervals. Also shown is the location of the limit between the Upper and Lower Oxide units within the oxidation zone.

	Primary Sulfides	Secondary Sulfides	OXIDATION	
			Lower Oxide (A)*	Upper Oxide (B)*
Atacamite				-----
Copper clays				_____
Chrysocolla				_____
Copper Wad				-----
Hematite			_____	
Chalcocite				
Covellite				
Pyrite Chalcopyrite Bornite				

See figure 11

FIG. 10. Schematic paragenesis of the Radomiro Tomic ore deposit.

in the base of the gravels. In the following paragraphs the arguments for these conclusions are described.

Based on the distribution of oxide minerals, chemical compositions, and physical variables a strong difference between the Upper Oxide and the Lower Oxide units is seen, as exposed previously. Most of the spatial distribution and proportions of ore minerals and other relevant related constituents, such as chlorine and total copper, can be explained as a consequence of paleotopography and the existence of the water table that oscillated in time. In relationship with the oscillation of the water table there is evidence of at least two different positions for the water table: one is the current position at an elevation of 2,850 m above sea level and the other is the location of the top of the sulfides, indicating there was a previous position. So, the zone comprised between the water table from the position of the top of the sulfides to the present one might correspond to the Lower Oxide unit, which was not substantially altered after this rise. In contrast, the oxide zone above this limit was exposed to subsequent changes caused by the action of oxidizing ground water circulation through it.

The mineral associations in the Upper Oxide zone show very distinct paleotopographic and phreatic controls and the main mineralogical variability is subvertical. Solutions associated with supergene processes flowed through the wall rock, moved downward along structures until they reached the water table (located now approx at an elevation of 2,850 m). As these solutions reached the water table dilution caused a decrease in salinity. This is supported by the sharp decrease of Cl content in the lower part of the Upper Oxide unit, possibly indicating the presence of less-saline ground water. Consequently, in this zone occurs the higher proportion of copper

clays and atacamite is almost absent. The water table also neutralized the solutions causing ion precipitation. On the other hand, a decrease of alkali activity in an intermediate pH water environment is required to cause argillic alteration in the wall rock (Anderson, 1982; Anderson, 1996), reflected in the higher proportion of Cu montmorillonite (copper clays) found between 2,870- and 2,780-m elevations (Fig. 9).

The main copper minerals in the oxidation zone (atacamite and chrysocolla) have similar conditions of formation (Newberg, 1965, 1967; Flint, 1986; Woods and Garrels, 1986; Bravo, 1998), so the differences among mineral associations are due to slight differences in precipitation conditions for each mineral.

As inferred from the Eh-pH diagram (Fig. 11), the distribution of copper minerals can be explained as follows: it is possible that solutions circulating through the Upper Oxide unit above the water table were slightly acidic (at present pH is about 6–6.5) and had salinity conditions favorable enough to produce atacamite and some montmorillonite. Passing downward through the rock, the solutions became less acidic until reaching the water table where they were diluted to higher pH values (around 7). In these conditions atacamite could not be formed, but other minerals such as copper wad and montmorillonite could be deposited. The decrease in salinity, as explained previously, allowed the precipitation of other copper compounds like copper wad and improved the ionic capture of copper by smectites. Apparently, chrysocolla formation was dependent on the presence of favorable local conditions, as it is restricted to structures and elevations near the water table. In many places there is an observed transition from copper clays to chrysocolla, possibly caused by the reaction of copper-rich

In the Lower Oxide unit, where atacamite predominates widely, the situation is quite different. Though the same mineral associations as are in the Upper Oxide unit are found, they are quite different in alteration, chemical, and physical properties, and forms of occurrence. The chlorine content is less variable than in the Upper Oxide unit (Fig. 9). Atacamite occurs mainly as veinlets, generally with sericitic halos and usually associated with hematite. Also, chalcocite is present as a remnant of the preexisting secondary enrichment, and its abundance increases downward to the top of sulfides. The spatial relationship of atacamite with chalcocite and hematite suggests that atacamite and hematite were produced by the oxidation of preexisting chalcocite (see Fig. 11). It is probably that atacamite was formed by a high chlorine activity and low availability of H_2SO_4 (Woods and Garrels, 1986), within a low pyrite supergene chalcocite blanket. Molybdenum is found in greater amounts than in the Upper Oxide unit, probably reflecting a different original pattern of hypogene sulfides for each of these units (Fig. 9).

In the Lower Oxide unit, chlorine content seems to be less variable spatially and would have received few contributions after the formation of atacamite, i.e., there is not a chlorine excess in the system. This may indicate that for chlorine, the system remained closed once atacamite was formed.

There is an excellent correlation between the decrease of atacamite at depth and the increase of chalcocite in the Lower Oxide unit (Fig. 9), suggesting a genetic relationship. The distribution patterns of hematite and atacamite are similar. Because hematite can be stable at slightly lower pH values in highly oxidizing environments (Anderson, 1982; Sato, 1992), it can be inferred that hematite mobility has been low and its spatial distribution is indicative of an original chalcocite oxidation pattern. This provides additional support to the hypothesis of an in situ origin for atacamite in the Lower Oxide unit. This seems to explain, in part, the strong breaks observed for some variables like total copper, molybdenum, hematite, and oxide ore minerals, which in all cases are located approximately at an elevation of 2,800 m (Fig. 9). These breaks are not necessarily due to the supergene processes but to the combined effect of them over those formed in hypogene alteration and mineralization stages.

Regarding argillic alteration, there is a very strong contrast between the Lower Oxide and Upper Oxide units. The montmorillonite, which is moderately abundant in the latter, is scarce in the former. The main physical and chemical control of copper precipitation in the Lower Oxide unit would be, in this case, the Eh conditions (see Fig. 11).

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