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# Manto Type Copper Deposits in Chile — a Review

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**Abstract:** Many manto type copper sulfide deposits occur in the Coastal Range of Chile being hosted by Jurassic to Early Tertiary volcanic-dominant formations. The host rocks are most commonly amygdaroidal lava flows and volcaniclastics of various compositions. Limestones and calcareous shales are also mineralized. Major ore minerals are chalcopyrite, bornite and chalcocite in association with pyrite, hematite and/or magnetite. Wallrock alteration is generally very weak or none.

By examining published data on geology, geochemistry and mineralogy of the host rocks and ore deposits, it is suggested that dehydration processes due to advanced burial metamorphism might be responsible for the formation of the Chilean manto type copper deposits. Accumulation of thick eugeosynclinal piles containing abundant copper-rich volcanics in the western part of the Andean geosyncline during the Jurassic and Cretaceous times may explain why the Chilean Coastal Range is rich in this unique type of copper deposits.

## 1. Introduction

Manto type stratiform copper sulfide deposits are widely distributed in the Coastal Range of north-central Chile (Fig. 1 and Table 1). They have several unique characteristics in comparison with other types of stratiform copper deposits; (1) they are hosted by marine and continental volcanics of Jurassic to Eocene in age and, less commonly, by limestones and shales interbedded with the volcanics; (2) amygdules of lavas and matrices of volcanic breccias and volcanic sandstones are the most favourable sites of mineralization; (3) chalcopyrite, bornite and chalcocite are the major copper sulfides coexisting with pyrite, hematite and/or magnetite; (4) wallrock alteration is generally very weak or none, being undistinguishable from regional diagenetic alteration.

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The purpose of this article is to review recent knowledge on this unique type of copper deposits from literatures and the present author's own observations during his stay in Chile in November-December, 1981.

## 2. General Geology—A Brief Review of the Tectonic and Magmatic Evolution of the Andean Geosyncline

The Jurassic to Eocene volcanics hosting the manto type copper deposits are the products of the Andean orogenic cycle, which is interpreted to have been controlled by the subduction of an oceanic (Pacific) crust under the South American continent (RUTLAND, 1971; COIRA *et al.*, 1982). COIRA *et al.* (1982) divided the Andean orogenic cycle into two principal stages, *i.e.*, the Jurassic-Early Cretaceous stage and the Late Cretaceous-Recent stage.

The Jurassic-Early Cretaceous stage is characterized by the accumulation of a thick pile of volcanic-dominant sequences in the

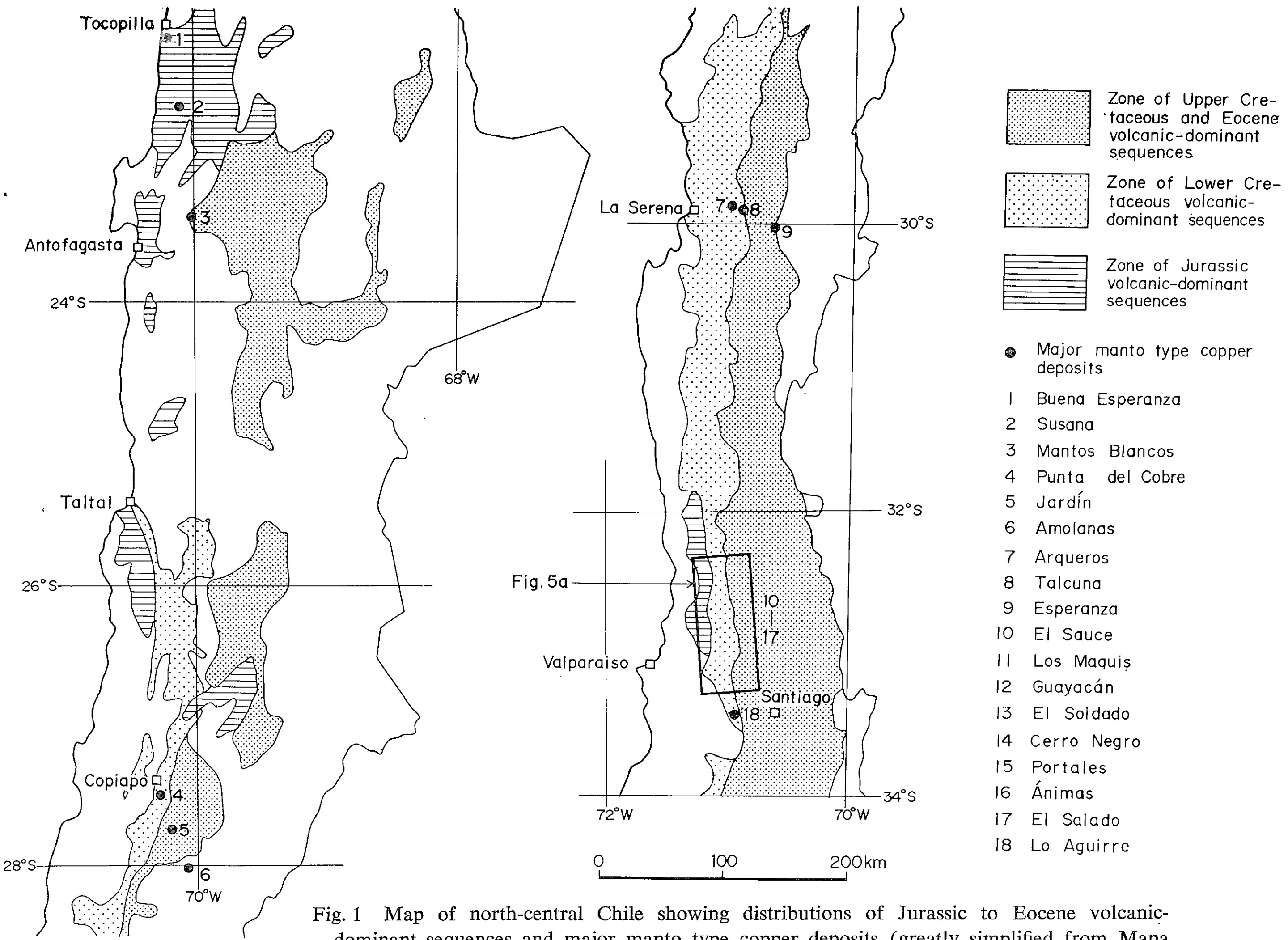


Fig. 1 Map of north-central Chile showing distributions of Jurassic to Eocene volcanic-dominant sequences and major manto type copper deposits (greatly simplified from Mapa Geológico de Chile (1 : 1,000,000), 1982/1983, Servicio Nacional de Geología y Minería).

Coastal Range of north-central Chile (Fig. 1). The volcano-sedimentaries, overlying marine sediments of early Liassic age, are several thousand meters thick and have great lateral extensions. They grade into fossilferous marine sediments toward east, and RUIZ *et al.* (1965) inferred an eugeosynclinal environment for the volcanic-dominant sequences and a miogeosynclinal environment for the marine sediments. According to a modern interpretation based on plate tectonics by COIRA *et al.* (1982), the former is attributed to a magmatic arc and the latter to an ensialic back arc basin.

The products of the Jurassic magmatic arc are typically exposed in the Antofagasta-Tocopilla region, where they host several manto type deposits (see Fig. 1). They are called the La Negra formation and consist mainly of lavas of andesite, low-silica andesite, high-K andesite and olivine basalt with occasional intercalations of volcanic breccias, tuffs and sandstones (LOSERT, 1973; 1974). PALACIOS (1978) distinguished tholeiitic, calc-alkaline and alkaline suites, but could not note any temporal nor spatial zonation among them. The initial strontium isotopic ratios of the Jurassic plutonic rocks, which are supposed to be comagmatic with the contemporaneous volcanics (LOSERT, 1973), are as low as 0.70344 suggesting a primitive source for the Jurassic magmas (SHIBATA *et al.*, 1984).

In the Early Cretaceous, the site of magmatism shifted eastward and the sedimentary basin was narrowed. COIRA *et al.* (1982) suggested eastward migration of the magmatic arc and shrinkage of the back arc basin at this stage.

The Early Cretaceous sequences are composed mainly of intermediate and felsic volcanics intercalated with marine sediments; ignimbrite and continental sediments occur locally. They are hosting many manto type deposits especially in the north Santiago area, which will be described in detail in a following chapter.

The site of magmatism shifted farther east in Late Cretaceous to the western foothills of the Cordillera Occidental, and the sedimentary environment of the Andean geosyncline became totally continental. COIRA *et al.* (1982) inferred that the previous arc-back arc basin pair was replaced by a single eastward migrating magmatic arc at the end of Early Cretaceous probably as a result of the final opening of the Atlantic and the active westward movement of the South American Plate. This can be interpreted as the change of plate subduction regime from Mariana type to Chilean type as defined by UYEDA and KANAMORI (1979).

The volcanism of Late Cretaceous and Early Tertiary is characterized by extrusion of felsic lavas and ignimbrites, but basalt and andesite were also produced. These volcanics host some manto type deposits including the wellknown Mantos Blancos deposit, which occurs in Late Cretaceous dacitic lavas.

The initial strontium isotopic ratios of the plutonic and volcanic rocks of this time span increase with time from 0.7022–0.7035 in Late Cretaceous to 0.7043–0.7057 in Early Tertiary (MCNUTT *et al.*, 1975). This time-dependent increase in initial ratio is recognized to continue in younger rocks, and MCNUTT *et al.* (1975) supposed that the magmas were generated by partial melting first in the subducted oceanic crust and then in the hangingwall mantle peridotite.

In summary, tectonic regime of the Andean geosyncline changed greatly at the end of Early Cretaceous, and at the same time the depositional environment changed in general from marine to continental. The chemistry of volcanics and the site of magma generation also appear to have changed with time. It is noteworthy that the manto type copper deposits occur in the rocks of whole time span from Jurassic to Early Tertiary and in various lithologies regardless of rock chemistry, sedimentary facies or regional tectonics.

Table 1 Some Major Manto Type

| No. | Name of Deposit or District (deposit type) | Location (lat. S/lon. W) | Formation (age) | Host Rock |
|---|---|---|---|---|
| 1 | Buena Esperanza (II) | 22°11′/70°14′ | La Negra (J) | Amyg. andesite and basalt |
| 2 | Susana (II) | 22°40′/70°15′ | La Negra (J) | Amyg. andesite and basalt |
| 3 | Mantos Blancos (III) | 23°26′/70°04′ | Augusta Victoria (LK) | Dacite |
| 4 | Punta del Cobre (I) | 27°30′/70°15′ | Chañarcillo (EK) | "Albitophyre" and breccia |
| 5 | Jardín (III) | 27°43′/70°12′ | Hornitos (E) | Rhyolite and ignimbrite |
| 6 | Amolanas (III) | 28°02′/70°03′ | Hornitos (E) | Rhyolite |
| 7 | Arqueros (II ?) | 29°45′/70°56′ | Arqueros (EK) | Limestone |
| 8 | Talcuna (I) | 29°53′/70°53′ | Quebrada Marquesa (EK) | Lapilli tuff and sandstone |
| | Socorro | | | |
| | Vasquez | | | |
| | Chilena | | | |
| | Coca-Cola | | | |
| | Andacollo | | | |
| | Poderosa and Bienvenido | | | |
| | Tambor | | | |
| 9 | Esperanza (I ?) | 30°04′/70°37′ | Pucalume (LK) | Conglomerate and sandstone |
| 10 | El Sauce (I ?) | 32°27′/71°04′ | Lo Prado (EK) | Limestone |
| 11 | Los Maquis (II) | 32°28′/71°04′ | Lo Prado (EK) | Limestone and shale |
| 12 | Guayacán (I) | 32°32′/71°05′ | Lo Prado (EK) | Andesite and calcareous shale |
| 13 | El Soldado (III) | 32°38′/71°06′ | Lo Prado (EK) | Limestone, tuff br. and andesite |
| 14 | Cerro Negro (I) | 32°34′/70°51′ | Las Chilcas (LK) | Volcanic breccia |
| 15 | Portales (I ?) | 32°38′/70°52′ | Las Chilcas (LK) | Carbonaceous and calcareous shale |
| 16 | Animas (I) | 32°40′/70°54′ | Cerro Morado (LK) | Andesitic breccia |
| 17 | El Salado (III) | 32°45′/70°58′ | Veta Negra (EK) | Rhyolite and welded tuff |
| 18 | Lo Aguirre (III) | 33°27′/70°56′ | Veta Negra (EK) | Andesite |

Abbreviations for age. J : Jurassic, EK : Early Cretaceous, LK : Late Cretaceous, E : Eocene.

## 3. General Characteristics and Classification of the Chilean Manto Type Copper Deposits

More than fifty manto type copper deposits are known in Chile (*e.g.*, RUIZ *et al.*, 1965). Of these, 18 deposits or districts are relatively well described and listed in Table 1. Traditionally they have been classified mainly on the basis of host rock lithology (CARTER, 1961; RUIZ *et al.*, 1965). In this paper, the deposits will be subdivided on the basis of the shape of deposits because the morphological classification appears to be more convenient to sort the characteristics of the manto type copper deposits that show various modes of occurrence.

**Type I : Stratabound tabular deposits**

This type is characterized by occurrence of many small orebodies in a particular stratigraphic horizon. Orebodies are tabular in form and are connected each other by a weakly mineralized zone. In many cases the mineralized horizon is a lithologic boundary

Copper Deposits in Chile.

| Sulfide Assemblage | Reserve (R) ; Production (P) (in 1,000 tons) | Grade | Source |
|---|---|---|---|
| cc, bn, cp, dg, cv, py | 2,500 (P) | 3%Cu | Ruiz *et al.* (1971) |
| cc, cp, py, cv, bn | 8,000 (R) | 1.7%Cu, 30-40g/tAg | Espinoza (1981b), Palacios and Definis (1981) |
| cc, bn, cp, py, cv, gn | 43,000 (P until 1981)<br>22,500 (R) | 1.51-1.90%Cu<br>1.6%Cu, 21g/tAg | Anonymons (1981) |
| cp, py | 3,500 (P for 1800-1978) | 6%Cu | Camus (1980) |
| cc, bn, dg, cv, cp, py, sp, gn | | | Zentilli (1974) |
| bn, cc, cp | 2,800 (R) | 2.0%Cu | Zentilli (1974) |
| cc, cv, bn, cp, py, gn | 3,800 (R) | 1.2%Cu, 10g/tAg | Kamono and Borić (1982) |
| bn, cp, cc, gn | | | Kamono and Borić (1982) |
| | 240 (R) | 1.50%Cu, 50g/tAg | |
| | 215 (R) | 1.50%Cu | |
| | 36 (R) | 2.32%Cu, 41g/tAg | |
| | 140 (R) | 1.5-1.7%Cu, 15g/tAg | |
| | 16 (R) | 2.5%Cu | |
| | 810 (R) | 1.2-1.5%Cu, 15g/tAg | |
| | 50 (R) | 1.13%Cu, 53g/tAg | |
| cp, cc | 650 (R) | 4.75%Cu | Kamono and Borić (1982) |
| cp, py | | 1.8-2.2%Cu | JICA (1980) |
| cp, py | | 1.5-2.0%Cu | JICA (1980) |
| cp, py, bn | | 1.8%Cu | Ruiz *et al.* (1971), JICA (1980) |
| cc, dg, bn, cp | 28,100 (R) | 1.9%Cu | Ruiz *et al.* (1965), I.I.M.Ch (1980) |
| bn, cp, cc, py | 1,600 (P until 1963) | 2.8%Cu | Ruiz *et al.* (1965, 1971) |
| | | | Ruiz *et al.* (1971) |
| cp, bn, cc, cv, py | 180 (P for 1978-1980) | 1.3-1.8%Cu | JICA (1980) |
| bn, cp, cv | | | JICA (1980) |
| bn, dg, cc, cv, py | 11,100 (R) | 2.14%Cu | I.I.M.Ch. (1980) |

Abbreviations for minerals. bn : bornite, cc : chalocite, cp : chalcopyrite, cv : covelline, dg : digenite, gn : galena, py : pyrite, sp : sphalerite.

such as a boundary between volcanics and sediments. Typical and well-described examples of this type are the Talcuna district near La Serena (Kamono and Borić, 1982) and the Punta del Cobre district near Copiapo (Camus, 1980).

In the Talcuna district, mineralization took place in a 2 to 12 meters thick lapilli tuff/tuffaceous sandstone horizon sandwitched by an underlying andesitic tuff breccia/lava unit and an overlying sandstone/siltstone unit (Fig. 2). Uppermost amygdaloidal parts of the underlying andesitic lavas are also mineralized. The mineralization continues at least 5 km along this horizon. Of this mineralized bed only restricted parts are of economic grade and minable. NW–SE trending vertical faults, which themselves are mineralized to economic grade, appear to have controlled the high grade parts (see Fig. 2). There is no distinct wallrock alteration observed, but the host volcano-sedimentaries are regionally altered into calcite-chlorite-analcime-hematite assemblage with epidote and prehnite de-

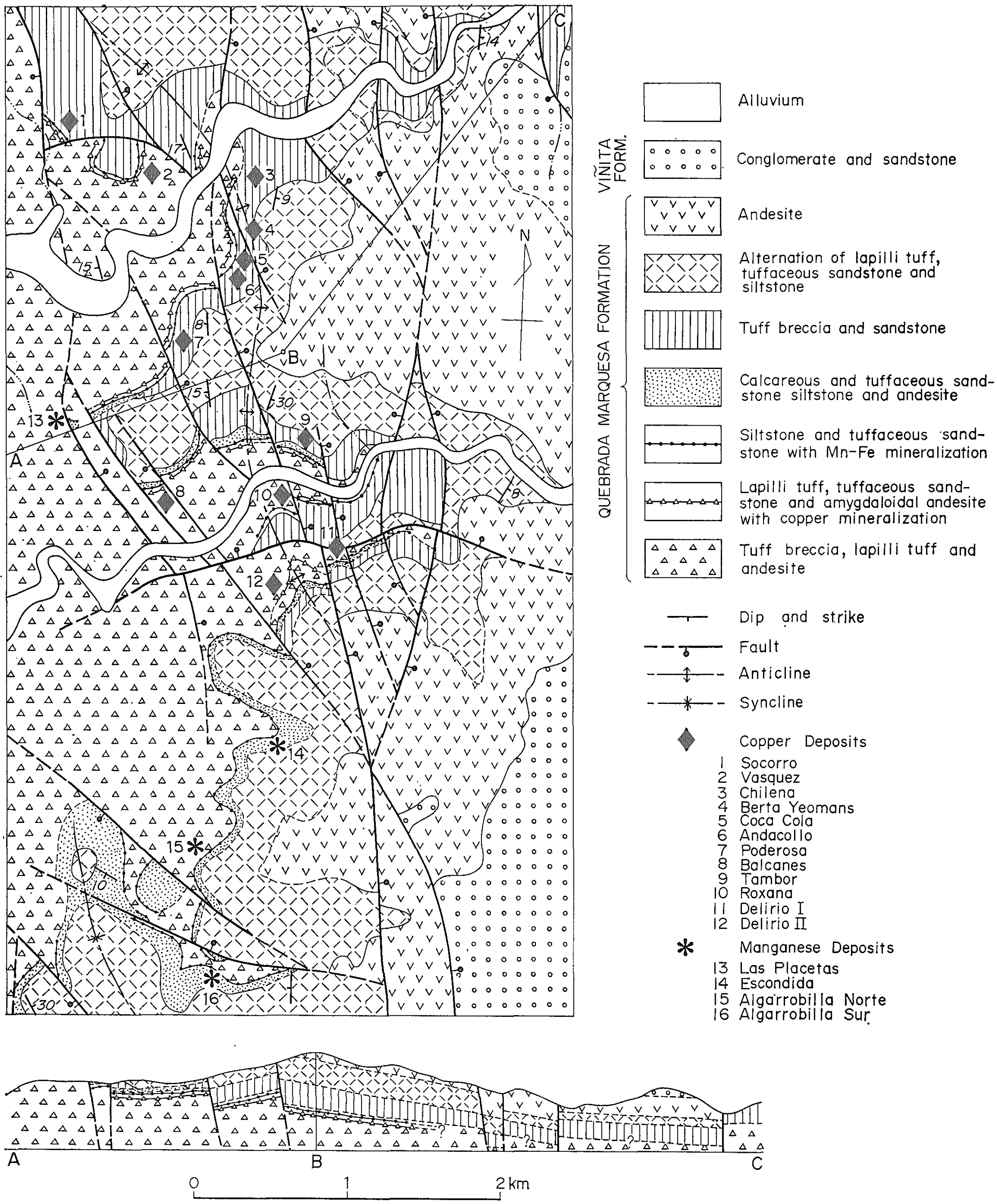


Fig. 2 Geologic map of the Talcuna district (modified from KAMONO and BORIĆ, 1982).

veloped in stratigraphically lower levels. It is noteworthy that bedded Mn–Fe oxide mineralization occurs in the tuffaceous sandstone/siltstone horizon overlying the copper horizon. It is more widespread than the copper mineralization and becomes thicker toward southwest, where the copper bed disappears (Fig. 2). Genetic relationship between the two mineralizations are not well understood.

In the Punta del Cobre district, many orebodies occur in an andesitic breccia horizon between underlying massive andesite and overlying shale. Here again the site of economic concentration of copper appears to be controlled by faults. Wallrock alteration is not clearly distinguished from regional alteration except for increase in amount of chlorite and sericite toward orebodies especially near the mineralized faults.

Other deposits with similar features include Guayacán (RUIZ *et al.*, 1971; CARTER, 1961), Cerro Negro (RUIZ *et al.*, 1971) and Animas (JICA, 1980). Though information is not sufficient, many of the small deposits listed in RUIZ *et al.* (1965) and JICA (1980) may be included in this type.

**Type II : Stacked tabular deposits**

In this type many tabular orebodies occur in lithologically favourable parts of host rocks, such as amygdaloidal flow tops of lavas and calcareous sediments alternating with shale or siltstone.

A well-described example of this type is

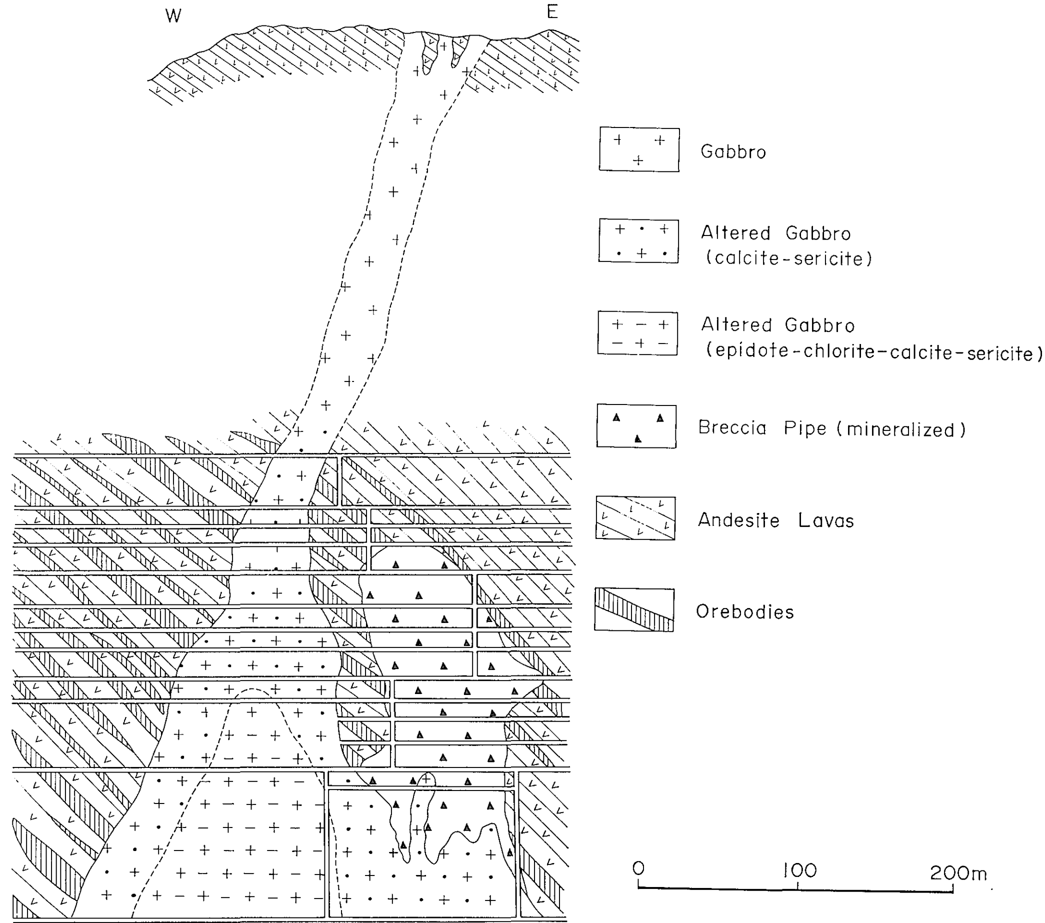


Fig. 3 W–E cross section of the Buena Esperanza deposit (PALACIOS and DEFINIS, 1981).

the Buena Esperanza deposits near Tocopilla (LOSERT, 1973, 1974; PALACIOS and DEFINIS, 1981). It is composed of at least 28 parallel orebodies occurring in the Jurassic La Negra formation (Fig. 3). Ore grade mineralization is confined to amygdaloidal flow tops of andesitic lavas and volcaniclastic lenses, occurring as amygdule-fillings, thin veinlets and disseminations. Weak mineralization extends to massive basal parts of the lava flows and to the gabbroic intrusive and the breccia pipe, which appear to have controlled the site of mineralization (Fig. 3). Wallrock alteration is not conspicuous, but detailed studies by LOSERT (1973) and PALACIOS and DEFINIS (1981) indicate that the alteration mineral assemblage in and near the orebodies is albite-calcite-sericite-chlorite-hematite, which is different from that of regional alteration in disappearance of zeolites, prehnite, pumpellyite and/or epidote. The Susana deposit situated about 50 km south of Buena Esperanza has similar features (ESPINOZA, 1981b).

The Los Maquis deposit near Cabildo (CARTER, 1961) is a good example of stacked tabular deposits in calcareous sediments. It occurs in a limestone member of the Early Cretaceous Lo Prado formation and consists of several tabular orebodies each 0.5 to 3 meters thick. Orebodies are separated each other by barren siltstone beds. The Los Maquis deposit is unique in that abundant grossular garnet occurs as a gangue mineral suggesting a contact metasomatic nature of the mineralization (CARTER, 1961).

**Type III : Pseudostaratiform deposits**

This type is characterized by irregular pseudostratiform orebodies generally obliquely cutting the stratification of host rocks. Ore minerals occur as fine dissemination and veinlets. Host rocks are various but most commonly acid lava flows and ignimbrites.

A typical example of this type is the Mantos Blancos deposit near Antofagasta (Fig. 4). Here irregular blanket-like orebodies, each 100 to 200 meters thick, occur in the Augusta Victoria continental volcanic formation of Late Cretaceous in age. Although the volcanic sequence in the Mantos Blancos district contains lava flows and flow breccias of andesite and dacite, only the dacitic units are mineralized (ANONIMOUS, 1981). Other examples of type III include

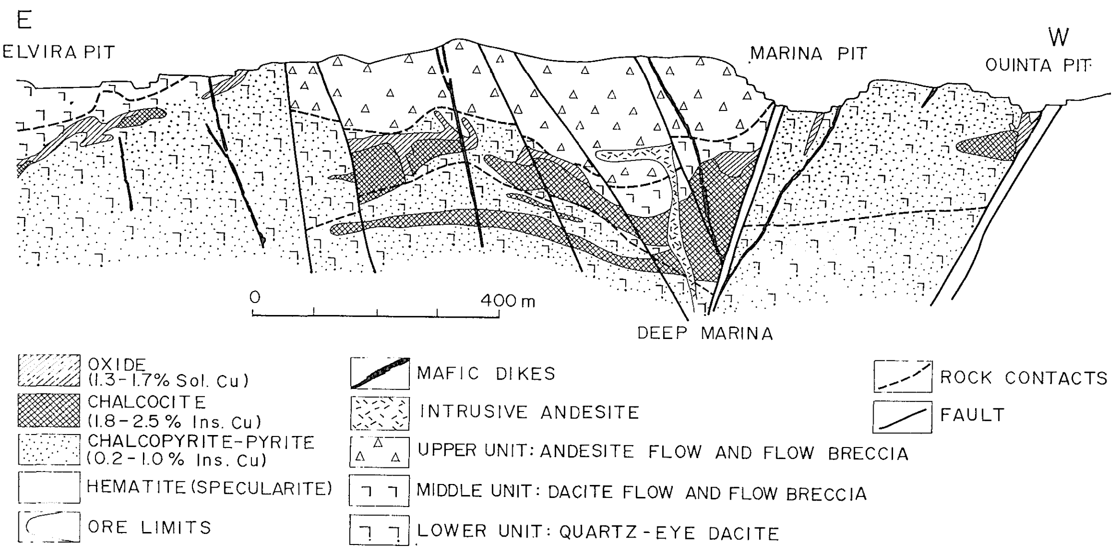


Fig. 4 E–W cross section of the western part of the Mantos Blancos deposit (after ANONIMOUS, 1981).

Jardín and Amolanas (in Eocene rhyolitic flows and ignimbrites), El Soldado (in Early Cretaceous volcano-sedimentaries including ignimbrites), El Salado (in Early Cretaceous dacitic flows and welded tuffs) and Lo Aguirre (in Early Cretaceous andesites and dacitic flows).

Another important feature of this type is the presence of well-developed alteration halos. For example, the Mantos Blancos ore-bodies are surrounded by extensive albitization and silicification (ANONIMOUS, 1981), the El Soldado by albitization (TERRAZAS, 1977), and the El Salado by silicification and sericitization (HUETE, 1969). This is contrastive to other types, whose alteration is generally very weak. Ore mineralogy of type III deposits is, however, similar to that of other types. It should be also noted that the deposits of type III tend to have much larger scales in terms of ore reserve and/or production than the deposits of other types (Table 1).

## 4. Distribution of Manto Type Copper Deposits in the North Santiago Area—An Example of their Regional Geologic Setting

In an area between Cabildo and Tiltil, about 50 to 100 km north-northwest of Santiago, there is a cluster of many manto type copper deposits (Figs. 5a and b). Examination of this area may provide basic information for understanding regional geologic setting of this type of deposits. The following descriptions are based mainly on THOMAS (1958), RUIZ *et al.* (1965), LEVI (1969, 1970) and JICA (1980).

### Geology

The area is geologically composed of volcanic-dominant sequences of more than 20 km in accumulated thickness and ranging in age from Jurassic to Early Tertiary as well as many granitoid stocks and batholiths intruded in them (Fig. 5 and Table 2). It provides a typical geologic traverse of the Coastal Range of the Andean orogenic belt, which corresponds to the "eugeosyncline" of RUIZ *et al.* (1965) and the "magmatic arc" of COIRA *et al.* (1982).

The Jurassic-Early Tertiary sequences are composed mainly of intermediate and felsic lavas, flow breccias, ignimbrites and pyroclastics with intercalations of limestone lenses and clastic sediments. The Jurassic to Lower Cretaceous units are characterized by relative abundance of ignimbrites, and the "Middle" and Upper Cretaceous units by andesitic lavas and flow breccias with subordinate felsic lavas and ignimbrites (Table 2). The depositional environment was partly marine (predominantly shallow water) and partly terrestrial during Jurassic and Early Cretaceous, and exclusively terrestrial during "Middle" Cretaceous to Early Tertiary.

There are three major unconformities in this thick volcano-sedimentary pile. They are the Patagua unconformity between the Middle Jurassic Melón formation and the Lower Cretaceous Lo Prado formation, the Peralillo unconformity between the "Middle" Cretaceous Cerro Morado formation and the Upper Cretaceous Las Chilcas formation, and the Lo Valle unconformity between the Las Chilcas formation and the Lo Valle formation of Late Cretaceous and/or Early Tertiary in age (see Table 2).

The plutonic rocks in the area are penecontemporaneous with the intruded sequences. They are mostly tonalite and granodiorite in composition and belong to I-type magnetite series. For details of the plutonic rocks, the reader should refer to ISHIHARA *et al.* (1984).

### Metamorphism/Regional Alteration

The rocks of the area as well as pre-Neogene sequences of the Andean geosyncline in general have been regionally altered into zeolite to greenschist facies (LEVI, 1970). The metamorphic grade increases stratigraphically downward and the isograds are essentially parallel with bedding without any apparent relation to granitoid intrusives; the original textures of the rocks are well preserved without any internal deformation (LEVI, 1969, 1970).

Although the above-mentioned features indicate that the regional alteration of this area corresponds to burial metamorphism as described in New Zealand (COOMBS, 1960), detailed studies by LEVI (1969, 1970) revealed out that the metamorphism of the area has some unique characteristics; that is, though metamorphic grade generally increases with stratigraphic depth, abrupt discontinuities in metamorphic grade are observed at major unconformities. Since there are three unconformities in the Jurassic to Lower

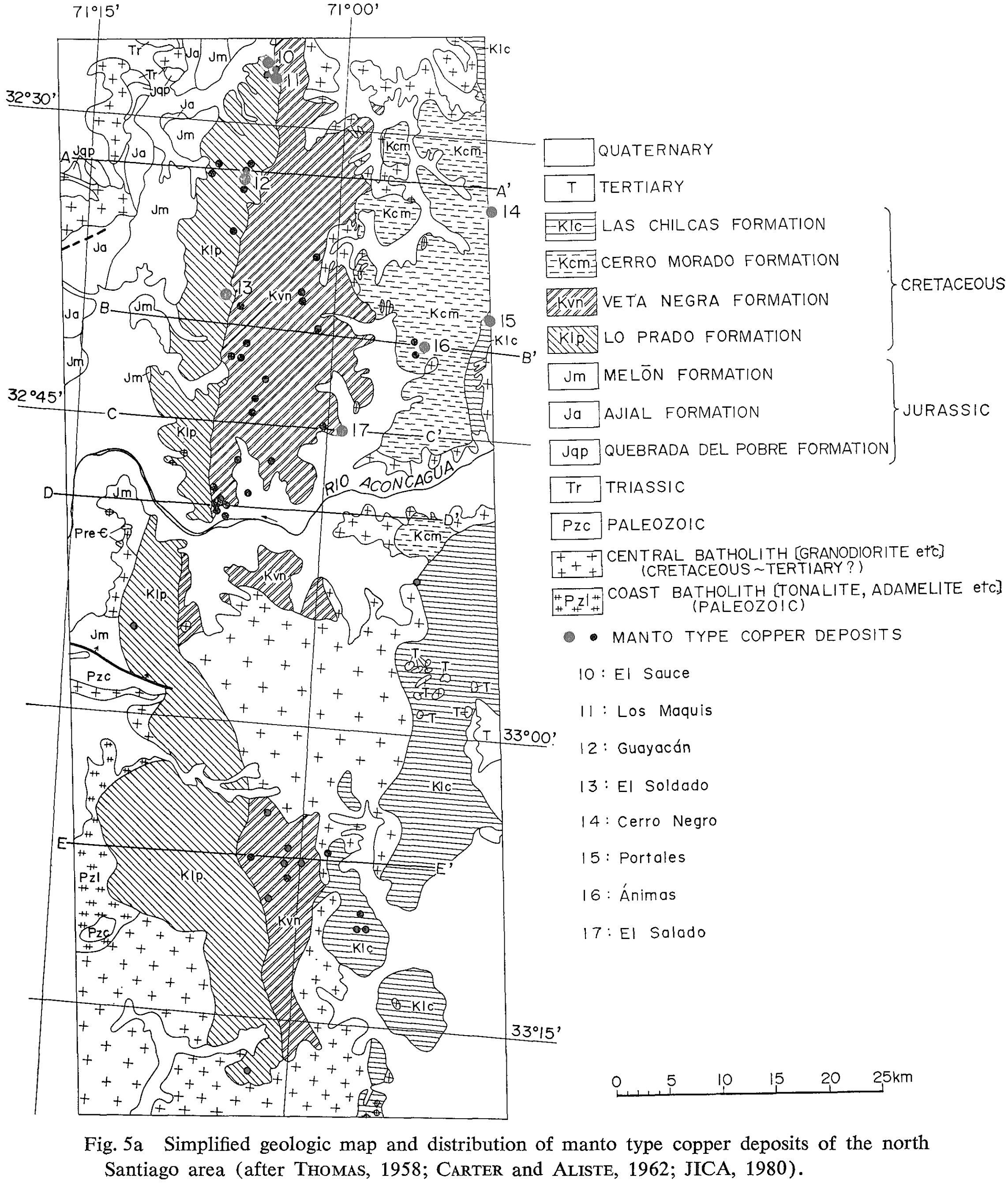


Fig. 5a Simplified geologic map and distribution of manto type copper deposits of the north Santiago area (after THOMAS, 1958; CARTER and ALISTE, 1962; JICA, 1980).

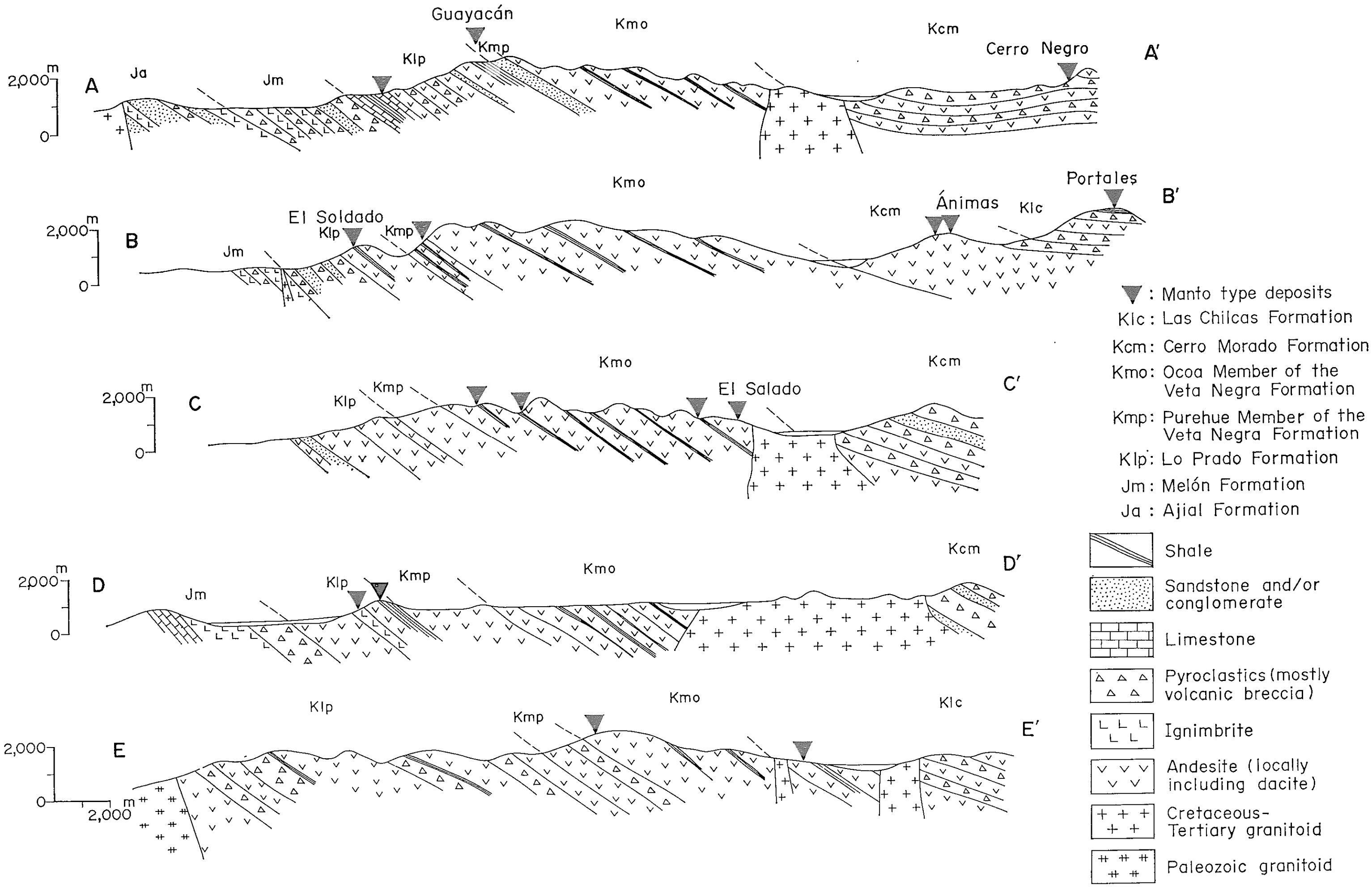


Fig. 5b Cross sections along A–A′ to E–E′ lines in Fig. 5a).

Table 2 Stratigraphic relations and lithologies of Jurassic to Early Tertiary formations of the Coastal Range of Central Chile (modified from LEVI, 1970).

| STRATIGRAPHIC UNIT | | AGE | THICKNESS | LITHILOGY AND DEPOSITIONAL ENVIRONMENT |
|---|---|---|---|---|
| LO VALLE FORMATION | | LATE CRETACEOUS AND/OR EARLY TERTIARY | 600m | Andesitic pyroclastic rocks, mostly ignimbrites, and lavas, partly brecciated; minor acid pyroclastic rocks, mostly ignimbrites; lacustrine, fluviatile and mud flow deposits, partly lahars. *LO VALLE UNCONFORMITY* |
| LAS CHILCAS FORMATION = PERALILLO STRATA | | LATE CRETACEOUS | 2600 to 7000m | Mostly fluviatile and mud flow (in part lahar) deposits; subordinate brackish-water sediments. Andesitic lavas partly brecciated, and subordinate andesitic pyroclastic rocks; scarce acid ignimbrites. *PERALILLO UNCONFORMITY* |
| VETA NEGRA FORMATION | NOVICIADO MEMBER = CERRO MORADO FORMATION | EARLY TO "MIDDLE" CRETACEOUS | 5500 to 7500m | Brecciated andesitic lavas and clastic rocks, mostly mud flows (probably lahars); subordinate acid lavas. |
| | OCOA MEMBER | | | Andesitic lavas, partly brecciated; scarce acid ignimbrites and continental clastic rocks, mostly mud flows (probably lahars) and lacustrine deposits. |
| | PUREHUE MEMBER | | | Andesitic lavas, partly brecciated, and continental clastic rocks, mostly lacustrine and deltaic deposits; subordinate acid ignimbrites and mud flows (probably lahars) |
| LO PARADO FORMATION | LO PRADO FORMATION s.s. | EARLY CRETACEOUS | 700 to 1500m | Acid pyroclastic rocks, mostly ignimbrites and brecciated lavas; marine near-shore clastic rocks and limestones; continental fluviatile and/or deltaic sediments; subordinate andesitic lavas |
| | PACHACAMA FORMATION | | 0 to 1000m | Acid ignimbrites and lavas, and continental clastic rocks; subordinate andesitic lavas. |
| | PATAGUA FORMATION | | 2000m | Marine clastic rocks, partly turbidites, and subordinate marine cherts and limestones; subordinate acid ignimbrites and andesitic lavas. *PATAGUA UNCONFORMITY* |
| MELÓN FORMATION | FORQUETA MEMBER | MIDDLE JURASSIC | 2100 to 5500m | Continental clastic rocks, mostly mud flows (probably lahars) and fluviatile sediments; andesitic lavas, mostly brecciated, and acid ignimbrites. |
| | NOGALES MEMBER | | | Acid ignimbrites, and marine near-shore clastic rocks and limestones. |
| AJIAL FORMATION | | EARLY TO MIDDLE JURASSIC | 750 to 1300m | Acid ignimbrites, very subordinate andesitic brecciated lavas, and marine near-shore clastic rocks and limestones. |
| QUEBRADA DEL POBRE FORMATION | | EARLY JURASSIC | 300 to 1250m | Marine clastic rocks and limestones; minor acid ignimbrites and scarce andesitic lavas. |
| PRE-JURASSIC BASEMENT | | | | |

Tertiary formations in this area (see Table 2), four metamorphic series are recognized in them; *i.e.*, one below the Patagua unconformity, one between the Patagua and the Peralillo unconformities, one between the Peralillo and the Lo Valle unconformities, and the last above the Lo Valle unconformity. Among these the first two range from prehnite-pumpellyite facies at the top to greenschist facis at the bottom; the third series in the Upper Cretaceous formations ranges from zeolite facies to prehnite-pumpellyite facies in most places with local occurrences of greenschist facies at the bottom; and the last series in the Upper Cretaceous and/or Lower Tertiary formation is of zeolite facies throughout.

LEVI (1969) also noted that, in a single lava flow unit, the non-amygdaloidal base is relatively unaltered, whereas the amygdaloidal top is strongly altered. This suggests that deuteric action has played an important role in the burial metamorphism in this area, which is supported by considerable changes in chemical composition during metamorphism (LEVI, 1974; CHAVEZ and NISTERENKO, 1974) and presence of veinlets containing calcite, zeolites, epidote, etc. in the altered rocks (LEVI, 1970).

**Ore Deposits**

The north Santiago area is one of the richest area of the manto type copper deposits. JICA (1980) listed up about 30 deposits in the area (Fig. 5), of which major eight are shown in Table 1.

Stratigraphic horizons of the host rocks range from the Lo Prado to the Las Chilcas formations; no deposits are known in the Jurassic formation or the Upper Cretaceous and/or Lower Tertiary Lo Valle formation (see Fig. 5). The deposits occur in various host rocks such as lavas, ignimbrites, flow breccias, volcaniclastics, calcareous shales and limestones. Their shapes and modes of occurrence are also various including all the three types mentioned earlier.

There is no apparent regional control on the site of mineralization. Although small intrusive bodies, faults and/or stratigraphic horizons appear to have locally controlled mineralization in some places (CARTER, 1961; HUETE, 1969; TERRAZAS, 1977; JICA, 1980), regional distribution of the deposits in this area are not related to any particular stratigraphic horizons, depositional environment of host rocks or plutonic bodies.

## 5. Discussions

**Genesis**

An exhalative sedimentary origin seems to be favoured by some Chilean geologists for the manto type copper deposits (*e.g.*, RUIZ *et al.*, 1971; CAMUS, 1980; ESPINOZA, 1981a). However these authors have failed to present, nor has the present author could observe in the field, any definite proof for the syngenetic origin of the deposits. For instance synsedimentary and other features characteristic to volcanic-hosted or sediment-hosted massive sulfide deposits, for which syngenetic origins are almost unanimously accepted, are completely lacking in the manto type deposits. The following discussions will therefore be made under a working hypothesis that the Chilean manto type copper deposits are of epigenetic origin.

In consideration of the mineralizing processes of the manto type deposits, the following characteristics of the deposits are important:

1) The mineralization occurs in various horizons in Jurassic to Eocene volcano-sedimentary sequences of marine and continental origins.

2) The mineralization took place most favourably in porous rocks such as amygdaloidal lavas and volcanic breccias or in chemically weak rocks such as calcareous beds.

3) The site of mineralization is locally controlled in many cases by faults and in some other cases by intrusive bodies.

4) Except for type III, there is no distinct wallrock alteration near the orebodies, but the host volcano-sedimentary pile is extensively altered by diagenetic or burial metamorphic processes.

5) The ore mineralogy is characterized by assemblages of low sulfur to metals ratios.
6) Calcite is the only common gangue mineral.

Many of these features suggest that the mineralization is definitely of hydrothermal origin, but the lack of distinct wallrock alteration might indicate that the responsible fluids did not posses very different chemistries nor temperatures from those of connate or metamorphic waters that must have been in equilibrium with the regionally altered host rocks.

NISTERENKO *et al.* (1973) reported filling temperature of fluid inclusions from some manto type deposits. In the Buena Esperanza deposit, filling temperatures of inclusions in calcite from the ores range from 65° to 195°C, which are almost the same with those in authigenic calcite and quartz from andesite stratigraphically far below the mineralized horizon. This suggests that the mineralizing fluid had similar temperatures to connate or metamorphic waters. It is also suggested from these temperature data that the gabbroic intrusive at Buena Esperanza (see Fig. 3) did not act as a source of the mineralizing fluid nor heat.

In contrast, filling temperatures of inclusions in amygdule-filling quartz from the El Salado deposit belonging to type III are very high ranging from 273° to 430°C, and halite crystals were observed in the inclusions suggesting high salinities of the inclusion fluids (NISTERENKO *et al.*, 1973). At El Salado, a granitic intrusive is intruded underneath the ore deposit. It is conceivable that the intrusive provided heat or possibly the mineralizing fluid itself responsible for the formation of the El Salado deposit. The same may apply to other type III deposits which are spatially in close association with granitoid intrusives and surrounded by well-developed alteration halos.

As to the source of mineralizing fluids, information is too scarce to draw any conclusion. However it appears very suggestive in considering the fluid source that the host rocks underwent advanced burial metamorphism, and that the alteration and gangue mineralogy is essentially the same with that of the metamorphosed host rocks except for some type III deposits.

As cited earlier, LEVI (1969, 1970) demonstrated that the burial metamorphism in the north Santiago area took place repeatedly. The manto type copper deposits in this area are confined to the sequences that underwent prehnite-pumpellyite to greenschist facies metamorphism; none is present in the Lo Valle formation that has suffered only zeolite facies metamorphism.

It is suggested here that metamorphic water produced by dehydration processes of prehnite-pumpellyite and higher facies metamorphism is one of the most plausible candidates for the mineralizing fluid responsible for the Chilean manto type copper deposits.

**Source of Copper**

If it is correct that the mineralizing fluid is of metamorphic origin, the source of copper is most likely the host volcano-sedimentary rocks. Trace element geochemistry of the Chilean volcanics have been studied by CHAVEZ and NISTERENKO (1974), ZENTILLI (1974), CAMPANO and GUERRA (1975) and PALACIOS (1978). Since all the Jurassic and Cretaceous volcanics have been more or less altered, the samples analyzed by these authors include "little altered" rocks.

CHAVEZ and NISTERENKO (1974) analyzed Cretaceous andesites from some localities of the Coastal Range and found that their copper contents vary considerably from place to to place. It is noteworthy in their data that the andesites of the Arqueros formation, which underlies the Talcuna district, contain anomalously high copper averaging 256 ppm.

ZENTILLI (1974) studied geochemistry of Jurassic to Quaternary volcanics along a latitudinal section between 26 and 29 degrees south. Although some elements such as Y exhibit systematic variations along the section, copper shows no regular pattern. By comparing the Chilean volcanics with their equivalents in the Circum-Pacific belt, he found that copper is slightly higher in the

Chilean rocks but when only andesites are compared Chilean andesites are lower in copper. However, although he did not note, his analytical data seem to indicate that the copper contents of the Chilean andesites vary with age. For example, the Jurassic andesites contain 90 to 375 ppm Cu while the Neogene andesites contain 10 to 32 ppm Cu.

Geochemistry of the Jurassic volcanics was studied in detail by CAMPANO and GUERRA (1975) and PALACIOS (1978). PALACIOS (1978) divided the Jurassic basalts and andesites of the La Negra formation in northern Chile into tholeiitic, calc-alkaline and alkaline suite, and reported their average copper contents as 66 ppm ($SiO_2=55.4\%$), 113 ppm ($SiO_2=57.8\%$) and 72 ppm ($SiO_2=55.6\%$), respectively. He also compared the Jurassic calc-alkaline suite with the Ceneozoic quartz-latiandesites from the Central Andes and found that the former is much higher in copper than the latter (44 ppm), again suggesting an apparent decrease of copper content with age.

Geochemistry of the altered or metamorphosed volcanics as compared with that of "fresh" equivalents has been studied by LOSERT (1973, 1974), CHAVEZ and NISTERENKO (1974) and LEVI (1974). All of these authors have noticed that copper was highly mobile during regional alteration or burial metamorphism. They are in general agreement with that copper as well as sulfur is depleted to a considerable degree in the altered rocks especially in epidotized rocks.

JOLLY (1974), in his study of the Michigan native copper district, showed that copper was leached from epidotized or more highly metamorphosed rocks in the zone of dehydration, percolated upward to lower temperature levels, and was precipitated in the zone of hydration where pumpellyite, prehnite laumontite and chlorite are the principal hydration minerals. This model can be reasonably applied to behaviour of copper in the metamorphosed rocks of the Andean geosyncline, and also to the genesis of the Chilean manto type copper deposits.

The available analytical data in the literatures cited above seem to suggest that some major districts of the manto type copper deposits are underlain regionally by thick volcanic sequences that are primarily rich in copper. The Antofagasta-Tocopilla district in the Jurassic volcanics and the Talcuna district underlain by the anomalously copper-rich Arqueros formation are such examples.

Combining the above discussions together, the Chilean manto type copper deposits may be concluded to be burial metamorphic or diagenetic-hydrothermal in origin. Some type III deposits may have been affected by local high-temperature convection cells caused by granitoid intrusives, which might have also provided mineralizing fluids and copper at least partially.

Other copper deposits of similar origin are those of the Michigan native copper district, U.S.A., which are associated with the subaerial Keweenawan basalts. According to JOLLY (1974), copper sulfides are rare in the Keweenawan rocks, because sulfur is oxidized to $SO_2$ gas in subaerial environment and escapes into the atmosphere before solidification. In contrast, the Jurassic to Cretaceous volcanics of the Andean geosyncline contains a significant proportion of subaqueous volcanics which were erupted under shallow marine or continental lacustrine environments. CHAVEZ and NISTERENKO (1974) estimate that 68 to 83% of the copper in the "fresh" Cretaceous andesites from Chile is present as sulfides probably in the form of magmatic sulfide globules. It is likely that these magmatic sulfides are the dominant source of both copper and sulfur in the manto type deposits. This may explain the low sulfur/metal ratio of the manto type deposits, because sulfur/metal ratios of magmatic sulfide globules are generally low (CZAMANSKE and MOORE, 1977; SKINNER and PECK, 1969).

In conclusion, advance of burial metamorphism to prehnite-pumpellyite or higher facies in copper-rich, subaqueous volcanics is suggested to be the necessary factor for the formation of the manto type copper deposits. Accumulation of thick eugeosynclinal piles containing abundant copper-rich volcanics in the Andean geosyncline during the Jurassic to Cretaceous times and repeated burial metamorphism having taken place in them may explain why the Chilean Coastal Range forms a unique metallogenic province characterized by this peculiar type of copper deposits.

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# チリ国のマント型銅鉱床

佐藤壮郎

## 要旨

チリの海岸山脈地域には，ジュラ紀から第三紀前期の火山岩に富む地層を母岩とする多くのマント型銅鉱床を産する．鉱床はアミグデュールに富む溶岩あるいは火山角礫岩を母岩とすることが最も普通であるが，石灰岩を母岩とすることもある．主要な鉱石鉱物は，黄銅鉱，斑銅鉱及び輝銅鉱であり，黄鉄鉱，赤鉄鉱，磁鉄鉱を伴う．母岩の変質は一般に非常に微弱である．

文献等により鉱床及び母岩の産状，地球化学的特性，鉱物組成などを検討した結果，埋没変成作用の進行により放出された変成水により鉱床が形成されたことが示唆される．初成的に銅に富む火山岩を多

量に含む地層が，アンデス地向斜に厚く堆積したことが，チリの海岸山脈地域がマント型銅鉱床で特徴づけられる特異な鉱床生成区を形成している理由であろう．

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