The stratiform Ag-Cu deposit El Jardín, Northern Chile

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1 Introduction

The El Jardín mine belongs to a belt of stratabound Cu, Ag-Cu and Ag deposits in the lower part of the Hornitos Formation (Upper Cretaceous?, Paleocene?) in northern Chile. Other examples of this belt are: Elisa de Bordos [Ag-(Hg); see Jurgeit and Fontboté this Vol.], Amolanas (Cu-Ag), El Venado (Ag-Cu), Boliviana [Ag-(Hg)], Altar de Cobre (Cu) and a great number of smaller deposits (Fig. 1). Exhibiting differences in ore textures, the deposits show similarities in host rock lithology, and mineralogic and geochemical composition. Vein-type deposits occur in the same stratigraphic position. Nordenskjöld (1897), Kuntz (1923), Little (1926), Cortés (1942), and Segerstrom (1959) provided early descriptions followed by Lortie and Clark (1974, 1987), Mayer and Fontboté (1984, 1986), Jurgeit et al. (1986) and Mayer (1988). This paper is based on field and laboratory work and presents a short description of host rock lithology, diagenetic evolution, ore geometry, composition, and zonation of the El Jardín mine (27°45′30″S/70°11′30″W), 47 km SEE of Copiapó, capital of the Atacama Province, N-Chile (Fig. 1). The main ore horizon is mined in several smaller mines at a length of about 3 km. A second ore horizon, stratigraphically 40 m above the main orebody, was mined during 1982 and 1983, but the production ceased due to processing problems. The production is about 100 t/day with an ore grade of 1.8% Cu and 100 g/t Ag. The present description is restricted to the main orebody in the sectors Zulema, San Pedro and San Antonio (Fig. 3).

2 Geology

The rocks found in the mining district have been deposited in intra-arc-basins during the second substage of the Andean Orogenic Cycle (Coira et al. 1982) and belong to the Cerrillos (lower Upper Cretaceous?) and Hornitos Formation (Upper Cretaceous?, Paleocene?) (Segerstrom 1959; Fig. 1). The Cerrillos Formation (Segerstrom and Parker 1959) up to 4500 m thick, unconformably overlies the Neocomian magmatic arc-back-arc pair represented by the Bandurrias Formation and the Chañarcillo Group as well as Jurassic rocks.

Based on lithologic comparison with the Abanico Formation of central Chile, a lower Upper Cretaceous age has been suggested for the Cerrillos Formation (Segerstrom 1968). Granites intruding the upper part of the formation yielded a

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Stratabound Ore Deposits in the Andes
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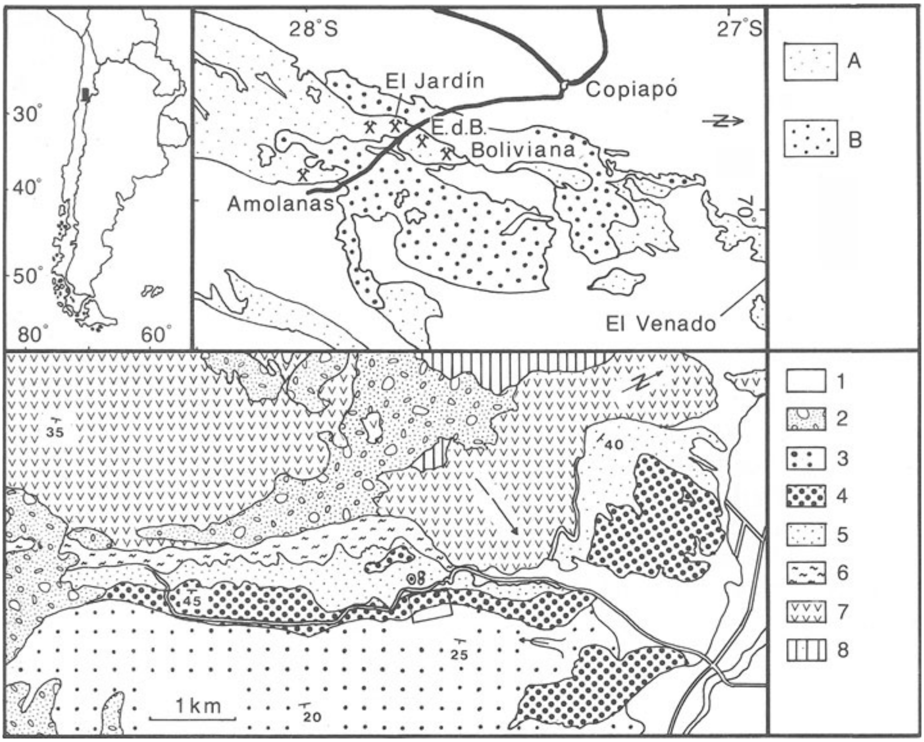

Fig. 1. Location and geology of the El Jardín Ag-Cu deposit. *A* Hornitos Formation (Paleocene?); *B* Cerrillos Formation (lower Upper Cretaceous); *E.d.B.* Elisa de Bordos Ag-(Hg) deposit; *1* Alluvium; *2* Miocene gravels; *3* gypsiferous sandstones with limy intercalations (Hornitos Fm.: *3–6*); *4* conglomerate; *5* unwelded top of ignimbrite; *6* welded tuff; *7* Cerrillos Fm.: volcanic rocks; *8* argillic alteration zone

K/Ar age of 105±10 m.y. Volcanic conglomerates, lacustrine carbonates, and sandstones are the dominating lithologies in the lower part of this formation. The upper 2000 m consist of andesitic lavas, dacitic tuffs, pyroclastic flows, felsic ignimbrites (Zentilli 1974) and subordinated volcanic conglomerates. Composition of the volcanics ranges between high alumina basalt and rhyolithic (Zentilli 1974). In the mining district of El Jardín volcanic rocks of the Cerrillos Formation have undergone intense argillic alteration in an area of about 2 km^2 (Fig. 1).

The Hornitos Formation overlies the Cerrillos Formation by a low-angle unconformity. The up to 2500 m thick volcano-sedimentary sequence has been described by Lortie and Clark (1987). Granitoid intrusions of the coastal batholith outcropping at distances of 7 km from the mine have no direct relation with the ore occurrence. The strata dip 5 to 60° SE-ESE. Both formations have undergone compressive tectonic events which affected them differently (Fig. 1). The main ore body dips 10 to 50° SE (Fig. 2).

In six sections, taken in the area Elisa de Bordos/El Jardín the following units have been distinguished in the lower part of this formation (Fig. 2; the analytical data mentioned below are discussed in detail in Mayer 1988):

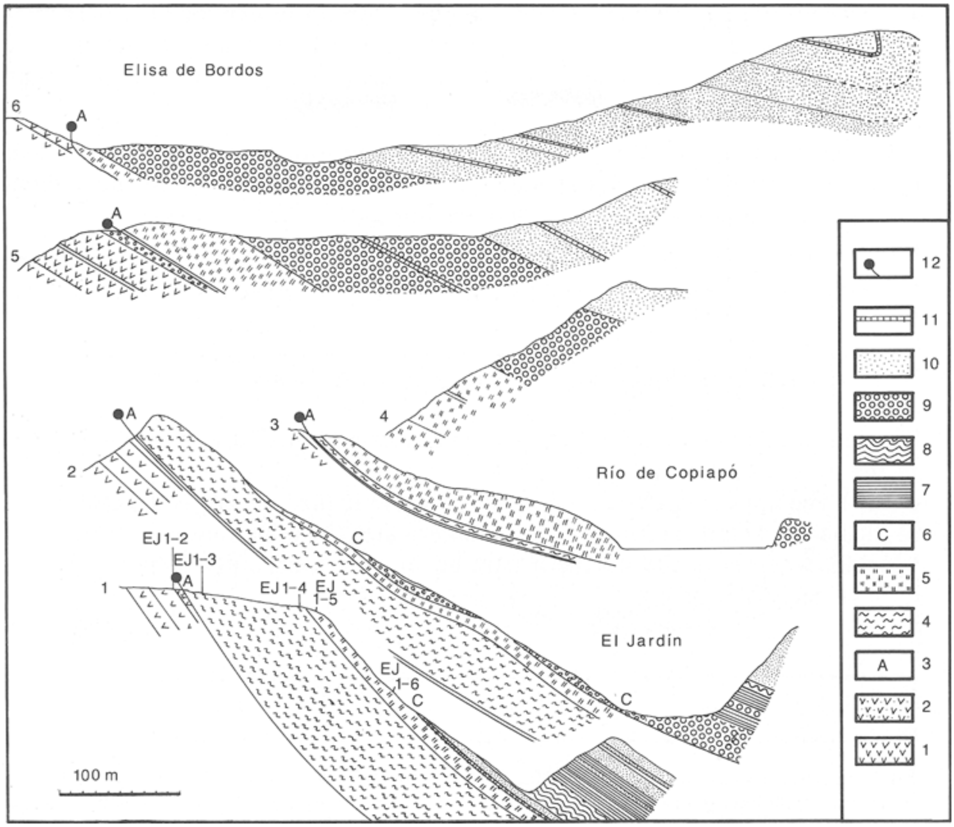

Fig. 2. W-E sections of the area Elisa de Bordos – El Jardín. *12* Unconformity Cerrillos/Hornitos Formation; *11* limestone; *10* gypsiferous sandstones; *9* coarse conglomerate; *8* marls, strongly folded; *7* marls; *6* main orebody; *5* unwelded tuff; *4* welded tuff; *3* air fall tuff; *2* volcaniclastic rocks (Cerrillos Formation); *1* volcanic rocks (Cerrillos Formation)

A) Unwelded Base of Ignimbrite (Air Fall Tuff) (0–6 m). Well-sorted pumice fragments, ash and glass particles are the major components of the unit hosting the Elisa de Bordos stratiform Ag-(Hg) ores.

B) Ignimbrite (0–90 m). The ignimbrite consists of an unwelded lower (unit A), a welded central (B 1; 0–80 m) and an upper unwelded unit (B2; 0–90 m). B 1 and B2 thin out to the North. B 1 is a pinkish gray, densely welded tuff with abundant andesitic fragments in the lower part. The tuff is recrystallized and the feldspar phenocrysts are completely decomposed to calcite and clay. The SiO_2 content ranges from 76.6–77.5 wt.% in the lower part (B 1) to 69.4–75.3 wt.% in the upper part. K_2O contents ranging between 4.7 and 5.5 wt.% are detected in the ignimbrite. The Ce_n/Yb_n relation of about 5.7 is comparable to those of Cenozoic ignimbrites described by Thorpe et al. (1979). In the El Jardín area unit B2 consists of a relatively thin cover of unwelded tuff whose upper 1–3 m locally are ore-bearing.

C) Cover of the Ignimbrite (2–6 m). Smaller depressions developed at the top of the ignimbrite had been filled by almost epiclastic ignimbritic material and euxinic coal-bearing lacustrine to fluviatile deposits hosting the main orebody.

D) Conglomerate (0–120 m). A coarse polymict volcanic conglomerate lens grades laterally into thinly bedded marls, sandstones and lacustrine carbonates, host lithology of the second ore horizon.

E) Sandstones and Marls (150–200 m). The gypsiferous thinly bedded sandstone and marl sequence with intercalations of limestone beds is strongly folded.

3 Lithostratigraphic Units in the Main Orebody

The following lithostratigraphic units can be distinguished in seven sections taken in the main orebody (Fig. 3):

B2) The upper unwelded part of the pyroclastic flow occurs as the oldest unit in the underground workings. In the southern area the uppermost 1–3 m are ore-bearing, whereas in the northern part no or only weak mineralization can be

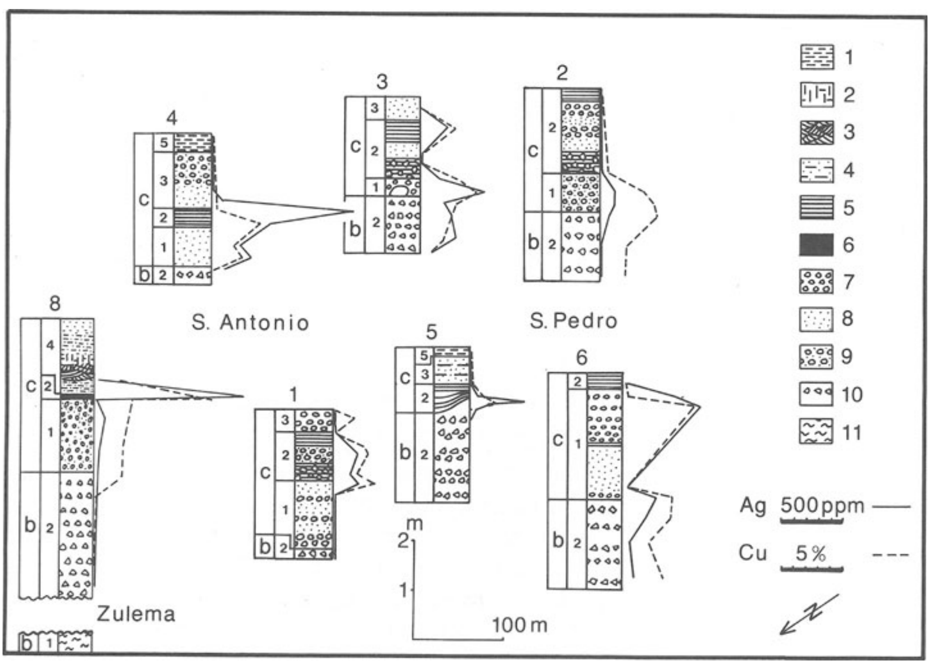

Fig. 3. Lithology and Ag-Cu distribution in the main orebody in the sectors Zulema, S. Antonio, and S. Pedro. *1* Red siltstones and sandstones; *2* rhyzolites; *3* cross-bedded siltstones; *4* sandstones with minor amount of organic material; *5* black siltstones and sandstones; *6* sandstones with coal layers; *7* sedimentary breccia; *8* sandstones; *9* sandstones with pumice fragments; *10* unwelded ash flow; *11* welded tuff

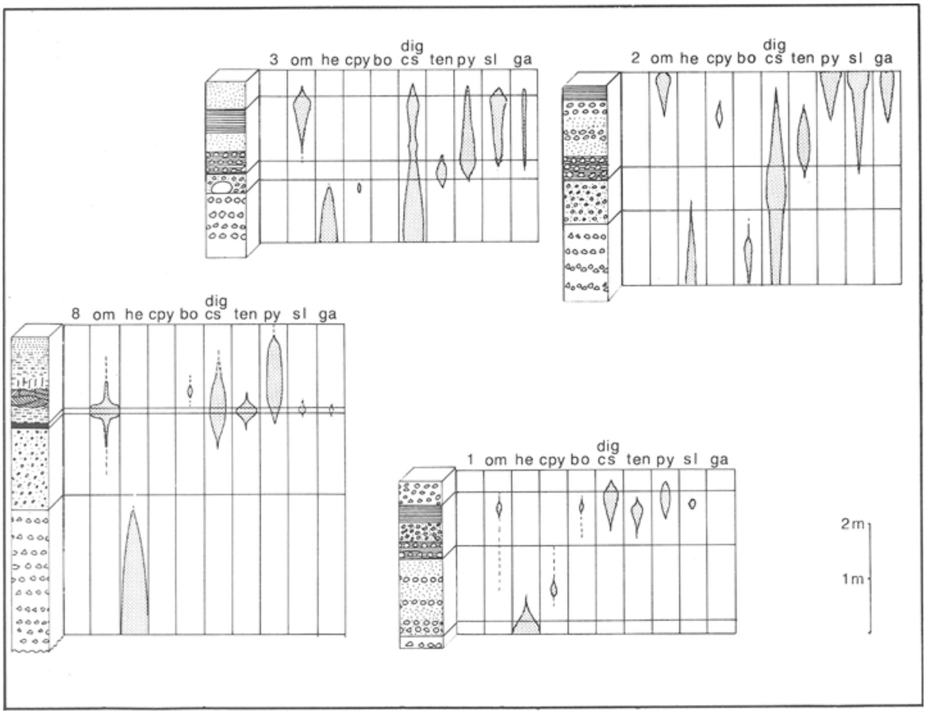

Fig. 4. Zonation in four representative sections in the main orebody. *om* Organic material; *he* hematite; *cpy* chalcopyrite; *bo* bornite; *dig* digenite; *cs* chalcocite; *ten* tennantite; *py* pyrite; *sl* sphalerite; *ga* galena. Symbols for lithology see Fig. 3

detected (Fig. 3). Pumice fragments up to 10 cm in size, glass and andesite fragments, plagioclase phenocrysts, and fragments of hematite-ilmenite intergrowths are embedded in ash material. Ash matrix, glass, and pumice fragments are altered to clay minerals and/or calcite and/or chalcedony. Unaltered plagioclase has been observed only in sections 3 and 4 (Fig. 3). Locally the upper part of the flow has been brecciated.

C 1) 0 – 2.5 m. Smaller NE-trending depressions are filled by fragments of the lower units. Their characteristic greenish color can be ascribed to the presence of chlorite. The unit is ore-bearing.

C 2) 0.1 – 2 m. Black to dark gray breccia, carbonaceous sand, and siltstones. The abundant organic material appears in the Zulema sector as up to 2-cm-thick coal seams. In the lower part of this unit organic material is strongly diluted by poorly sorted subrounded to angular pumice fragments. The upper part consists of black finely bedded carbonaceous gypsiferous silt- to sandstones. The unit is ore-bearing.

C 3) Ore-bearing breccias and sandstones overlying unit C 2 with a maximum thickness of 1.6 m.

C 4) Unit C 3 grades laterally into an up to 1.2-m-thick well-sorted glauconitic sediment of silt to fine sand particle size which exhibits cross-lamination and rhyzolites (?). It consists mainly of carbonatized glass and pumice fragments and clay material.

C 5) An almost barren reddish silt-to-sandstone represents a sudden change to oxidizing conditions.

The widespread alteration (argillic alteration, carbonatization, etc.) indicates a quite normal development during diagenesis of silica-rich volcanic glass (Fisher and Schmincke 1984). A later hydrothermal overprint need not necessarily be taken into account.

4 Ore Geometry, Composition, and Zonation

At least 95% of the ore occurs as disseminations both in fragments and matrix. Veins, veinlets, stringers, small lenses, and unusual cylindric bodies (description below) provide the rest of the ore. Main sulfide phases are chalcocite (djurleite and anilite), digenite, tennantite (up to 1% Ag and 7% Hg), bornite, covellite, chalcopyrite, pyrite, sphalerite (up to 1.5% Cd and up to 0.8% Fe), and galena (Ag contents below detection limit of microprobe analysis). Native silver, atacamite, malachite, azurite, and barite also occur. Cross-cutting veins contain

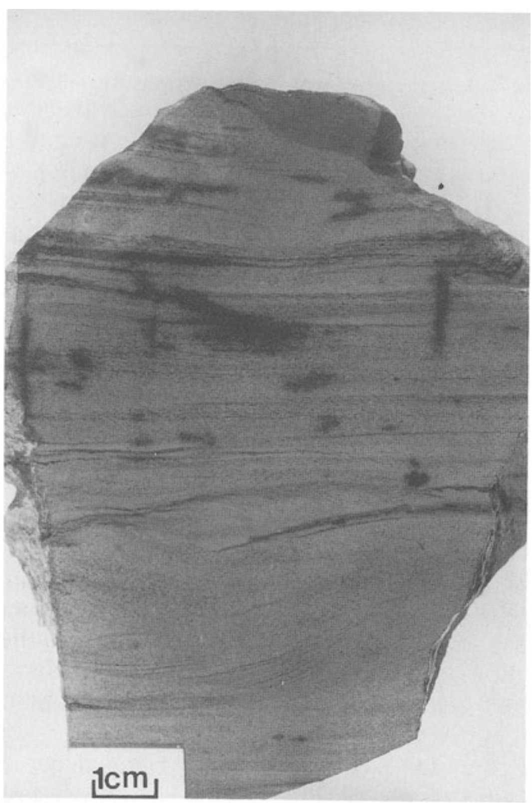

Fig. 5. Hand specimen from Unit C4 with cross-bedding. Perpendicular to bedding rhyzolites consisting of sulfides (mainly chalcocite, digenite, tennantite, bornite, and pyrite) can be recognized

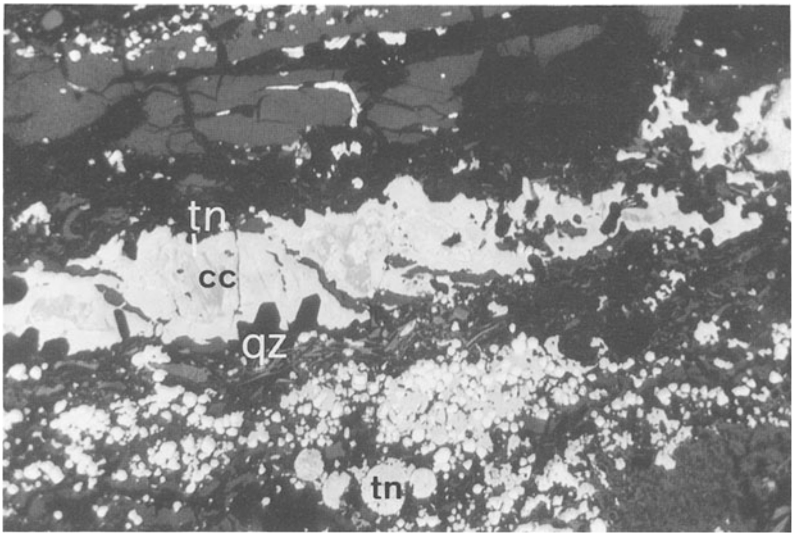

Fig. 6. Diagenetic veinlet in a coal seam of unit C2 filled by quartz, tennantite, chalcocite, and digenite. Photo length: 7 mm. Polished section, uncrossed nicols

rare pearceite, cinnabar, proustite, stromeyerite, and mckinstryite (Lortie and Clark 1987).

Main sulfide phases of the disseminated type are chalcocite and digenite, which often replace hematite-ilmenite intergrowths (unit B2), rim and/or replace anatase/brookite fragments (C1), occupy cores of former glass, pumice and plagioclase fragments and fill pore space (Fig. 7). In the latter a sequence (rim to core) of quartz-digenite-djurleite can be observed. In stringers subparallel to coal seams of unit C2, a crystallization sequence of quartz-tennantite-digenite-chalcocite can be observed (Fig. 6). In this case digenite and chalcocite reveal a laminar intergrowth. Chalcocite, digenite and tennantite replace early diagenetic framboidal pyrite. The copper phases contain up to 1.6 wt.% Ag showing a heterogeneous distribution. Silver probably occurs as smallest silver sulfide inclusions within the copper sulfides. In pore spaces the core (djurleite) is often silver-rich, whereas the rim (digenite) is nearly silver-free. Chalcopyrite is found in smallest quantities as laminar intergrowth in bornite or as fine dispersions in bornite.

The organic matter consists of fusinites, semi-fusinites with well-preserved cell structures and vitrinite. Reflection measurements (50) of vitrinite yield an average of 1.79% oil reflectivity (Teichmüller, written commun.) which represents an "Esskohle" with about 16% volatile components. This fact is consistent with the about 2500 m thickness of burial. The organic matter represents probably carbonized rods, sedge, and eel-grass of the genus *Zostera* (Lortie and Clark 1987). Sphalerite and galena occur of ten as cell fillings.

Cylindric bodies with a diameter of up to 0.9 cm and up to 15 cm length occur in unit C3 and especially in unit C4 perpendicular to bedding (Figs. 3, 5). They

Fig. 7. Glasshards in unwelded tuff (unit B2) replaced by quartz, chalcocite, and bornite. Photo length: 0.33 mm. Polished section, uncrossed nicols

consist of chalcocite, digenite, tennantite, all of them mainly replacing early diagenetic framboidal pyrite. In some of these bodies organic material occurs. Parallel to bedding and cross-bedding the same sulfide assemblage is intercalated in the siltstone. Lortie and Clark (1987) discuss these bodies as possible conducts ("pipes") of a fumarolic system. An interpretation as rhyzolites (also discussed by the above-cited authors) is favored by the present author because of: (1) the considerable amount of organic material in the "pipes" and wall rock, (2) the absence of alteration halos around the "pipes", (3) the absence of feeder channels below the "pipes", (4) the presence of ore parallel to bedding and cross-bedding without direct spacial relationship with the "pipes" and (5) the environment (levee sequence) of which rhyzolites are a typical constituent.

In all the observed sections a clear vertical zonation can be detected (Fig. 4). This zonation is quite similar to other stratiform Cu and Cu-Ag deposits of the Kupferschiefer and red bed type.

5 Conditions of Ore Formation

Ore textures and the peneconcordant geometry suggest that sulfide formation started during early diagenesis (framboidal pyrite) and culminated during final cementation of pore space. The formation of ore in the veinlets and veins can be explained by remobilization after lithification. Cross-cutting features like in El Jardín are a typical component in red-bed deposits. Temperatures on base of vitrinite reflectivity (Teichmüller and Teichmüller 1967) and Cu-Fe-S phase relationships (Roseboom 1966) are estimated below 103 °C. Laminar intergrowths of digenite and djurleite indicate temperatures above this point. Fluid inclusions in quartz of veins yielded homogenization temperatures about 140° ± 20 °C with maximum temperatures up to 250 °C (Lortie and Clark 1987). Sulfur isotope analyses of a few more or less coexisting sulfide and sulfate samples support low temperatures and are in "permissive agreement with a bacterial reduction system" (Lortie and Clark 1987). Supergene alteration can be documented by the oxidation of pyrite, depleted zinc contents, and abundant occurrence of Cu-carbonates in near-surface sections. As source of the metals, either the volcanic rocks of the Cerrillos Formation or the ignimbrite itself can be considered. Leached out by meteoric waters and probably transported as chloride or bisulfide complexes, the metals have been trapped during diagenesis under euxinic conditions in small basins developed on the surface of the ignimbrite and in the ignimbrite itself. A direct supply of a part of the metals by fumarolic activity in the vicinity cannot be excluded, but evidence is lacking. The El Jardín Ag-Cu deposit thus constitutes an unusual deposit, in many respects revealing similarities with red-bed and Kupferschiefer-type deposits. The close relationship to continental acid explosive volcanism should be pointed out.

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