PERGAMON

Journal of South American Earth Sciences 14 (2001) 401–433

Journal of
South American
Earth Sciences

www.elsevier.com/locate/jsames

The Punta del Cobre Formation, Punta del Cobre–Candelaria area, northern Chile

Robert Marschik[a,b,*], Lluís Fontboté[b]

[a]Institut für Mineralogie, TU Bergakademie Freiberg, D-09596, Freiberg, Germany
[b]Section des Sciences de la Terre, Université de Genève, Rue des Maraîchers 13, 1211 Genève 4, Switzerland

Received 1 March 2000; revised 1 December 2000; accepted 1 March 2001

Abstract

The Punta del Cobre Formation hosts the iron oxide-rich Cu–Au(–Zn–Ag) deposits of the Punta del Cobre belt, Chile. Hydrothermal alteration associated with mineralization and/or contact metamorphism caused by the Coastal Batholith exposed in the west resulted in new mineral assemblages and significant changes in the geochemical composition of its rocks. This paper presents a redefinition of the Punta del Cobre Formation and discusses its geologic context. The Punta del Cobre Formation is subdivided, from bottom to top, into: (1) the 'Geraldo–Negro Member', composed mainly of massive andesitic volcanic rocks (>300 m) and locally dacitic rocks (up to 200 m) that overlie the latter, and (2) the 'Algarrobos Member' (up to >800 m) comprising mainly volcaniclastic rocks, basalt andesitic and basaltic flows, and volcanic breccias. The Punta del Cobre Formation is overlain by the Chañarcillo Group, the lowest part of which is represented by alternating carbonate and volcaniclastic beds of the Abundancia Formation, which pass vertically and laterally into limestones of the Nantoco Formation. The contact between the Punta del Cobre Formation and the overlying Abundancia Formation is transitional and defined by the first *continuous* bed of massive limestone or its metamorphosed equivalent. A pre-upper Valanginian age for the Punta del Cobre Formation is suggested by ammonites of Berriasian age found in the upper part of the Algarrobos Member and Late Valanginian–Early Hauterivian fauna in the overlying Abundancia Formation. Despite the intense alteration, immobile element compositions of the volcanic rocks of the Punta del Cobre Formation enable the recognition of a calc-alkaline suite with a trend to more primitive, less differentiated magmas towards the top of the stratigraphic sequence, reflecting initial stages of basin development. The transgressive nature of the sedimentary part of the Punta del Cobre Formation marks the onset of increased subsidence that eventually culminated in the Early Cretaceous marine backarc basin south of Copiapó (Chañarcillo Group). The present investigation shows that the Punta del Cobre Formation could be considered as the lower part of the Bandurrias Group, both having similar lithologies and geochemical affinities and occupying similar paleogeographic positions.

Keywords: Atacama region; Bandurrias Formation; Candelaria; Chañarcillo Group; Cretaceous volcanic rocks; North Chile; Punta del Cobre Formation; Stratigraphy

1. Introduction

The mainly volcanic–volcaniclastic Tithonian(?) to pre-upper Valanginian Punta del Cobre Formation hosts the iron oxide-rich Cu–Au(–Zn–Ag) deposits of the Punta del Cobre belt (Marschik and Fontboté, 1996). The belt, located to the south of Copiapó, Chile, includes the Candelaria deposit (470 Mt at 0.95% Cu, 0.22 g/t Au, 3.1 g/t Ag; Marschik et al., 2000) and several medium- and small-sized mines such as Alcaparrosa, Carola, Las Pintadas, Socavón Rampa, and Santos (estimated combined reserves plus production >120 Mt at 1.5% Cu, 0.2–0.6 g/t Au, 2–8 g/t Ag; Figs. 1 and 2). Mineralization is controlled by structure and stratigraphy (e.g. Camus, 1980; Marschik and Fontboté, 1996; Marschik et al., 2000). Despite its importance for mineral exploration in the area, the Punta del Cobre Formation is only poorly defined. Lacking continuous marker horizons, quick lateral facies changes and exposure in disconnected outcrops makes correlation within the belt difficult. In places, intense hydrothermal alteration associated with the metallic mineralization as well as contact metamorphism caused by the Coastal Batholith exposed in the west (Fig. 2) resulted in new mineral assemblages, obliteration of rock textures, and significant changes of the original geochemical composition (Marschik and Fontboté, 1996). The position and nature of the upper

* Corresponding author. Department of Mineralogy, Freiberg University of Mining and Technology, Brennhausgasse 14, 09596 Freiberg, Germany. Tel.: +49-3731-39-4306; fax: +49-3731-39-2610.
E-mail address: robert_marschik@yahoo.com (R. Marschik).

0895-9811/01/$ - see front matter
PII: S0895-9811(01)00036-0

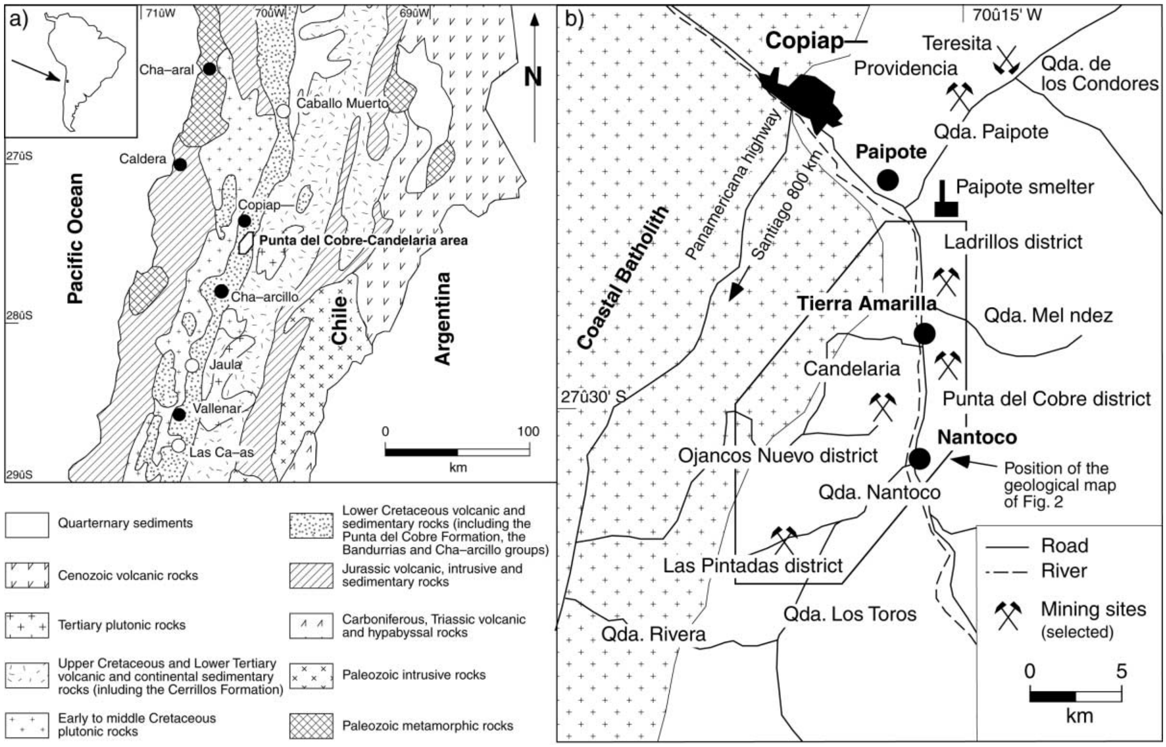

Fig. 1. (a) Geologic map of the area between Chañeral and Vallenar (after Mapa Geológico de Chile, SERNAGEOMIN, 1982). Locations of the Punta del Cobre–Candelaria area and outcrops of the Bandurrias Group (open circles) sampled by Griem (1994) and Lieben (2000), and Nova (1997) are indicated. (b) Location map of the Punta del Cobre–Candelaria area. The position of the geologic map of Fig. 2 is indicated.

contact of the Punta del Cobre Formation is still a matter of discussion, and no consensus exists whether or not the formation should be integrated into the overlying Chañarcillo Group (e.g. Segerstrom, 1968) or into the lithologically similar Bandurrias Formation (e.g. Jurgan, 1977a; Lino, 1984; Cisternas, 1986; Marschik and Fontboté, 1996), respectively, Bandurrias Group (see below).

New field data has accumulated over the last several years. The opening of the Candelaria mine, the expansions of mines in the Punta del Cobre district, and exploration drilling have provided new rock exposures. During our investigations, it became evident that the current definitions of the Punta del Cobre and Abundancia Formations are not compatible with the new findings.

In this contribution, we present a redefinition and a comprehensive description of the Punta del Cobre Formation based on the study of 22 representative profiles and numerous geochemical analyses (major, trace, and rare-earth elements). Special attention is paid to the volcanic rocks and their geotectonic setting. The regional significance of the results is discussed. This study concentrates on the area between Copiapó and Quebrada Rivera, although our field investigations have extended farther to the north and south; analytical data from other authors (Griem, 1994; Nova, 1997; Lieben, 2000) on volcanic rocks of the Bandurrias Group between latitudes 26°40′S and 28°50′S have been included for comparison (Fig. 1). The present work was carried out within the frame of a metallogenic investigation of the Punta del Cobre belt, the main results of which have been published elsewhere (Marschik and Fontboté, 1995, 1996; Marschik et al., 1997a–c, 2000).

2. Geology of the Copiapó area

The mainly volcanic and volcaniclastic Punta del Cobre Formation (Segerstrom and Ruiz, 1962; Marschik and Fontboté, 1996; Ortiz et al., 1966) underlies upper Valanginian to Aptian shallow marine carbonate sediments of the Chañarcillo Group south of Copiapó (Figs. 3 and 4; Corvalán, 1974; Jurgan, 1977a,b; Cisternas, 1986; Cisternas and Díaz, 1990; Pérez et al., 1990). The total thickness of the Chañarcillo Group is between 1700 and 2000 m (Corvalán, 1974; Arévalo, 1994, 1995). These rocks represent the northern part of the Early Cretaceous 'aborted' marginal basin of central Chile (lat. 33°S), which formed as an ensialic trough on partly eroded Jurassic rocks and the pre-Andean basement (Levi and Aguirre, 1981; Åberg et al., 1984; Aguirre, 1985). However, unlike in the backarc basin of central Chile, large amounts of Hauterivian–Albian flood basalts are absent near Copiapó.

Towards the north and west, the Chañarcillo Group interfingers with terrestrial deposits of the volcanic arc, which are composed mainly of andesitic volcanic and volcaniclastic rocks (Segerstrom, 1968; Jurgan, 1977b) of the Bandur-

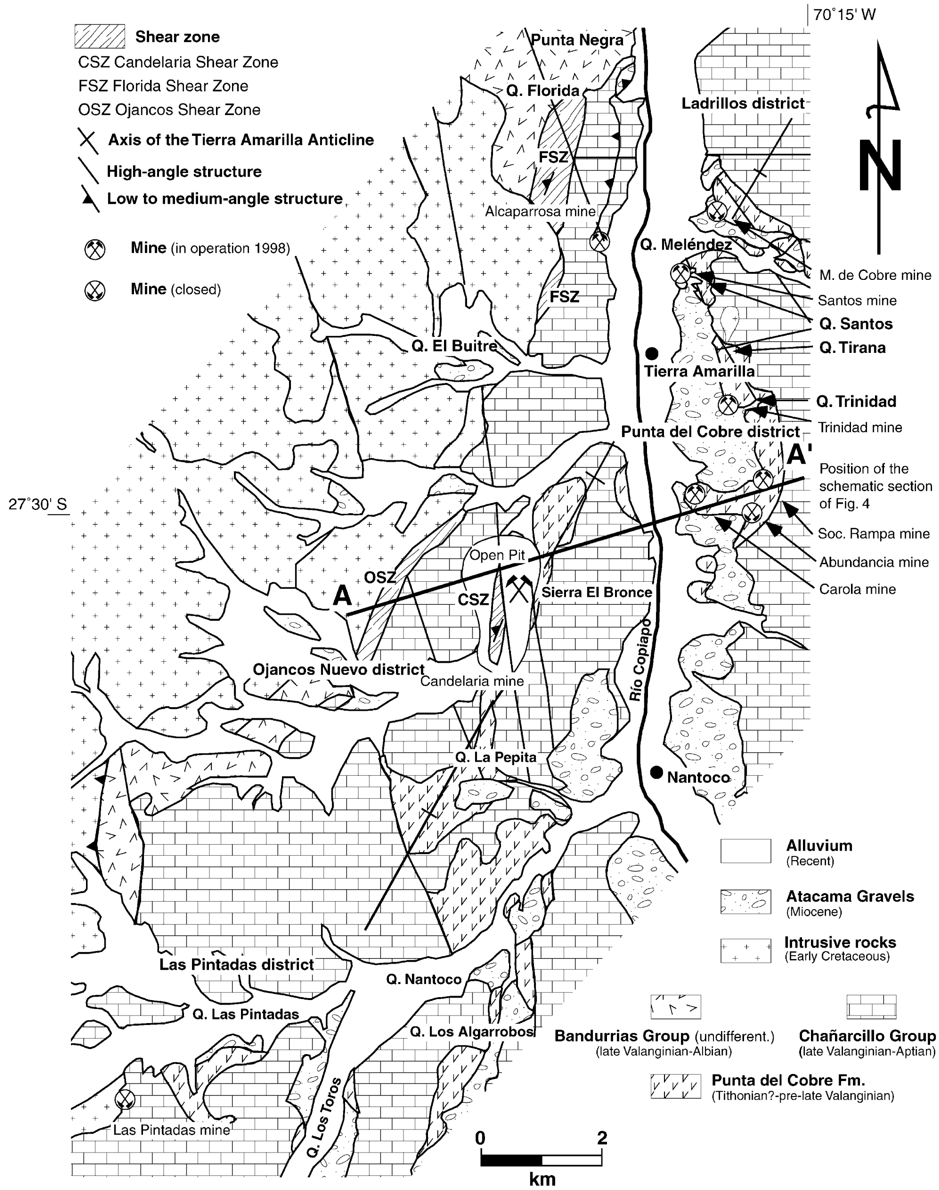

Fig. 2. Geologic map of the Punta del Cobre–Candelaria area (geology modified from Tilling, 1976).

rias Formation (Segerstrom, 1960), respectively, of the Bandurrias Group (Moscoso et al., 1982; see below). South of the Chañarcillo mining district, the Chañarcillo Group is underlain by the lower part of the Bandurrias Group. The interface between the Chañarcillo Group and the Bandurrias Group is considered to be the western coastline of the Early Cretaceous marine backarc basin in the Copiapó area (Segerstrom, 1968; Abad, 1977; Cisternas, 1986). Marine sedimentation ended in Late Aptian time. The lens-shaped Albian(?)–Late Cretaceous Cerrillos Formation unconformably overlies the Chañarcillo Group and the Bandurrias Group (Fig. 3). It consists of a 2300 m thick lower unit of conglomerates intercalated with tuffs, fresh water limestones, and siltstones, and an upper unit comprising mainly andesitic lavas and pyroclastic rocks; the maximum total thickness is about 4500 m (Segerstrom and Parker, 1959; Segerstrom, 1968; Moscoso et al., 1982; Aguirre, 1985). The lower unit contains reworked marine fossils of Hauterivian to Barremian age, which is consistent with important uplift and erosion in Late Aptian–Albian times recognized in central and northern Chile (Aguirre, 1985, p. 310 ff).

In the Atacama region, several intrusive episodes of Permian–Triassic, Early Jurassic, Early to mid-Cretaceous, Early Paleocene, and Late Eocene ages have been distinguished between 26°S and 29°S (e.g. Farrar et al., 1970; Zentilli, 1974; Dallmeyer et al., 1996). An eastwards migration of the magmatic front between Early Jurassic and Late Eocene is indicated by the decreasing age of intrusive bodies from the present coastal region towards the Andean

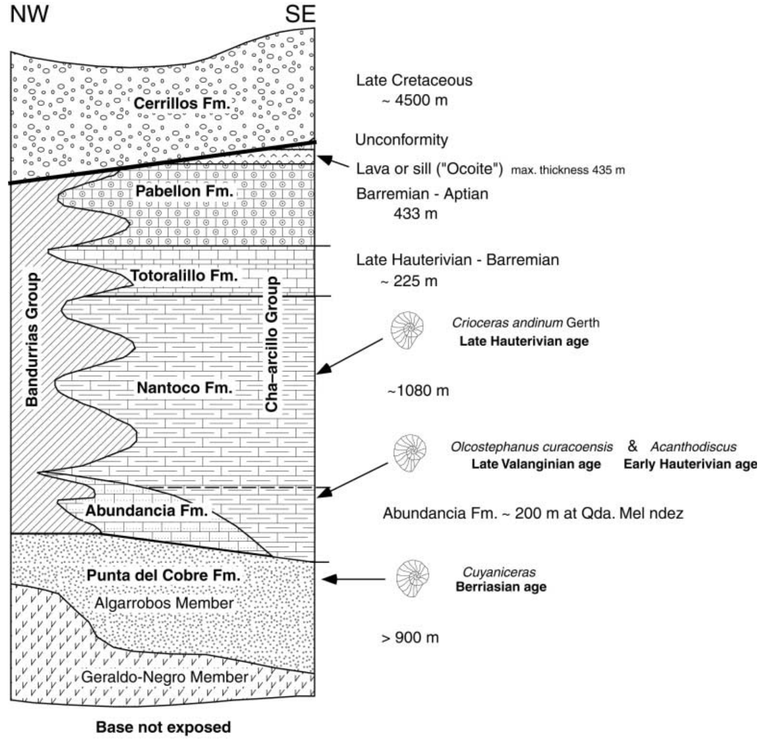

Fig. 3. Schematic stratigraphy of the western margin of the Early Cretaceous backarc basin near Copiapó.

Cordillera. By the mid-Cretaceous, the intrusion foci were at the longitude of Copiapó (Arévalo, 1994, 1995). Multiple granitoid intrusions emplaced in the west of the Punta del Cobre–Candelaria area caused extensive metamorphism in the country rocks (Tilling, 1962, 1963a,b; Marschik and Fontboté, 1995, 1996).

The main structural elements in the study area are the NNE-trending Tierra Amarilla Anticlinorium (Segerstrom,

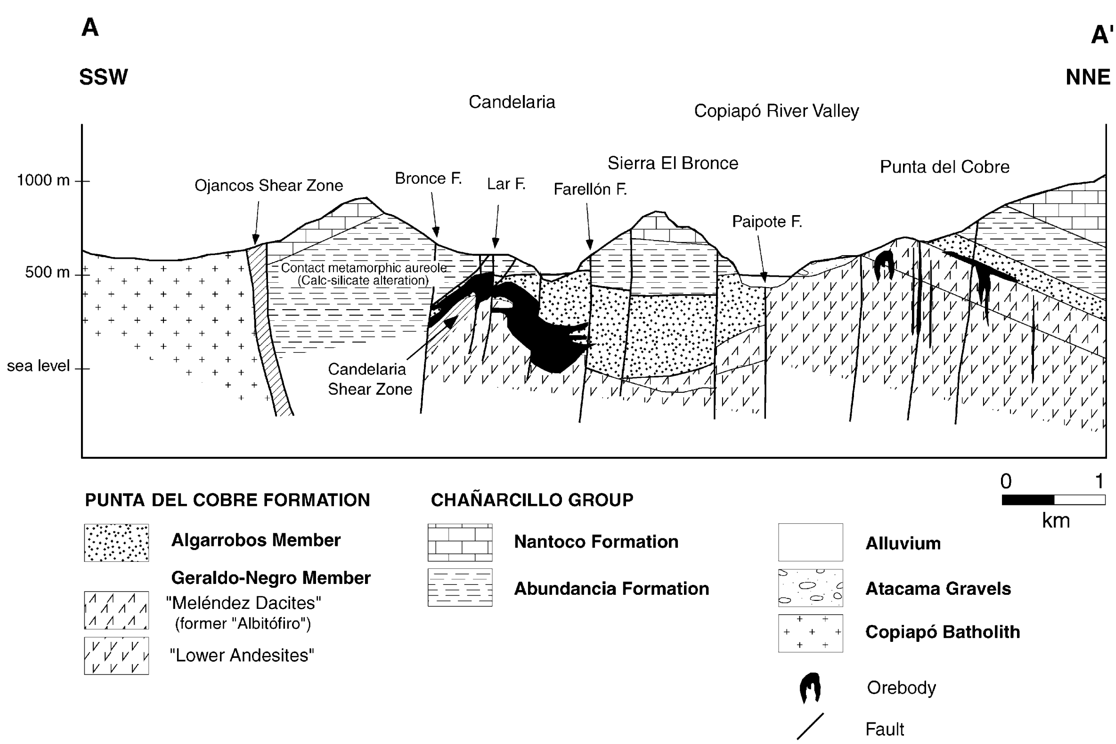

Fig. 4. Cross-section through from the Copiapó Batholith to the Punta del Cobre district (see Fig. 2 for location).

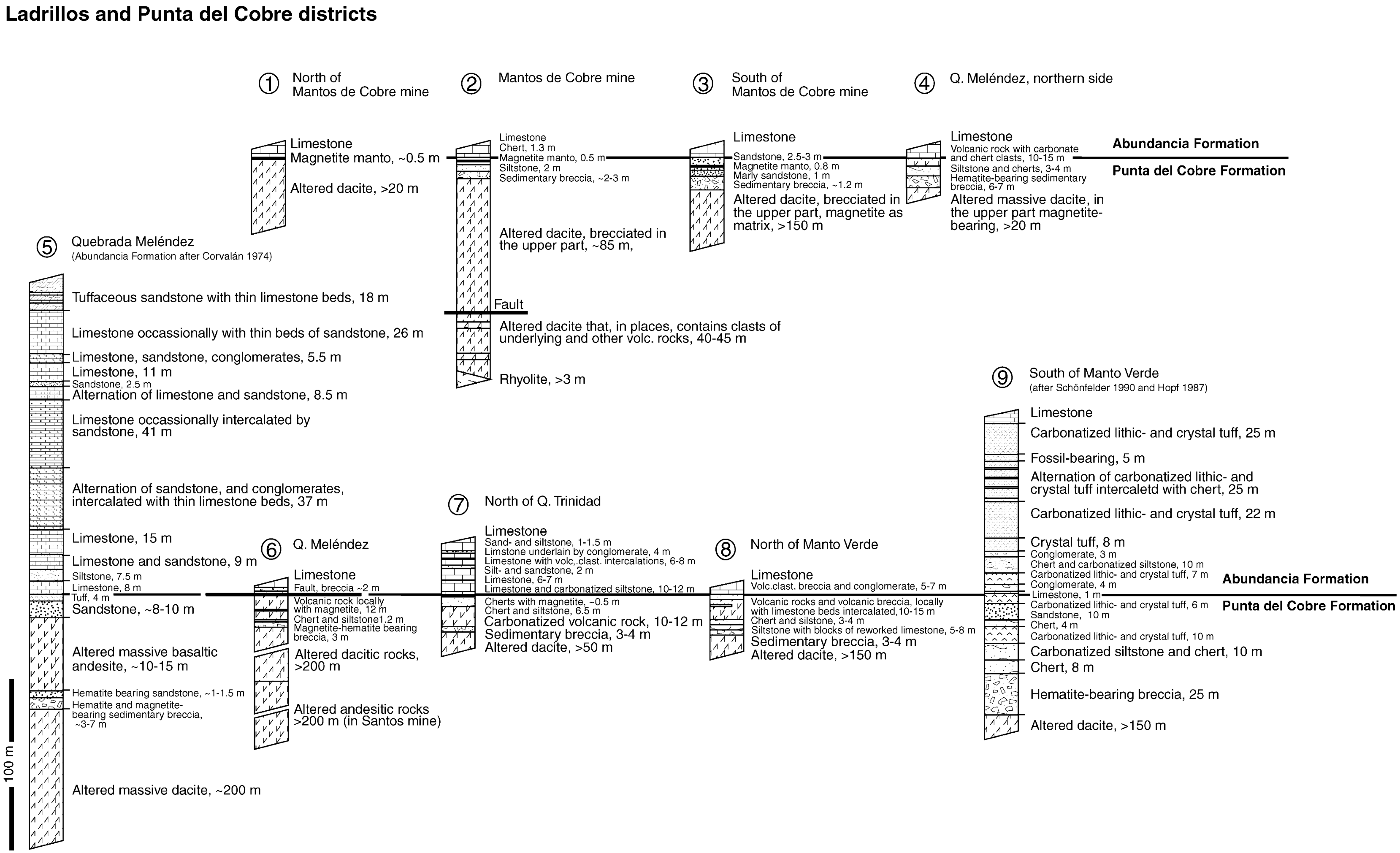

Fig. 5. Stratigraphic columns from field profiles: (a) in the Ladrillos and Punta del Cobre districts, (b) in the Candelaria mine area, and north of the Alcaparrosa mine, and (c) at the Quebradas Nantoco, Los Algarrobos, Los Toros, and Las Pintadas (descriptions by Corvalán, 1974; Díaz, 1990; Schönfelder, 1990; Hopf, 1987 are included). Positions of columns are shown in Fig. 6.

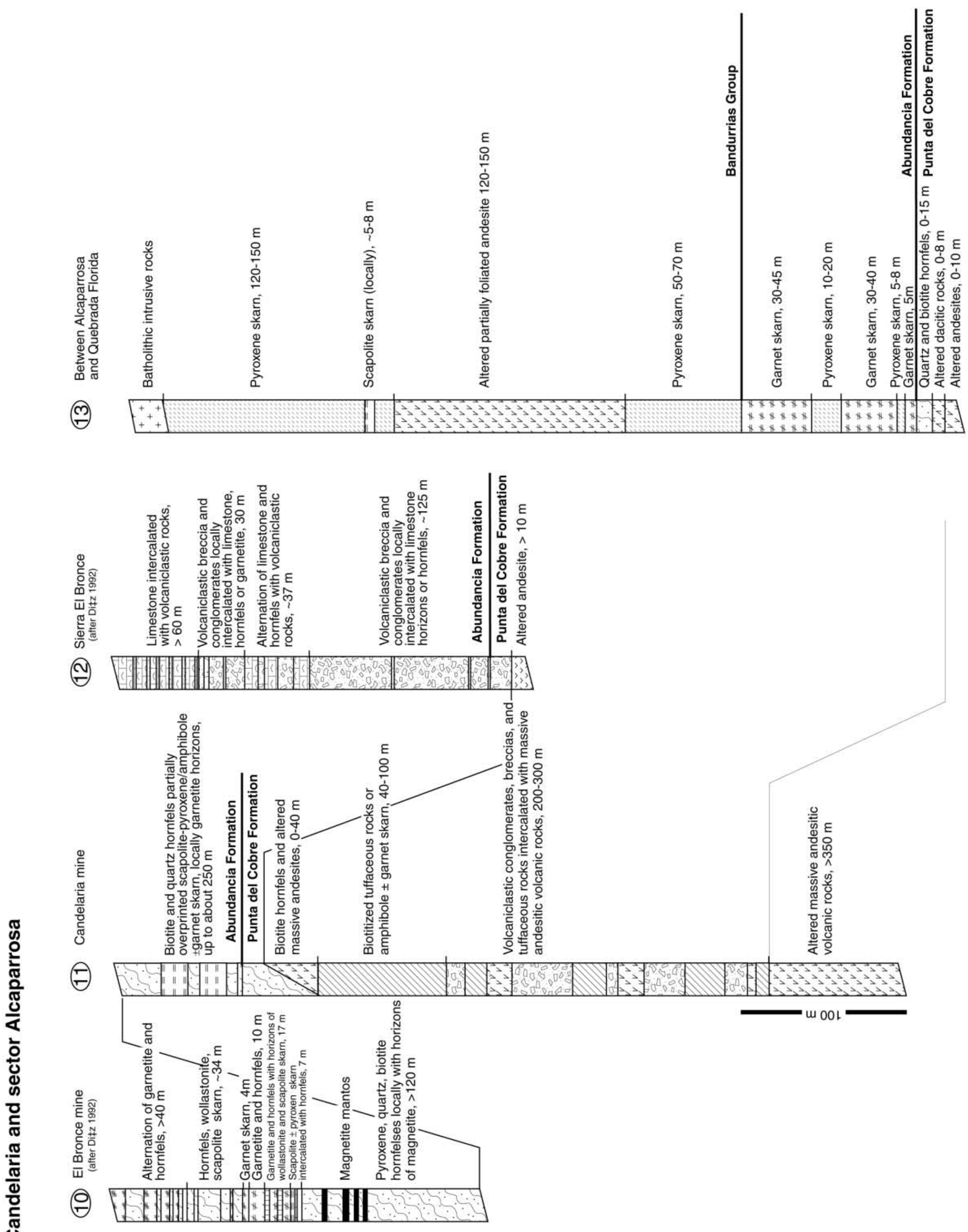

Fig. 5. (*continued*)

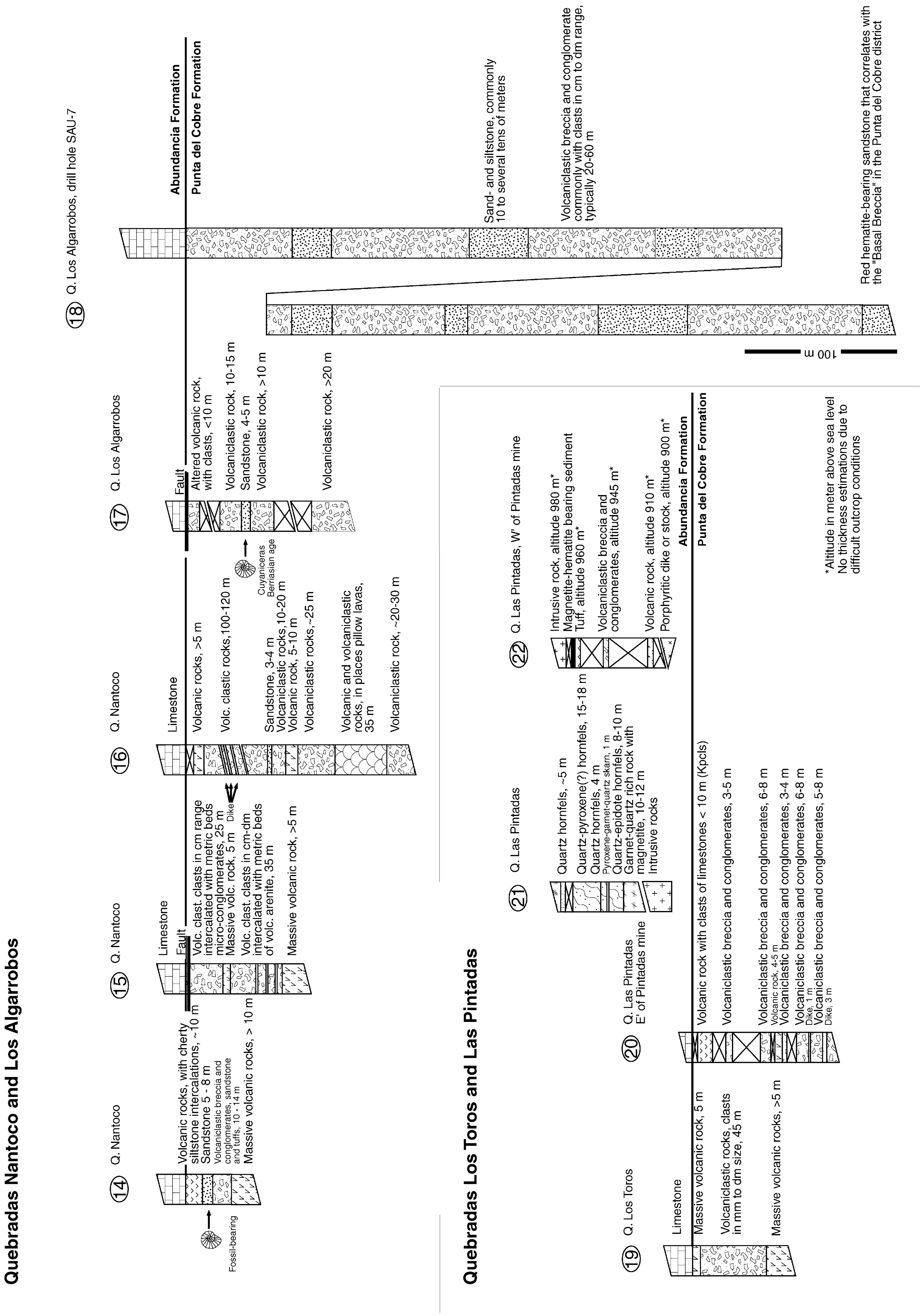

Fig. 5. (*continued*)

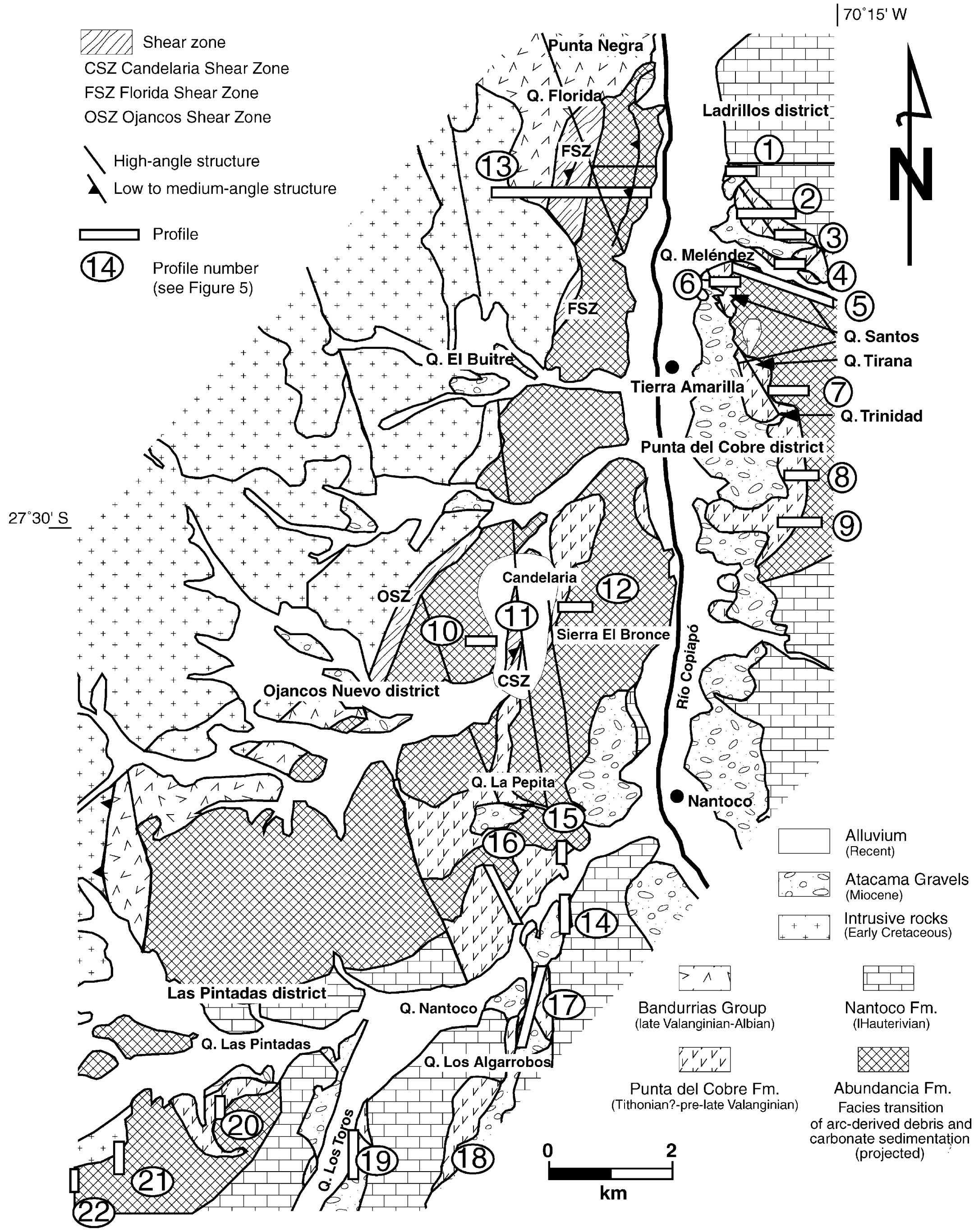

Fig. 6. Map showing the distribution (projection) of the facies transition between continental volcanic arc-derived clastic and shallow marine carbonate sedimentation referred to as the Abundancia Formation. The positions of the stratigraphic profiles of Fig. 5 are indicated.

1967), the SE-verging El Bronce fold-thrust system (Arévalo and Grocott, 1997), and a dense set of subparallel NNW- to NW-trending high-angle faults with vertical displacements between 10 m and more than 150 m (Ryan et al., 1995). Occasionally observed subhorizontal slickensides suggest sinistral lateral movement. NW- to NNW-trending faults control parts of the metallic mineralization (e.g. Camus, 1980; Marschik and Fontboté, 1996). E–W and NE-trending faults are also observed; their magnitudes and senses of displacement are still to be determined. In places, cataclastic or mylonitic rocks occur along the eastern margin of the Early to mid-Cretaceous batholith, where they form the contact between intrusive rocks and metamorphosed Neocomian country rocks. A particular example for mylonitic deformation is the NNE- to NE-trending subvertical Ojancos Shear Zone east of the Candelaria mine (Fig. 2). Shear deformation affected volcanic and volcaniclastic rocks of the Punta del Cobre Formation at Candelaria

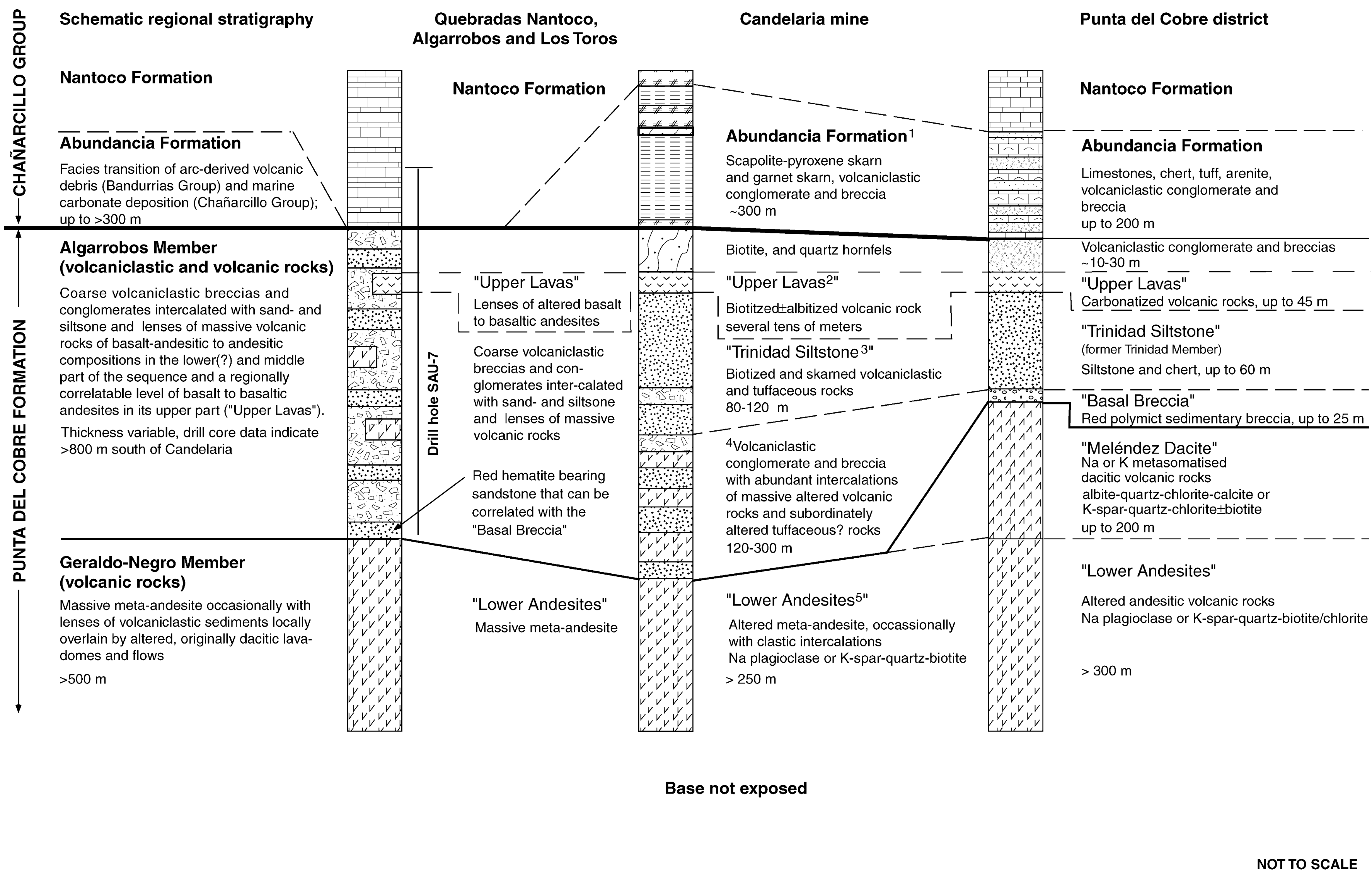

Fig. 7. Schematic stratigraphy of the Punta del Cobre Formation at Quebradas Nantoco, Algarrobos, Los Toros, and Las Pintadas, at Candelaria, and in the Punta del Cobre district. The stratigraphic columns were constructed mainly from profiles indicated in Fig. 5 and using stratigraphic descriptions by Hopf (1987) and Schönfelder (1990). Stratigraphic units established for Candelaria by Ryan et al. (1995) are: (1) Metasediments, (2) Upper Andesites, (3) Tuffs and Volcaniclastic Rocks, and (4,5) Lower Andesites.

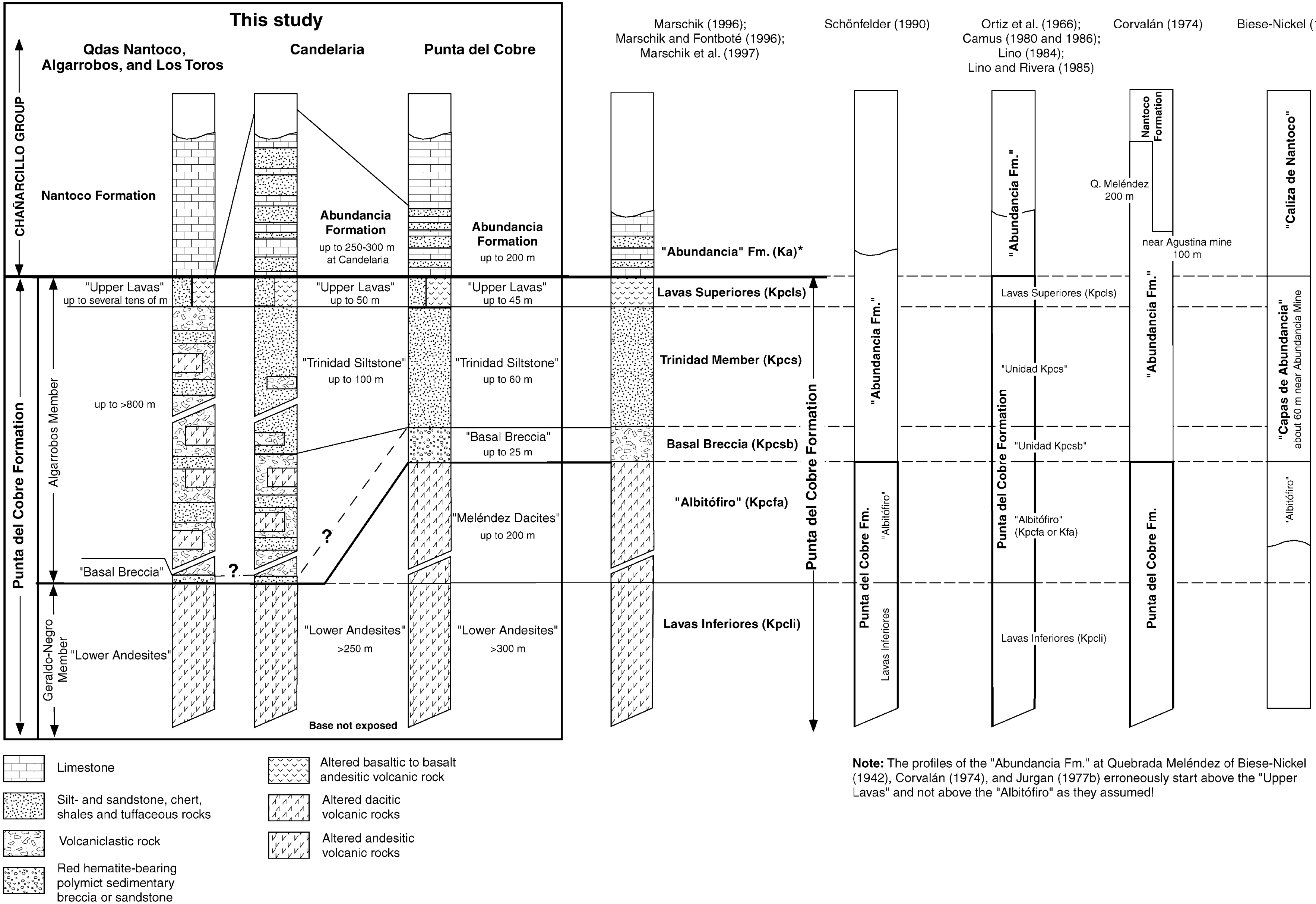

Fig. 8. Comparisons and correlation of lithostratigraphic units in the Punta del Cobre district with those of earlier works.

(Candelaria Shear Zone; Figs. 2 and 4) and the Bandurrias Group, west and northwest of Alcaparrosa mine (Florida Shear Zone; Fig. 2). It is manifested in several tens to over 100 m wide, broadly NNE- to NE-trending, 30–70° west-dipping zones of pervasive foliation. Affected rocks are biotite–quartz rich or amphibole ± biotite rich, respectively, having a schist-like appearance. This shear deformation is the oldest recognized in the Candelaria mine so far; it is interpreted to represent early heat-induced ductile deformation related to the earlier stages of batholith emplacement.

According to Arévalo (1995) and Arévalo and Grocott (1996), the Bandurrias Group and the Chañarcillo Group form tectonic units that are separated from the Punta del Cobre Formation by the Punta del Cobre detachment, which shows features consistent with extension. The existence of this generalized tectonic contact between the Punta del Cobre Formation and the Chañarcillo Group–Bandurrias Group is not confirmed by the present investigation.

3. Punta del Cobre Formation

The oldest rocks exposed in the Punta del Cobre–Candelaria area are massive altered volcanic rocks. These are overlain by a volcaniclastic succession that, in places, contains lenses of massive volcanic rocks. This succession, in its upper part, passes vertically and laterally into the overlying carbonatic Nantoco Formation of the Chañarcillo Group. The Chañarcillo Group was defined by Segerstrom and Parker (1959); it comprises the Abundancia, Nantoco, Totoralillo, and Pabellón Formations. The underlying Punta del Cobre Formation, first defined and subdivided by Francisco Ortiz (Ortiz, pers. commun. cited in Segerstrom and Ruiz, 1962; Ortiz et al., 1966) in the Punta del Cobre district, was later incorporated into the Chañarcillo Group by Segerstrom (1968) and subsequently excluded by Jurgan (1977a,b) because of its 'unconformable' relationships to the overlying formations.

The Punta del Cobre Formation has significant variations in lithology, thickness of rock-types, and alteration-type throughout the area of its exposure, which were not taken into account by the previous works. New field data collected from outcrops, underground exposures, and drill cores throughout the study area show that the current stratigraphic concept of the Punta del Cobre Formation is not entirely compatible with the observations. Fig. 5 shows selected stratigraphic profiles taken to construct the schematic stratigraphic columns presented in this paper (Figs. 7 and 8, see below). The positions of these profiles are indicated in Fig. 6.

4. Redefinition and subdivision of the Punta del Cobre Formation

The country rocks in the Punta del Cobre–Candelaria area can be subdivided, from bottom to top, into: (1) massive volcanic rocks, occasionally with small intercalations of clastic sediments, herein referred to as the 'Geraldo–Negro Member'; (2) volcaniclastic sediments with lenses of massive volcanic rocks, named here the 'Algarrobos Member', and (3) an alternation of carbonate and volcaniclastic beds, previously defined as the Abundancia Formation (Figs. 4, 5, 7, and 8). The latter passes vertically and laterally into the limestones of the Nantoco Formation. The Algarrobos Member and the Geraldo–Negro Member make up the Punta del Cobre Formation.

The boundary between the Algarrobos Member and the Abundancia Formation, i.e. between the Punta del Cobre Formation and the Chañarcillo Group, is defined by the first *continuous* massive carbonate bed or its metamorphosed equivalent (commonly a garnetite horizon) that is intercalated in the volcaniclastic succession. It must be pointed out that this boundary does not correspond to a single stratigraphic level on regional scale. Fig. 8 shows the units and terminology presented here and their relationships to units defined in previous works.

5. The Geraldo–Negro Member

The massive volcanic rocks at the base of the Punta del Cobre Formation are named the Geraldo–Negro Member. This unit is subdivided into two major informal subunits: from bottom to top, the 'Lower Andesites' and the 'Meléndez Dacites', both exposed near the old Manto Geraldo and Manto Negro mines in the southern Punta del Cobre district, after which the Geraldo–Negro Member is named.

The Lower Andesites consist of altered, originally andesitic (see Section 10), massive volcanic rocks occasionally intercalated with small lenses of clastic sediments. In the field, these commonly porphyritic rocks show a dark gray–green weathering surface. They are exposed in the Punta del Cobre district south of Quebrada Tirana and in the Candelaria open pit mine. Drill cores and mine workings indicate that the Lower Andesites are over 300 m thick. The Lower Andesites host a part of the ore in the Punta del Cobre belt (Ryan et al., 1995; Marschik and Fontboté, 1996). The Lower Andesites are equivalent to the 'Lavas Inferiores' of Ortiz et al. (1966), but they only partially correspond to the Lower Andesites in the sense of Ryan et al. (1995) at Candelaria that include parts of the Algarrobos Member.

In the Punta del Cobre and southern Ladrillos districts, the Lower Andesites are overlain by massive, originally dacitic rocks (see Section 10) that underwent intense albitization and also, in places, potassic alteration (e.g. Hopf, 1990; Marschik and Fontboté, 1994, 1995, 1996). They were first interpreted to be intrusive and considered to form a marginal facies of the Andean batholith (e.g. Brüggen, 1934; Flores, 1938). Ruiz (1942) described them as laccoliths. At Quebrada Meléndez, Ruiz (1942, p. 1204) considered the rocks to be 'relatively fresh' and called them 'Albitófiro' due to the common albite–quartz–chlorite assemblage. We propose the term Meléndez Dacites for these rocks because of their original composition.

A long-debated issue has been the intrusive, respectively, extrusive nature of the Meléndez Dacites (e.g. Segerstrom and Ruiz, 1962; Ortiz et al., 1966; Camus, 1980; Jurgan, 1977b). The present work gives evidence for an extrusive character of the Meléndez Dacites. In the Ladrillos district and in the Carola mine (formerly Agustina; Lino and Rivera, 1985; Hopf, 1990), clastic intercalations are observed in the Meléndez Dacites. They usually consist of poorly to well-rounded clasts to about 1 cm in size. In the lower part of a possible lava flow exposed at the entrance to the Mantos de Cobre mine, the Meléndez Dacites contain centimetric to decimetric angular clasts of underlying originally rhyolitic volcanic rocks (samples PC 981, PC, 999, PC 1000; see Fig. 11 and Table 2 below). The latter have been found in only one outcrop at the same place. Between Quebrada Meléndez and the southern end of the Punta del Cobre district, the Meléndez Dacites are almost everywhere covered by a reddish clastic sediment, the 'Basal Breccia', that forms part of the Algarrobos Member (see below). In the Carola mine, the contact between the Meléndez Dacites and the overlying sediments is erosive, as already described by Hopf (1990). A particularly well-exposed paleosurface is observed at mining level N7, where a red laminated sandstone fills a strong paleorelief. At the Quebrada Meléndez, the Meléndez Dacites appear as a volcanic dome, a common feature of dacitic rocks. At the southern face of Quebrada Meléndez, the erosive character of the contact is not obvious, but it can be recognized that the overlying sedimentary breccia follows the outcrop contours of the Meléndez Dacites. At the northern face of Quebrada Meléndez, it seems that the contact is also erosive, although the outcrop conditions do not allow a definitive judgment.

All these features together point to an extrusive origin for the Meléndez Dacites. Hydrothermal alteration that, in places, affected the overlying sediments at the contact with the Meléndez Dacites is a feature that caused confusion because it appears to have been misinterpreted as contact metamorphism, which could have supported an intrusive nature for the Meléndez Dacites (e.g. Ruiz, 1942; Corvalán, 1974). For example, Ruiz (1942, p. 1204) mentioned that 'contact metamorphism' is very weakly developed in the sediments at the contact with the Meléndez Dacites. However, Ruiz recognized the strong alteration near the old mines Buena Esperanza, Manto Verde, and Agustina (now included in the Carola operation) in the southern Punta del Cobre district, which he related to the mineralization.

The lava dome at Quebrada Meléndez shows an apparent thickness of more than 200 m; towards the north and south, its thickness is smaller and variable. At Quebrada Tirana, the Meléndez Dacites are absent. They are exposed again about 400 m south of Quebrada Tirana where a sedimentary breccia containing fragments of limestone, chert, and siltstone rest unconformably on the Meléndez Dacites and the Lower Andesites.

6. The Algarrobos Member

The volcaniclastic succession that overlies the Geraldo–Negro Member is named the Algarrobos Member. The type locality of this unit lies in the area of the junction of Quebrada Los Algarrobos and Quebrada Nantoco, where the upper part of this unit is exposed (Fig. 5, profiles 15–17). The almost complete section of the Algarrobos Member is known from drill core brought down at Quebrada Los Algarrobos (access to drill core SAU-7 was kindly provided by Mantos Blancos Exploraciónes). The Algarrobos Member shows significant lithological variations and lateral facies changes throughout the area of exposure. Several mappable informal subunits, respectively, marker horizons of local importance, can be distinguished. West of the Copiapó River, the Algarrobos Member is represented by a successions of coarse, poorly bedded volcaniclastic conglomerates and breccias with centimetric to decimetric clasts, and finer grained sediments such as siltstones, arenites, coarse sandstones, and micro-conglomerates. Drill core data show that the finer grained sediments occur as intercalations, commonly in the order of 10 to about 40 m thick, in several stratigraphic levels within the coarser deposits and that the thickness of the Algarrobos Member exceeds 800 m south of Candelaria mine. In places, these sediments contain lenses of massive volcanic rocks of andesitic to basaltic compositions (see Section 10). Volcanic rocks with weakly defined pillow shapes and Berriasian ammonites (*Cuyaniceras sp.*; Tilling, 1962; Bengtson, pers. commun.) indicate submarine deposition for the upper part of the Algarrobos Member. The ammonites are the only time marker known for the Punta del Cobre Formation.

East of the Copiapó River, in the Punta del Cobre district, the Algarrobos Member is more heterogeneous in composition and includes epiclastic rocks with clasts of volcanic and marine origin. There, the thickness of this unit is considerably reduced compared with its equivalents west of the Copiapó River because of a paleotopographic high caused by the presence of the Meléndez Dacites and because of a general decrease in the thickness of the arc-derived clastic deposits towards the east, i.e. towards the basin interior.

The sedimentary succession that covers a partly erosional surface on top of the Geraldo–Negro Member in the Punta del Cobre district starts with a reddish sedimentary breccia, occasionally conglomeratic, named here the 'Basal Breccia'. The Basal Breccia comprises mainly fragments of volcanic rocks, chert, and siltstone; in general, it is poorly sorted. Centimetric to decimetric clasts of volcanic rocks similar to those of the underlying volcanic rocks, floating in a sandy matrix composed of volcaniclastic material, chert, and hematite occur in the unsorted lower parts. Interdigitations with sandstones are common (Hopf, 1987;

Schönfelder, 1990) and, as mentioned above, in parts of the Carola mine the Basal Breccia is represented by red sandstone. The Basal Breccia is interpreted to have formed essentially in a fluviatile environment (Hopf, 1990), which is consistent with its locally disconformable lower and upper contacts, graded and cross-bedding observed in centimetric to decimetric beds, and the absence of marine fossils. The Basal Breccia can be traced almost throughout the whole Punta del Cobre district and the southwestern part of the Ladrillos district. The thickness of the Basal Breccia is variable; in general, it increases towards the south, from about 1 m in the Ladrillos district to 25 m in the southern Punta del Cobre district (Schönfelder, 1990). The red sandstone that forms the Basal Breccia in parts of the Carola mine can be correlated with a red hematite-bearing sandstone, observed in the drill core SAU-7, which directly overlies the Geraldo–Negro Member at Quebrada Los Algarrobos (Figs. 5 and 7). At Candelaria, the correlation of this unit is difficult because of the presence of several similar horizons and because the red color of the Basal Breccia is masked by intense hydrothermal alteration. In places, the Basal Breccia hosts stratiform ore, which is mined mainly in the Socavón Rampa mine. The top of the Basal Breccia marks the upper limit of the economic metallic mineralization in the Punta del Cobre district.

The Basal Breccia is commonly overlain by predominantly siltstone, chert, and tuffaceous layers that compose the 'Trinidad Siltstone' unit. These sediments, in places, are in turn overlain by volcanic breccias, massive volcanic rocks, and lava flows, which form a discontinuous correlateable horizon named the 'Upper Lavas'. The Trinidad Siltstone correlates with the 'Tuffs or Volcaniclastic Sediments' of Ryan et al. (1995) that underlie rocks equivalent to the Upper Lavas at the Candelaria deposit. In the Trinidad mine property, the silty and cherty sedimentary rocks contain elongate, decimetric to metric clasts of a whitish weathered, dark colored brecciated limestone. The Trinidad Siltstone is characterized by strong lateral changes in facies and thickness. In parts of the Socavón Rampa mine, the red siltstone contains platy clasts of limestone covering a local erosional surface above the Basal Breccia. The contact beneath the Upper Lavas, in places, is also erosive (Camus, 1986, p. 624). North of Quebrada Santos, the Trinidad Siltstone is absent and the Upper Lavas directly overlie the Basal Breccia.

The Upper Lavas largely consist of altered basalt to basalt andesitic volcanic rocks (see below). In the Punta del Cobre district, this subunit is usually only a few meters thick but may attain a thickness of over 40 m (e.g. near the Santos mine). At Quebrada Meléndez, the Upper Lavas are volcanic flows in part containing decimetric clasts of chert and limestone. Above the open pit of the Santos mine, between Quebrada Meléndez and Quebrada Santos, the volcanic rocks, in places, contain lenses of limestones. In the southern Punta del Cobre district, in the area of the Abundancia and old Agustina mines, the 'Lavas Superiores' laterally grade into tuffs and reworked tuffs, siltstones, cherts, and carbonatic rocks (Lino, 1984; Lino and Rivera, 1985; Schönfelder, 1990).

At the northern end of the Quebrada Los Toros, the Upper Lavas show features similar to those at Quebrada Meléndez. Lava flows there contain centimetric limestone fragments and occasionally also decimetric to metric limestone blocks. In places, feldspar phenocrysts of the volcanic matrix are completely replaced by calcite. Massive volcanic rocks at the southern part of Quebrada Los Toros, at Quebrada Rivera, and at Quebrada La Pepita correlate with the Upper Lavas because they underlie limestones of the Chañarcillo Group, respectively, their metamorphosed equivalents, and show a similar geochemistry. The 'Upper Andesites' unit of Ryan et al. (1995) at Candelaria has a thickness of up to 200 m. This unit includes volcaniclastic rocks stratigraphically above and below lenses of porphyritic volcanic flows that are equivalent to the Upper Lavas in the Punta del Cobre district. Therefore, the Upper Andesites unit of Ryan et al. (1995) only in parts corresponds to the Upper Lavas.

7. Abundancia Formation (Chañarcillo Group)

Biese-Nickel (1942) subdivided the Chañarcillo Formation, originally defined by Whitehead (1919) into four units: 'Capas de Abundancia', 'Caliza de Nantoco', 'Marga de Totoralillo', and 'Caliza de Pabellón'. He described the Capas de Abundancia at its type locality east of the Abundancia mine in the southern Punta del Cobre district (Figs. 2 and 8; Biese-Nickel, 1942). As base, he considered the 'Albitófiro', respectively, the Meléndez Dacites ('Roca Eruptiva Basal Albitófiro', see also Corvalán, 1974; Jurgan, 1977a,b) and determined a thickness for the Capas de Abundancia of about 60 m. Another section of the Capas de Abundancia at Quebrada Meléndez starts above the Upper Lavas, which he interpreted to be part of the Meléndez Dacites (Biese-Nickel, 1942, p. 432, 433, and photo 5). Therefore, the 'Capas de Abundancia' of Biese-Nickel (1942) near the Abundancia mine corresponds to the Basal Breccia, the Trinidad Siltstone, and the Upper Lavas, whereas at Quebrada Meléndez the Capas de Abundancia start at a higher stratigraphic level, i.e. above the Upper Lavas. The fossils collected by Biese-Nickel (1942) were later revised by Tavera (1956), who identified Valanginian and Early Hauterivian cephalopods from an unprecise location, probably from the Abundancia Formation at Quebrada Meléndez, and also cephalopods of Berriasian age or Berriasian to Early Valanginian age (*Kilianella* cf. *burckardti*) that may have been taken from what we now call the Trinidad Siltstone near the Abundancia mine. After Biese-Nickel (1942, p. 443, 446), the Capas de Abundancia are separated from the overlying 'Calizas de Nantoco' (Nantoco Formation) by a gray 'tuff horizon' ('Tobas Superiores') that may correspond to the Upper Lavas in the section near the

Table 1
Selected whole-rock X-ray fluorescence analyses of volcanic rocks of the Algarrobos Member, Punta del Cobre Formation. Other analyses used for the diagrams but not contained in the table are given in Marschik (1996) (Abbreviations. Qda: quebrada; V: valley; LOI: loss on ignition)

Sample	PC 924	PC 934	PC 973	PC 1054	PC 1057	PC 1074	PC 1076	PC 1077	PC 1082	PC 1125
Location	Trinidad Claim	Trinidad Claim	Qda. Meléndez	Qda. Los Toros	Qda. Los Toros	Qda. La Pepita	V. Río Copiapó	V. Río Copiapó	Qda. La Pepita	Qda. Rivera
UTM East	377 416	377 351	376 260	370 130	370 180	372 120	374 290	374 320	371 925	364 400
UTM North	6 958 259	6 958 668	6 961 130	6 948 300	6 948 320	6 953 220	6 957 525	6 957 660	6 953 045	6 943 500
wt%										
SiO_2	49.75	48.41	46.02	49.37	46.83	52.84	53.52	52.23	52.22	48.55
TiO_2	0.81	0.97	0.83	1.18	0.98	1.16	0.87	0.93	0.95	1.13
Al_2O_3	16.13	17.91	14.96	19.94	17.06	18.33	17.16	16.79	16.50	16.93
Fe_2O_3[a]	6.14	5.97	10.06	10.66	6.04	8.86	7.95	8.35	8.69	12.53
MnO	0.31	0.31	1.21	0.09	0.43	0.05	0.21	0.24	0.14	0.60
MgO	6.44	5.68	4.79	6.65	2.58	3.78	7.11	7.61	6.34	7.66
CaO	5.36	5.36	8.58	1.20	10.27	7.32	3.36	3.22	10.11	4.08
Na_2O	4.88	4.70	3.89	5.33	5.72	4.37	6.42	5.80	3.17	3.80
K_2O	2.12	2.20	1.16	1.42	1.49	1.55	2.28	3.14	0.78	2.90
P_2O_5	0.15	0.20	0.13	0.15	0.15	0.20	0.14	0.16	0.13	0.18
LOI	7.38	6.92	4.95	4.35	8.22	0.87	1.02	1.08	0.86	1.11
Total	99.47	98.63	96.58	100.34	99.77	99.33	100.04	99.55	99.89	99.47
ppm										
Ni	37	59	90	26	6	5	24	54	76	23
Cr	232	152	414	103	69	64	152	172	269	60
V	209	154	216	257	196	237	175	173	221	332
Ba	1489	420		254	898	287	239	329	214	
Zr	85	117	67	131	108	128	127	133	106	82
Y	20	31	21	33	19	22	17	16	18	22
Sr	177	297	200	268	152	326	217	198	234	257
Rb	42	106	31	51	44	63	86	153	37	61
Nb	< 5	8	4	< 5	5	5	5	5	6	2
Ce	20			19						
Th	< 1			< 1						
La	7			10						
Co	30			40						
Pb	< 2			< 2						
Zn	187			47						
Cu	< 4			3427						
Ga	15			24						
Hf	3			11						
Nd	< 3			4						
U	< 2			< 2						
S	336			5						

Table 1 (*continued*)

Sample	PC 1126	PC 1204	PC 1210	PC 862	PC 904	PC 1028	PC 1031	PC 1213	PC 1214	PC 1325
Location	Qda. Rivera	Qda. La Pepita	Qda. La Pepita	Qda. Nantoco	Qda. Nantoco	Qda. Las Pintadas	Qda. Las Pintadas	Qda. Las Pintadas	Qda. Los Toros	Qda. Nantoco
UTM East	364 400	371 420	371 800	373 190	372 000	367 410	368 215	369 360	370 100	372 380
UTM North	6 943 500	6 952 470	6 952 830	6 951 620	6 951 370	6 948 270	6 948 700	6 949 180	6 947 840	6 951 750
wt%										
SiO_2	48.50	54.78	51.97	52.43	53.71	53.69	57.18	61.24	46.70	53.20
TiO_2	1.16	0.89	1.29	1.13	1.02	0.71	0.74	0.97	1.05	1.04
Al_2O_3	16.44	17.66	19.62	18.74	17.69	17.86	15.77	16.38	19.02	17.56
Fe_2O_3[a]	12.74	7.37	6.71	8.53	7.85	7.09	7.02	7.15	9.52	8.82
MnO	0.50	0.11	0.07	0.21	0.17	0.04	0.09	0.01	0.16	0.16
MgO	7.25	4.33	5.51	2.97	5.10	4.70	5.05	1.76	4.65	5.32
CaO	5.74	8.83	3.61	8.13	8.66	8.26	5.25	0.95	6.02	4.56
Na_2O	4.08	3.36	4.98	3.32	2.92	5.38	6.86	7.85	5.23	4.31
K_2O	1.57	0.60	3.25	1.17	0.79	0.57	0.38	0.38	1.12	2.29
P_2O_5	0.19	0.10	0.08	0.18	0.14	0.17	0.14	0.16	0.14	0.17
LOI	1.06	0.61	0.74	2.63	2.23	1.85	1.03	1.59	5.41	3.00
Total	99.23	98.64	97.83	99.44	100.28	100.32	99.51	98.44	99.02	100.43
ppm										
Ni	56	< 2	17	5	11	22	16	< 2	< 2	24
Cr	71	26	19	17	45	56	5	33	48	102
V	313	170	163	200	217	249	140	176	187	229
Ba		123	111	880	294	180	195	40	164	553
Zr	85	118	211	165	132	112	162	135	140	140
Y	24	16	22	37	32	22	20	15	17	29
Sr	331	357	353	746	468	820	190	122	210	172
Rb	38	17	149	33	30	23	19	13	36	62
Nb	3	< 5	< 5	6	2	6	6	< 5	< 5	8
Ce		19	< 6					64	< 6	34
Th		< 1	< 1					< 1	< 1	6
La		11	5					34	6	14
Co		113	261					83	43	33
Pb		< 2	< 2					< 2	< 2	6
Zn		27	40					11	53	40
Cu		22	< 4					71	< 4	13
Ga		10	12					11	12	17
Hf		< 2	2					< 2	< 2	5
Nd		8	6					30	7	18
U		< 2	< 2					< 2	< 2	3
S		64	64					202	71	28

[a] Total Fe as Fe_2O_3.

Table 2
Selected whole-rock X-ray fluorescence analyses of volcanic rocks of the Meléndez Dacites, Punta del Cobre Formation.Other analyses used for the diagrams but not contained in the table are given in Marschik (1996) (Abbreviations. Qda: quebrada; V: valley; LOI: loss on ignition)

Sample	PC 627	PC 650	PC 661	PC 671	PC 693	PC 725	PC 748	PC 756	PC 766	PC 771
Location	N of Qda. Trinidad	Qda. Trinidad	N of Carola Mine	Trinidad Claim	Qda. Meléndez	Qda. Trinidad	N of Carola Mine	Trinidad Claim	N of Carola Mine	Trinidad Claim
UTM East	376 226	377 240	376 995	376 781	376 260	376 960	377 215	377 048	377 147	377 286
UTM North	6 959 600	6 958 300	6 957 973	6 959 446	6 961 235	6 959 304	6 958 125	6 958 751	6 957 889	6 958 308
wt%										
SiO_2	64.07	65.82	62.45	65.88	66.40	67.39	65.31	65.45	62.44	62.61
TiO_2	0.50	0.51	0.55	0.55	0.41	0.45	0.51	0.53	0.50	0.51
Al_2O_3	14.98	15.75	15.40	15.76	15.94	14.54	15.68	15.85	14.82	14.68
Fe_2O_3[a]	3.89	5.81	6.03	6.34	6.03	1.60	4.37	7.26	6.48	4.59
MnO	0.02	0.02	0.04	0.03	0.04	0.06	0.04	0.04	0.10	0.08
MgO	0.34	1.22	1.36	0.96	0.79	0.10	1.41	1.39	1.63	0.66
CaO	0.33	0.41	0.29	0.54	0.31	3.40	0.57	0.38	0.40	2.57
Na_2O	0.33	7.44	1.09	7.52	8.71	8.40	4.12	8.09	0.88	0.09
K_2O	11.68	0.69	10.66	0.88	0.18	0.26	4.85	0.16	9.79	9.45
P_2O_5	0.10	0.15	0.13	0.17	0.07	0.04	0.13	0.17	0.19	0.19
LOI	1.69	1.28	1.34	1.20	1.01	2.92	2.00	1.30	1.65	3.41
Total	97.93	99.10	99.34	99.83	99.89	99.16	98.99	100.62	98.88	98.84
ppm										
Ni	< 5	< 5	5	< 5	8	< 5	9	< 5	7	< 5
Cr	< 5	< 5	5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
V	43	51	37	48	53	32	43	49	40	27
Ba	3858	60	2661	213	86	49	741	5	1995	3982
Zr	184	199	176	200	198	202	192	188	173	170
Y	15	23	10	22	13	31	10	8	18	20
Sr	210	37	126	57	32	48	33	32	63	57
Rb	182	35	166	40	17	19	100	14	138	166
Nb	6	11	6	10	7	11	10	6	9	8
Ce										
Th										
La										
Co										
Pb										
Zn										
Cu										
Ga										
Hf										
Nd										
U										
S										

Table 2 (*continued*)

Sample	PC 781	PC 835	PC 894	PC 981	PC 987	PC 999	PC 1000	PC 1003	PC 1071	PC 1110
Location	Trinidad Claim	Qda. Meléndez	Qda. Meléndez	Ladrillos	Ladrillos	Ladrillos	Ladrillos	Ladrillos	Qda. Meléndez	Qda. Santos
UTM East	377 060	375 980	376 525	375 970	376 030	376 014	375 940	376 360	377 005	375 950
UTM North	6 958 960	6 961 040	6 961 570	6 962 705	6 962 805	6 962 760	6 962 710	6 962 370	6 961 715	6 960 980
wt%										
SiO_2	65.47	66.42	66.70	66.77	65.82	74.34	72.82	64.28	66.18	67.71
TiO_2	0.47	0.47	0.46	0.11	0.44	0.18	0.17	0.48	0.39	0.48
Al_2O_3	14.99	15.28	15.97	13.52	15.73	13.15	11.39	15.55	14.96	16.08
Fe_2O_3 [a]	6.69	6.45	4.20	7.87	5.99	3.47	8.99	6.75	6.22	3.92
MnO	0.10	0.03	0.03	0.04	0.04	0.01	0.01	0.02	0.06	0.06
MgO	0.91	0.69	1.23	0.21	1.31	0.13	0.08	0.63	1.48	0.08
CaO	1.09	0.41	0.67	2.01	0.38	0.51	0.21	0.77	0.58	0.36
Na_2O	7.36	6.50	7.94	7.73	4.98	7.18	6.15	6.25	4.45	7.87
K_2O	0.79	2.96	0.99	0.21	4.21	0.29	0.26	3.88	3.58	1.37
P_2O_5	0.18	0.17	0.16	0.03	0.10	0.07	0.03	0.14	0.11	0.05
LOI	1.91	0.94	1.49	1.89	1.41	0.72	0.56	1.10	1.94	1.30
Total	99.96	100.32	99.84	100.39	100.41	100.05	100.67	99.85	99.95	99.28
ppm										
Ni	6	22	12	< 2	< 2	7	7	5	36	37
Cr	< 5	35	< 5	12	8	< 5	20	5	7	5
V	38	34	43	29	56	20	41	40	38	29
Ba	169	1006	252	29	2153	< 20	499	591	2513	556
Zr	193	215	203	197	193	197	227	183	164	209
Y	26	26	27	16	20	23	16	21	15	24
Sr	37	36	42	31	90	29	19	26	58	55
Rb	23	58	27	7	70	21	13	60	83	28
Nb	9	9	9	< 5	< 5	9	31	9	5	< 5
Ce				24	28		24			< 6
Th				< 1	< 1		17			< 1
La				12	7		16			3
Co				16	13		95			57
Pb				9	54		27			< 2
Zn				20	37		18			42
Cu				280	64		245			405
Ga				13	17		11			20
Hf				8	6		15			8
Nd				< 3	< 3		11			< 3
U				< 2	< 2		9			< 2
S				532	354		214			577

[a] Total Fe as Fe_2O_3.

Table 3
Selected whole-rock X-ray fluorescence analyses of volcanic rocks of the Lower Andesites, Punta del Cobre Formation. Other analyses used for the diagrams but not contained in the table are given in Marschik (1996)

Sample	PC 692	PC 799	PC 805	PC 917	PC 920	PC 1102	PC 1103
Location	Qda. Trinidad	Trinidad Mine	N of Carola Mine	S of Carola Mine	S of Carola Mine	Qda. Tirana	Qda. Tirana
UTM East	376 672	376 782	376 125	375 560	375 520	375 853	376 030
UTM North	6 959 188	6 959 242	6 957 865	6 956 420	6 955 920	6 960 015	6 959 946
wt%							
SiO_2	59.47	58.67	55.01	58.37	55.43	58.90	55.34
TiO_2	0.58	0.68	0.65	0.63	0.75	0.63	0.62
Al_2O_3	13.29	16.33	15.29	14.97	16.10	15.02	15.04
Fe_2O_3[a]	12.68	9.25	10.43	7.89	9.59	9.48	13.39
MnO	0.11	0.11	0.16	0.11	0.10	0.10	0.16
MgO	4.23	5.25	4.80	4.65	1.60	3.97	3.03
CaO	0.25	0.35	0.34	0.31	1.14	0.83	0.35
Na_2O	0.78	4.63	0.12	0.13	0.15	3.04	1.61
K_2O	4.92	1.39	6.82	8.44	10.99	5.90	7.00
P_2O_5	0.12	0.12	0.17	0.12	0.14	0.10	0.12
LOI	2.91	3.44	3.59	3.43	2.68	1.33	3.01
Total	99.34	100.22	97.38	99.05	98.67	99.30	99.67
ppm							
Ni	< 5	14	14	7	8	15	< 5
Cr	28	39	13	46	59	330	48
V	117	98	67	146	153	89	148
Ba	1113	158	1961	1666	1313	970	1248
Zr	144	175	137	148	166	171	138
Y	9	9	8	16	29	12	9
Sr	93	58	107	122	56	107	63
Rb	110	47	116	139	259	154	197
Nb	2	5	3	< 5	3	5	4
Ce				14			
Th				< 1			
La				2			
Co				29			
Pb				< 2			
Zn				78			
Cu				196			
Ga				18			
Hf				5			
Nd				< 3			
U				< 2			
S				917			

[a] Total Fe as Fe_2O_3.

Abundancia mine, taking into account the determined thickness of 60 m for the Abundancia Formation in that particular place. At Quebrada Meléndez, where Biese-Nickel (1942) apparently considered the Upper Lavas as the base of the Capas de Abundancia, similar gray volcaniclastic and/or tuffaceous horizons are intercalated within the sedimentary sequence (Jurgan, 1977b, p. 28, 29). Biese-Nickel's (1942) formation boundary at that place was probably at a higher stratigraphic level.

In the definition of Segerstrom and Ruiz (1962), the Abundancia Formation is the part of the Chañarcillo Group overlying the Upper Lavas and should have a Late Valanginian age, in contrast to the Nantoco Formation which, according to Corvalán (1974), is considered to start in the Early Hauterivian based on the attribution of a Late Hauterivian age to its upper part. Ammonites (e.g. *Olcostephanus curacoensis* and *Acanthodiscus*) assigned to the Late Valanginian and Early Hauterivian are found in the Abundancia Formation about 150 m above the Upper Lavas at Quebrada Meléndez (Corvalán, 1974, p. 18, 19). The Late Hauterivian age of the upper part of the Nantoco Formation is based on the occurrence of the only significant time marker, the ammonite *Crioceras andinum* Gerth, 500 m above the contact with the Abundancia Formation (Corvalán, 1974, p. 24, 34). In fact, a distinction between the Abundancia and Nantoco Formations based on their age is not possible owing to the scarce paleontological data available. A lithologic distinction is not practicable either, since in the sedimentary sequence above the Upper Lavas there exists a continuous transition between a more terrigenous volcaniclastic lower part and a dominantly marine carbonatic upper part. Therefore, it is difficult to map a limit

Table 4
Selected whole-rock X-ray fluorescence analyses of volcanic rocks of the Bandurrias Group. Other analyses used for the diagrams but not contained in the table are given in Marschik (1996) (Abbreviations. Qda: quebrada; V: valley; QLC: Qda Las Cañas; LCA: Las Cañas area; LOI: loss on ignition)

Sample	PC 1096	PC 1220	PC 1221	PC 604	PC 605	PC 1342	WG 85[a]	WG 87[a]	WG 88[a]	FX 349-1[b]
Location	Paipote	Paipote	Paipote	Qda. Paipote	Qda. Paipote	NW of Chañarcillo	CaballoMuerto	Caballo Muerto	Caballo Muerto	Jaula
Rel Strat Lev										
UTM East	375 830	374 400	374 420	376 750	376 750	360 000				
UTM North	696 6280	6 965 580	6 965 480	6 972 600	6 972 780	6 927 000				
wt%										
SiO_2	54.47	49.66	52.34	63.32	61.63	49.67	63.98	70.48	55.98	56.56
TiO_2	1.18	0.90	0.80	0.52	0.60	0.89	0.4	0.44	1.26	0.7
Al_2O_3	17.04	17.43	15.88	15.28	16.60	16.09	16.61	13.7	15.63	16.94
Fe_2O_3[c]	9.25	10.91	8.44	5.93	6.76	9.46	4.28	3.64	9.43	7.18
MnO	0.28	0.31	0.36	0.07	0.14	0.40	0.07	0.08	0.14	0.11
MgO	5.74	6.25	7.58	2.23	3.22	3.30	1.74	0.27	2.86	3.5
CaO	3.80	5.21	5.00	1.38	0.99	9.05	5.15	0.49	2.53	5.02
Na_2O	6.40	5.31	5.63	8.43	5.68	3.94	3.2	0.16	4.53	3.95
K_2O	0.43	0.64	0.55	0.72	3.39	0.68	2.52	9.32	4.17	2.75
P_2O_5	0.08	0.07	0.04	0.10	0.11	0.23	0.1	0.12	0.39	0.16
LOI	1.28	1.66	1.71	1.97	1.92	6.02	1.95	1.29	3.08	3.13
Total	99.95	98.35	98.33	99.95	101.04	99.72	100.00	100.00	100.00	100.00
ppm										
Ni	27	8	29	< 2	4	11	7	29	25	1
Cr	106	23	289	9	14	11	95	31	48	21
V	287	279	272	107	120	173	93	47	318	149
Ba	< 3	269	482	7	658	238	579	612	778	1012
Zr	156	70	70	114	127	106	101	386	243	113
Y	39	10	17	20	24	20	12	44	39	23
Sr	144	357	228	88	193	381	413	117	228	472
Rb	14	20	14	9	60	22	62	406	144	74
Nb	< 5	< 5	< 5	< 5	< 5	8	3.5	11	23	6
Ce	127	23	13	31	37	28				
Th	< 1	< 1	< 1	< 1	< 1	3				
La	56	7	3	12	11	12				
Co	52	97	142	12	18	32				
Pb	< 2	< 2	< 2	3	7	13				
Zn	72	77	88	92	154	81				
Cu	54	47	55	< 4	< 4	12				
Ga	21	15	11	17	21	15				
Hf	6	2	2	5	6	6				
Nd	79	10	9	6	12	20				
U	< 2	< 2	< 2	< 2	< 2	2				
S	< 10	183	325	331	343	38				

Table 4 (*continued*)

Sample	FX 350-1[b]	FX 353-1[b]	FX 357-2[b]	FX 412[b]	AN 7[d]	AN 8[d]	AN 17[d]	AN 55[d]	CL 4[d]	CL 14[d]
Location	Jaula	Jaula	Las Cañas	QLC	QLC	QLC	QLC	QLC	LCA	LCA
Rel Strat Lev			Beneath Nantoco Fm.[e]	Nantoco Fm.	Beneath Nantoco Fm.[e]	Beneath Nantoco Fm.[e]	Nantoco Fm.	Totoralillo Fm.	Nantoco Fm.	Nantoco Fm.
UTM East										
UTM North										
wt%										
SiO_2	57.34	55.96	49.63	55.04	49.06	49.17	57.29	48.99	52.15	52.06
TiO_2	0.74	0.63	0.89	1.45	0.89	0.87	1.59	0.67	1.45	1.44
Al_2O_3	16.95	18.44	17.77	15.59	17.62	16.91	15.42	15.14	16.95	16.7
Fe_2O_3[c]	7.21	8.28	9.59	9.29	9.75	9.76	8.08	6.16	10.31	10.56
MnO	0.14	0.12	0.18	0.25	0.25	0.36	0.29	0.2	0.22	0.23
MgO	2.86	3.5	6.34	2.71	6.44	7	1.91	1.39	3.57	3.57
CaO	6.3	3.15	9.14	5.63	6.17	3.44	4.7	10.85	7.7	8.03
Na_2O	3.78	5.25	2.77	7	4.07	5.09	7.21	5.87	3.48	3.26
K_2O	1.94	1.92	1.26	0.8	1.9	1.58	1.36	1.85	2.04	1.97
P_2O_5	0.17	0.18	0.19	0.25	0.11	0.2	0.18	0.06	0.35	0.35
LOI	2.57	2.58	2.24	1.98	3.74	5.62	1.98	8.83	1.78	1.83
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
ppm										
Ni	1	1	44	22	39	39	24	2.5	2.5	2.5
Cr	55	14	113	45	125	106	25	5	25	36
V	137	109	238	396	241	233	317	133	327	347
Ba	952	1791	289	93	640.9	280.9	52.01	222.8	438.27	492.06
Zr	124	112	67	142	75.42	86.6	139.8	63.81	174.82	178.59
Y	24	22	24	33	17.2	19.3	31.7	13.3	36.7	37.6
Sr	489	468	521	245	862	322.9	117.3	225.8	425.13	424.03
Rb	61	52	52	27	80.57	47.78	50.98	56.36	55.37	55.85
Nb	2.5	2.5	0.5	4	2.26	2.65	4.05	1.95	6.8	6.91
Ce										
Th										
La										
Co										
Pb										
Zn										
Cu										
Ga										
Hf										
Nd										
U										
S										

[a] Griem (1994).
[b] Lieben (2000).
[c] Total Fe as Fe_2O_3.
[d] Nova (1997).
[e] Correlates with the Upper Lavas of the Punta del Cobre Fm.

between the Abundancia Formation and the Nantoco Formation. In this point we disagree with Corvalán (1974, p. 17, 18), who stated that the upper limit of the Abundancia Formation can be recognized at any place in the Punta del Cobre district because of the differences in lithologies and faunal content. Therefore, we interpret the Abundancia Formation as representing the lower part of the interfingering zone of arc-derived volcanic debris (Bandurrias Group) with the carbonatic sedimentation of a shallow marine backarc basin (Nantoco Formation; Figs. 3 and 6). In fact, the Abundancia Formation could be ranked as a member and included in the Nantoco Formation, but for the sake of consistency with the existing literature we maintain the terminology. The Abundancia Formation has been recognized only in this northern part of the Early Cretaceous Atacama marine basin. In the south, e.g. at Chañarcillo or Quebrada Las Cañas, volcanic–volcaniclastic deposits of the Bandurrias Group are directly overlain by carbonate rocks of the Nantoco Formation.

The Abundancia Formation consists of bedded limestones and layers of whitish weathered chert. Intercalations of volcanic arenite, tuff, and volcaniclastic breccias and conglomerates are a typical feature (Jurgan, 1977b). The contact between the Abundancia Formation and the underlying Punta del Cobre Formation is defined by the first continuous bed of massive limestone within the predominantly volcaniclastic rocks commonly located above the Upper Lavas. At the Candelaria deposit, the Upper Andesites unit is overlain by up to 300–400 m of skarns and hornfelses ('Metasedimentary Rocks' of Ryan et al., 1995) that represent the metamorphosed equivalents of the Abundancia Formation.

8. Bandurrias Group

Segerstrom (1960) defined the Bandurrias 'Formation' in the Copiapó area. It is composed of a 2500–3000 m thick sequence of volcanic rocks, mainly basaltic andesites, andesites, trachyandesites and dacites, continental volcaniclastic sediments, and tuffs, which also contains intercalations of shallow marine limestones and sandstones. The degree of rounding and the maturity of the volcaniclastic deposits increase from Sierra Bandurrias, southeast of Copiapó, towards the south, whereas the thickness diminishes in this direction. Thus, a main source area lying towards the north is assumed (Jurgan, 1977a,b). A complete facies transition into the carbonatic shallow marine depositional environment of the Chañarcillo Group can be observed between Quebrada Paipote and Quebrada Meléndez (Segerstrom, 1961; Jurgan, 1977b). The Bandurrias Formation interfingers with all the formations of the Chañarcillo Group, suggesting an Late Valanginian to probably Aptian age, which in other localities is also supported by its fossil content (Segerstrom, 1961, 1967, 1968; Jurgan, 1977b; Sepúlveda and Naranjo, 1982). The Bandurrias Formation is recognized between 26°40′S and 29°35′S (Moraga, 1977; Moscoso et al., 1982; Cisternas, 1986; Mayer, 1988; Pincheira, 1991; Abad 1977, 1980; Griem, 1994). Moscoso et al. (1982) proposed to change the rank of the Bandurrias Formation to 'Group', based on observations in the Río Elqui valley near La Serena; they included the Hauterivian–Barremian Arqueros Formation and the Aptian–Albian Quebrada Marquesa Formation (Aguirre and Egert, 1965) in the Bandurrias Group. We follow the suggestion of Moscoso et al. (1982), taking the situation in the Copiapó area into account, where the Bandurrias Group represents the terrestrial–terrigenous time equivalent of the Chañarcillo Group.

In the study area, rocks of the Bandurrias Group are best exposed in the northern (Quebrada Paipote, Punta Negra, and Quebrada Florida) and southwestern parts (Figs. 1 and 2). These interfinger and overlie strata of the Abundancia Formation, which in turn overlies the Punta del Cobre Formation in the area between Punta Negra and the Alcaparrosa mine (Figs. 2 and 5b). A distinction between the Punta del Cobre Formation and the Bandurrias Group can only be made based on their stratigraphic position relative to the Chañarcillo Group. Rock types of the Algarrobos Member and the Bandurrias Group are essentially the same.

9. Intrusive rocks

Early to mid-Cretaceous intrusive rocks exposed south of Copiapó are part of the Coastal Batholith of northern Chile. The Copiapó Batholith is composed of several plutons, predominantly dioritic, granodioritic, and quartz monzonitic (adamellitic) in composition. Locally, these plutons are separated by tectonic contacts. According to Tilling (1976), felsic magmatic phases generally intrude the more mafic ones. Available $^{40}Ar/^{39}Ar$ and K–Ar ages for the Copiapó Batholith range from 119 to 97 Ma (Farrar et al., 1970; Zentilli, 1974; Arévalo, 1994, 1995, 1999).

In places, the batholith is bound by shear zones or zones of brecciated intrusive rocks at its eastern margin that define subvertical contacts. An emplacement at high crustal levels is suggested by a probable maximum overburden of 1700–2000 m in Aptian times, i.e. the thickness of the Chañarcillo Group. This accords with the results of regional studies that suggest shallow level emplacement of other Early Cretaceous intrusions between Copiapó and Chañaral based on concordant U–Pb zircon and $^{40}Ar/^{39}Ar$ hornblende isotope correlation ages indicating rapid cooling (Berg and Breitkreuz, 1983; Dallmayer et al., 1996) and on pressure calculations using the Al-in-hornblende geobarometer (Dallmayer et al., 1996).

The batholith caused extensive contact metamorphism (Ruiz, 1940; Tilling, 1962, 1963a,b, 1976; Marschik and Fontboté, 1996). In the contact metamorphic aureole, limestones of the Chañarcillo Group are converted to diopside–andradite ± sodic scapolite skarn (Tilling, 1962, 1963a,b).

Table 5
Chondrite-normalized rare-earth element compositions of volcanic rocks of the Punta del Cobre Formation and the Bandurrias Group (abbreviations: AM = Algarrobos Member; BG = Bandurrias Group; LA = "Lower Andesites"; MD = "Meléndez Dacites"; UL = "Upper Lavas"; < = under detection limit; LCA = Las Cañas area (Qda Cabezita Larga); QLC = Qda Las Cañas. Reference chondrite of Nakamura (1974))

Sample	PC 1057	PC 934	PC 973	PC 1125	PC 1126	PC 862	PC 904	PC 1028	PC 1031	PC 671	PC 781	PC 835
Unit	UL	UL	UL	UL	UL	AM	AM	AM	AM	MD	MD	MD
La	30.49	19.51	15.85	22.26	14.02	27.74	29.88	32.01	36.59	61.28	53.05	15.55
Ce	26.94	21.97	14.34	24.16	12.14	24.51	26.13	28.55	28.67	65.66	44.86	27.98
Pr	26.02	26.83		25.20	13.82	24.39	25.20	22.76	24.39	44.72	39.84	15.45
Nd	23.49	27.30	12.86	24.76	13.81	22.70	21.11	19.05	20.32	37.62	33.02	11.75
Sm	16.26	19.70	11.33	21.18	14.29	18.72	18.72	13.30	13.30	24.14	20.69	10.34
Eu	13.77	18.05	10.26	19.61	14.55	17.40	14.29	10.52	17.66	17.92	13.25	7.92
Gd	10.79	16.30	10.14	14.13	11.59	15.58	15.22	8.33	12.32	15.58	13.04	9.42
Dy	10.50	11.95	8.75	12.83	10.79	12.83	12.83	6.71	11.66	12.83	11.95	13.99
Ho	8.21	8.46	7.69	11.62	9.62	10.90	11.67	5.64	9.87	10.90	11.54	12.95
Er	6.22	8.44	7.56	10.22	9.78	9.78	9.78	5.33	8.89	9.78	11.11	12.89
Tm	5.59	7.94	7.06	8.82	9.41	9.71	9.40	5.29	9.41		11.18	11.47
Yb	5.00	7.27	6.36	7.27	9.09	8.64	9.09	4.55	8.18	9.55	11.82	12.73
Lu	4.41	6.47	6.76	7.06	8.24	7.35	8.24	4.41	8.24	9.41	10.88	10.88

Sample	PC 1003	PC 692	PC 799	PC 805	PC 920	PC 1102		PC 604	PC 605	PC 1096	PC 1220	PC 1221
Unit	MD	LA	LA	LA	LA	LA		BG	BG	BG	BG	BG
La	41.16	6.40	7.93	127.44	12.50	9.76		45.12	30.79	64.33	29.57	19.82
Ce	29.36	3.82	4.80	79.42	9.36			35.03	24.86	55.14	24.05	18.15
Pr	21.95			57.72	8.94			30.08	23.58	52.03		
Nd	18.57	3.49	3.33	34.44	8.10	4.92		25.87	20.95	44.76	22.22	19.21
Sm	11.33			16.75	7.88			20.69	19			
.21	39.90	21.67										
Eu	7.14	1.69	1.56	7.66	4.94	1.30		11.82	10.39	16.75	15.32	11.69
Gd	7.61			6.52	6.52			11.96	10.87	22.10	12.68	13.77
Dy	8.45	2.92	2.62	2.92	6.71	3.21		9.04	8.75	16.62	9.91	12.24
Ho	8.72	3.08	3.85	2.82	5.77	3.59		8.72	8.46	13.46	7.82	10.38
Er	10.67			3.11	5.33	4.89		8.44	8.00	12.44	7.56	9.78
Tm	10.29					5.59		7.94	7.94	11.18	6.18	8.82
Yb	12.27	4.09	4.09		5.41	5.91		8.64	8.18	10.45	5.91	8.18
Lu	13.53	5.29			6.18	6.18		7.65	6.76	7.65	4.71	6.47

Table 5 (*continued*)

Sample	AN 7[a]	AN 8[a]	AN 17[a]	CL 4[a]	CL 14[a]	AN 55[a]
Location	QLC	QLC	QLC	LCA	LCA	QLC
Rel Strat Level	Beneath Nantoco Fm.[b]	Beneath Nantoco Fm.[b]	Nantoco Fm.	Nantoco Fm.	Nantoco Fm.	Totoralillo Fm.
La	29.63	38.69	45.52	55.79	57.65	27.47
Ce	25.54	32.27	38.74	50.14	51.49	19.47
Pr	20.57	25.85	32.60	39.43	40.33	13.33
Nd	21.13	25.71	34.19	41.35	40.89	12.86
Sm	15.62	19.85	26.75	34.19	34.68	9.85
Eu	13.90	15.45	21.95	21.43	22.34	8.96
Gd	12.28	13.88	22.07	25.04	25.07	8.15
Tb	9.81	10.38	16.54	20.77	21.15	6.92
Dy	9.27	10.17	17.17	20.76	20.73	6.88
Ho	8.46	8.97	15.00	17.95	18.21	6.15
Er	8.89	9.51	16.13	18.40	19.29	7.20
Tm	8.53	9.12	15.00	17.06	17.35	7.35
Yb	8.50	9.32	15.55	17.14	16.91	7.73
Lu	9.71	10.00	17.35	18.53	19.41	8.53

[a] Data of Nova (1997).
[b] Correlates with the Upper Lavas of the Punta del Cobre Fm (Nova, 1997).

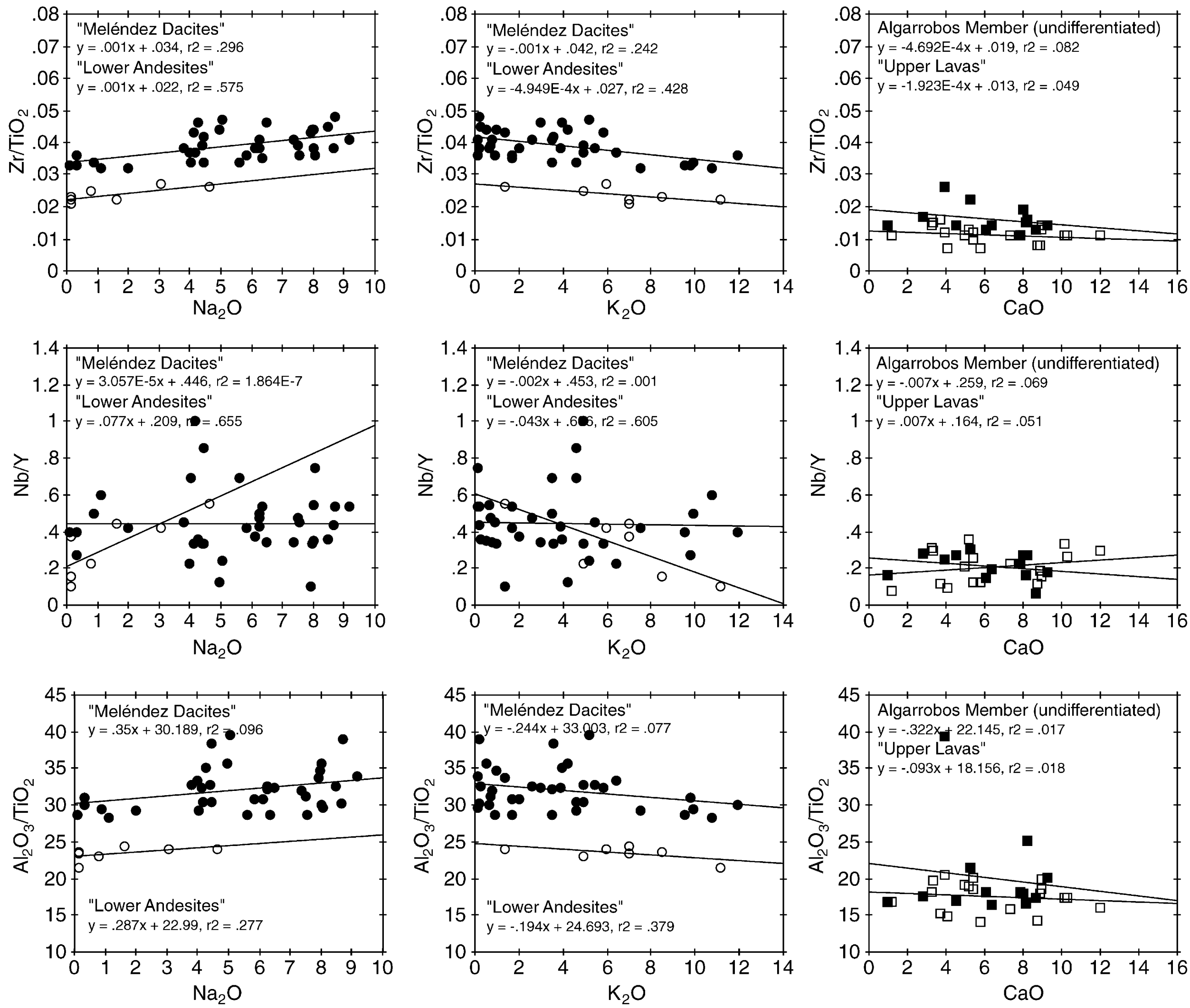

Fig. 9. Ratios of elements considered as largely immobile are relatively constant, even in rocks that suffered intense hydrothermal alterations. Selected whole-rock X-ray fluorescence analytical results are given in Tables 1–3.

In volcanic rocks of the Punta del Cobre Formation, contact metamorphism is expressed in overlapping alteration zones characterized by calcic-amphibole dominated assemblages locally overprinting biotitized rocks and grading into epidote–chlorite-rich assemblages with increasing distance from the batholith contact. Sodic and sodic–calcic alteration are recognized in batholithic rocks west of the Candelaria deposit.

Dikes and small intrusive bodies occur throughout the study area. Dacitic dikes and sills were emplaced in the rocks of the Punta del Cobre Formation and the lower part of the Chañarcillo Group. Locally, these dacitic dikes and sills host pyrite ± chalcopyrite disseminations and are affected by ore-related hydrothermal alteration. A lamprophyric laccolith intruded the limestones of the Abundancia Formation between Quebrada Meléndez and Quebrada Tirana. It shows pronounced columnar jointing, as already mentioned by Tilling (1962). Ruiz (1942) included this laccolith in the Albitófiro, respectively, Meléndez Dacites unit, but field evidence and geochemical composition do not support Ruiz's interpretation.

In the Punta del Cobre and Ladrillos districts, lamprophyric dikes (up to 2 m thick) occur along NNW- to NW-trending faults or occasionally follow NE directions. They cut the Lower Andesites, the Meléndez Dacites, and the Trinidad Siltstone (Lino, 1984). In places, these dikes occur in contact with NNW- to NW-trending ore veins (Carola mine, level N11) or breccia orebodies (Mantos de Cobre mine). The dikes commonly show strong carbonatization and are not mineralized, suggesting a post-mineralization emplacement.

10. Geochemistry of volcanic rocks of the Punta del Cobre Formation

Samples from each informal volcanic unit of the Punta

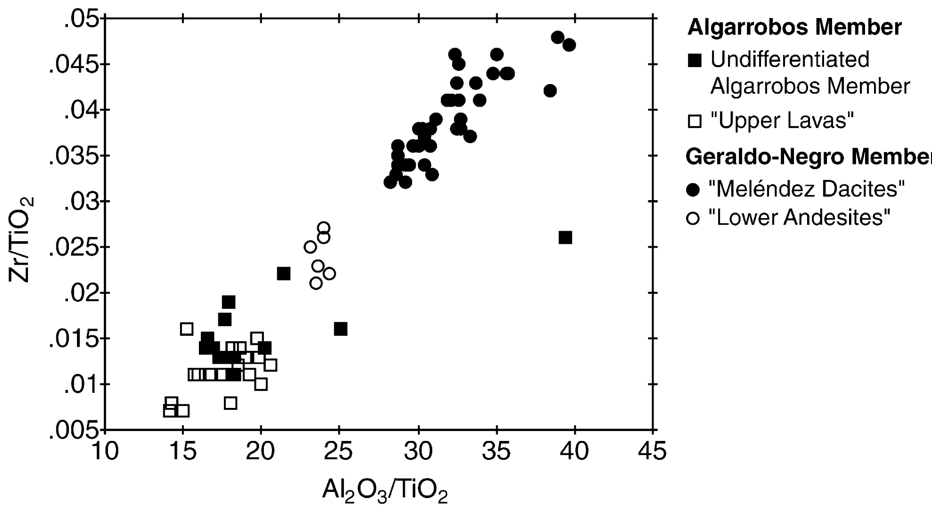

Fig. 10. Al_2O_3–TiO_2 vs. Zr–TiO_2 diagram. The volcanic rocks of the Punta del Cobre Formation follow a continuous fractionation trend which, however, is not continuous in time. Selected whole rock X-ray fluorescence analytical results are given in Tables 1–3.

del Cobre Formation were analyzed for major, trace, and in part rare-earth elements. The data set comprises a total of 103 whole-rock major and trace element and 29 rare-earth element analyses (Tables 1–5; see Marschik, 1996, for analytical results not contained in the tables). The data set also includes analyses from volcanic rocks of the Bandurrias Group for comparison, which were carried out during the present investigation as well as taken from other authors (Griem, 1994; Nova, 1997; Lieben, 2000; Fig. 1).

10.1. Effects of hydrothermal alteration

Almost all known outcrops of the Punta del Cobre Formation show strong effects of hydrothermal alteration, preventing a rock classification based on major elements. Studies on metamorphic terranes, ore deposits, and other related geologic environments showed that Zr, Ti, Al, Y, Nb, and V, as well as REE, can be considered as largely immobile under most conditions (e.g. Floyd and Winchester, 1978; Finlow-Bates and Stumpfl, 1981; MacLean and Kranidiotis, 1987; MacLean, 1990; Barrett and MacLean, 1994). Mass losses or gains due to metasomatic processes may dilute or concentrate a single immobile element, whereas the ratio of two immobile elements should be constant within the same volcanic rock. The volcanic rocks of the Punta del Cobre Formation show wide ranges in their Na_2O, K_2O, and CaO contents. Fig. 9 illustrates that the ratios of Zr–TiO_2, Al_2O_3–TiO_2, and Nb–Y remain fairly constant throughout the whole range of Na_2O, K_2O, and CaO values, which mainly expresses different types and degrees of alteration. This, and also the fact that the immobile elements plot largely in groups coinciding with lithologic units, indicate that Al, Ti, Zr, Nb, and Y contents allow the petrogenetic classification of the volcanic rocks of the Punta del Cobre Formation despite the strong alteration.

10.2. Classification of the volcanic rocks

Pairs of incompatible (e.g. Zr, Y, Nb) and compatible (e.g. Al, Ti) immobile elements can monitor fractionation trends. However, fractionation lines established from unaltered or least altered rocks as outlined in MacLean and Barrett (1993) and Shriver and MacLean (1993) cannot be applied here, because of the lack of adequate least-altered rocks. A combination of an incompatible/compatible pair as an indicator for magmatic fractionation and a ratio of two immobile elements that remains constant during alteration can display such trends. Fig. 10 shows that the different volcanic rocks of the informal units distinguished in the field plot close together and apparently follow a continuous fractionation trend which, however, is not continuously in time. The Nb–Y vs. Zr–TiO_2 diagram of Floyd and Winchester (1978) reveals a magmatic suite ranging from basalt to dacite in which the Upper Lavas are altered basalts to basaltic andesites, the other volcanic intercalations in the Algarrobos Member basaltic andesites to andesites, the Lower Andesites andesites, and the Meléndez Dacites, as already pointed out, dacites (Fig. 11). This is supported by microprobe analyses on unaltered or little altered plagioclases (Table 6). The least altered plagioclase of the Lower Andesites is labradorite (e.g. $An_{60–62}$, PC 1100). In the volcanic rocks of the Algarrobos Member, labradorite and bytownite (e.g. $An_{57–72}$, PC 863, PC 904, PC 1028), and in the Upper Lavas, bytownite (e.g. $An_{70–75}$, PC 1082, PC 1204, at Quebrada La Pepita), are present.

It is interesting to note that the strong alteration drastically changes the Na_2O, K_2O, and CaO contents, whereas the SiO_2 values are only slightly modified. The limited mobility of Si is illustrated by the Zr–TiO_2 vs. SiO_2 diagram (Winchester and Floyd, 1977), which shows that the groups discriminated in the Nb–Y vs. Zr–TiO_2 diagram can also be roughly distinguished by their SiO_2 content (Fig. 12).

The magma type discrimination for basic igneous rocks (after Pearce and Cann, 1973) indicates that the extrusive

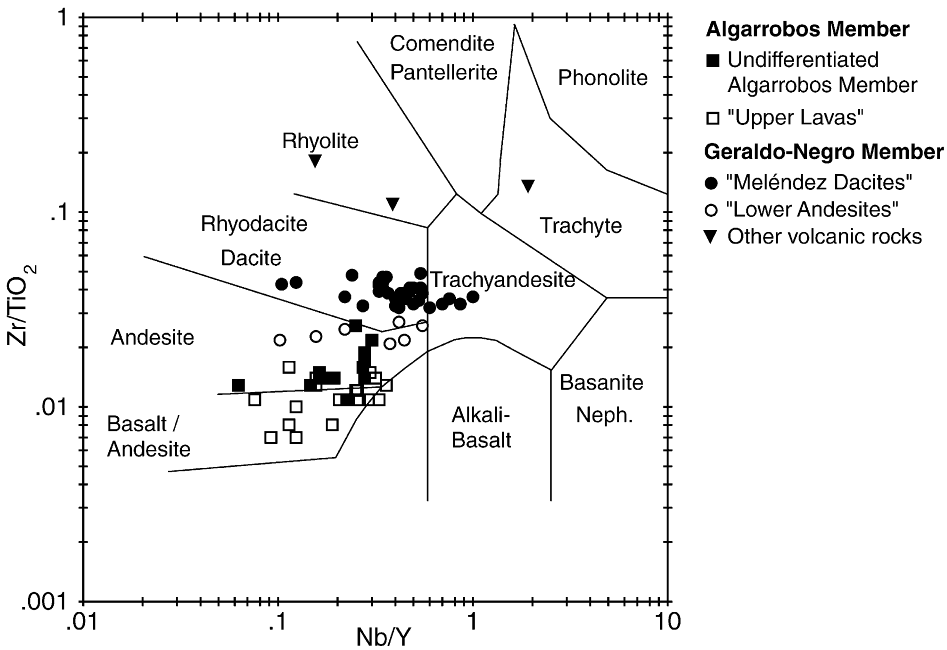

Fig. 11. The Nb–Y vs. Zr–TiO_2 discrimination diagram (Floyd and Winchester, 1978) reveals a compositional range from basalt to dacite for all but three volcanic rock samples of the Punta del Cobre Formation. These latter three samples were taken from an outcrop at the entrance to the Mantos de Cobre mine and underlie rocks of the Meléndez Dacites. Selected whole rock X – ray fluorescence analytical results are given in Tables 1–3.

sequence essentially follows a calc-alkaline trend (Fig. 13). A similar discrimination can be achieved with the Zr vs. Y diagram according to MacLean and Barrett (1993) in which a tendency towards more tholeiitic magmas is indicated for the Upper Lavas (Fig. 14). The arc-setting of the rocks of the Punta del Cobre Formation is confirmed by the Zr vs. Ti diagram (Fig. 15; Pearce, 1982). Selected samples of the Bandurrias Group are included in the diagrams of Figs. 12, 13, and 15. They span a compositional range similar to the volcanic rocks of the Punta del Cobre Formation (Fig. 12) and occupy the same fields in the discrimination diagrams (Figs. 13 and 15).

10.3. Rare-earth elements

Chondrite normalized rare-earth element patterns reflect the magmatic evolution already seen in the trace element distribution (Fig. 16). Some patterns of the Lower Andesites and the Meléndez Dacites are obviously disturbed as result of the strong hydrothermal alteration. In general, however, the volcanic rocks reflect their original magmatic signature.

The Lower Andesites show relatively flat slopes and low total REE concentrations that may indicate a low-K affinity, while the REE patterns of the Meléndez Dacites are similar to those of medium-K magmatic suites (Gill, 1981). The

Table 6
Results of electronprobe microanalysis of plagioclase of volcanic rocks of the Punta del Cobre Formation (Abbreviations. UL: Upper Lavas; AM: undifferentiated Algarrobos Member; LA: Lower Andesites; Or: orthoclase; Ab: albite; An: anorthite)

Sample	PC 1082	PC 1082	PC 1204	PC 1204	PC 863	PC 904	PC 904	PC 1028	PC 1100	PC 1100
Location	UL	UL	UL	UL	AM	AM	AM	AM	LA	LA
UTM East	371 925	371 925	371 420	371 420	373 210	372 000	372 000	367 410	376 055	376 055
UTM North	6 953 045	6 953 045	6 952 470	6 952 470	6 951 590	6 951 370	6 951 370	6 948 270	6 959 710	6 959 710
wt%										
SiO_2	49.86	48.68	49.94	50.17	49.42	53.75	49.73	52.46	52.50	52.29
Al_2O_3	30.49	31.56	31.49	31.14	31.49	27.65	30.91	30.21	29.10	29.40
FeO	0.67	0.69	0.43	0.62	0.51	0.81	0.70	0.46	0.52	0.54
MgO	0.10	0.15	0.00	0.00	0.06	0.14	0.08	0.05	0.04	0.04
CaO	14.26	15.32	14.63	14.41	14.40	11.70	14.82	12.68	12.47	12.72
Na_2O	3.37	2.69	3.39	3.37	3.05	4.74	3.15	3.95	4.43	4.19
K_2O	0.10	0.11	0.04	0.10	0.30	0.20	0.10	0.20	0.29	0.19
Total	98.85	99.20	99.90	99.81	99.23	98.99	99.50	100.01	99.34	99.37
Or	0.59	0.66	0.21	0.57	1.78	1.15	0.60	1.20	1.64	1.10
Ab	29.80	24.00	29.50	29.60	27.21	41.83	27.62	35.64	38.54	36.97
An	69.61	75.34	70.29	69.83	71.01	57.02	71.78	63.16	59.82	61.94

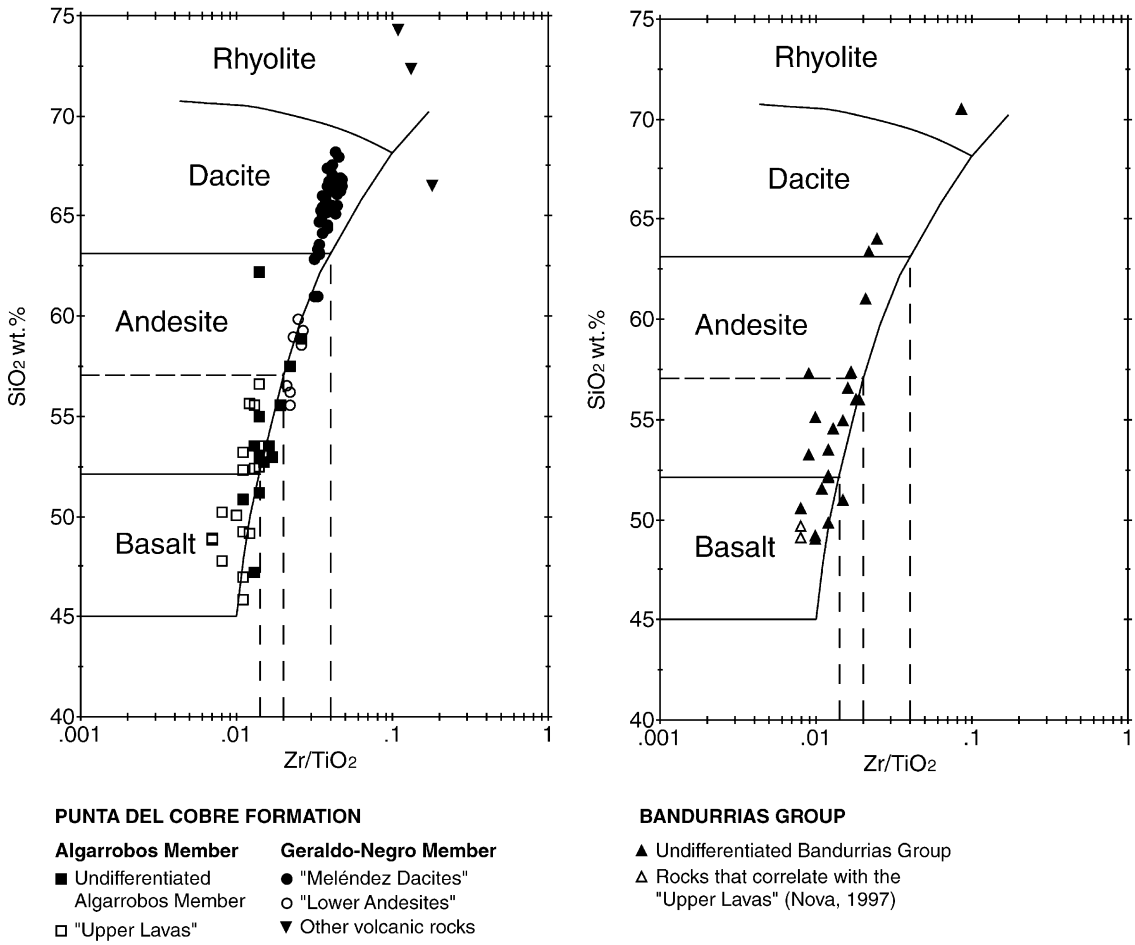

Fig. 12. The Zr–TiO_2 vs. SiO_2 diagram (Winchester and Floyd, 1977) shows that the volcanic rocks of the Punta del Cobre Formation are not affected by significant large scale silicification and that surface samples can roughly be distinguished by their SiO_2 content. Volcanic rocks of the Bandurrias Group collected between 26°40′S and 28°50′S and of the Punta del Cobre lie in the same compositional range. Selected whole rock X-ray fluorescence analytical results are given in Tables 1–4.

volcanic rocks of the Algarrobos Member also represent a medium-K suite, whereas the Upper Lavas show medium-K to low-K affinities.

Hydrothermal alteration seems to have larger effects on La content than on Yb, which appears to remain largely unchanged. This behavior results in snapped off REE patterns as observed, for example, in samples from the Meléndez Dacites (Fig. 16). Slope determinations on the basis of the La_N–Yb_N ratio, therefore, do not provide meaningful results.

11. Discussion

11.1. Depositional environment of the Punta del Cobre Formation and age constraints

The sedimentary record of the Punta del Cobre Formation in the Punta del Cobre district (Basal Breccia and Trinidad Siltstone) indicates a partly subaerial environment that was close to sea level. The presence of epiclastic intercalations within the Lower Andesites and the Meléndez Dacites is consistent with predominantly continental conditions during deposition. This interpretation is supported by the presence of local erosional unconformities truncating the Meléndez Dacites, the Basal Breccia, and also the Trinidad Siltstone; it is consistent with several disconformities within the Punta del Cobre Formation reported by Ryan et al. (1995) from the Candelaria area. The local absence of the Meléndez Dacites at Quebrada Tirana may be the result of its erosion or may be explained by an original restricted lateral extent of this unit. Syntectonic sedimentation that accompanied incipient deepening of the basin and the existence of erosion surfaces are indicated by the variety of sedimentary breccias observed and the deposition of decimetric to metric blocks of limestones and volcanic rocks.

The small outcrop with poorly defined pillow structures and the fossil-bearing beds in the upper portion of the Algarrobos Member at the Quebrada Nantoco appear not to be representative for the entire Punta del Cobre Formation. The sedimentary sequence overlying the Meléndez Dacites (Basal Breccia, Trinidad Siltstone, and

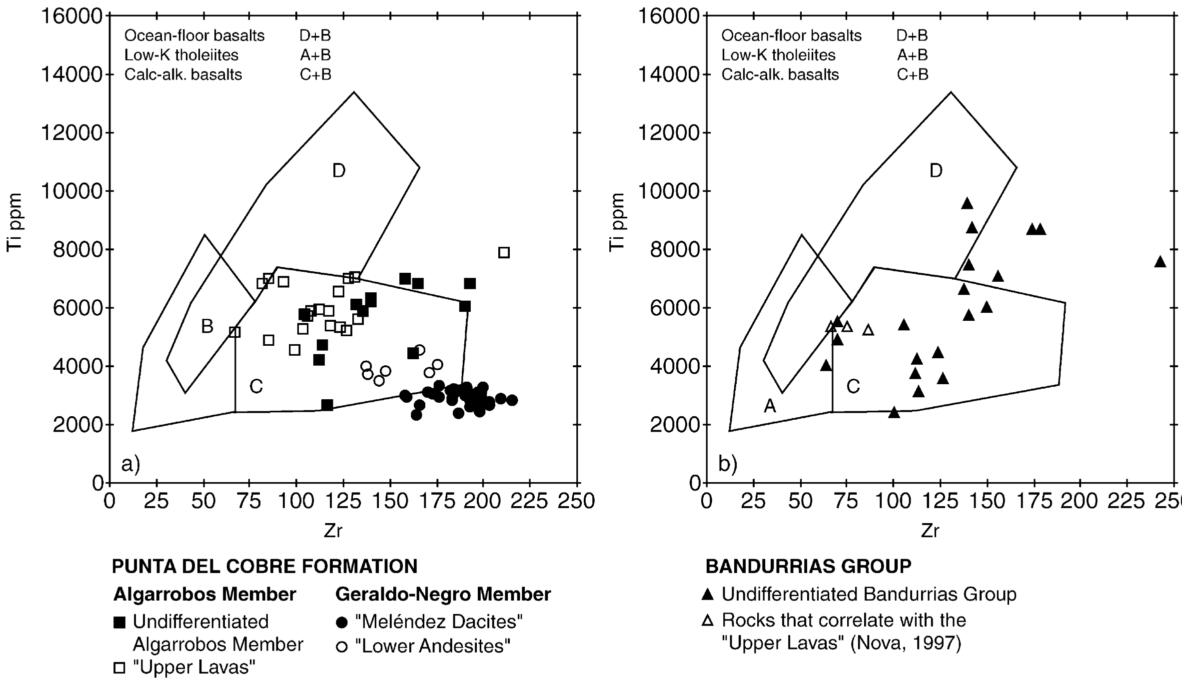

Fig. 13. The Zr vs. Ti magma type discrimination diagram for basic igneous rocks (Pearce and Cann, 1973). Diagram (a) indicates that the extrusive sequence of the Punta del Cobre Formation essentially follows a calc-alkaline trend. The originally dacitic Meléndez Dacites is only shown for completeness. Samples from the Bandurrias Group collected between 26°40′S and 28°50′S are shown in diagram (b) for comparison with those of the Punta del Cobre Formation. Selected whole rock X-ray fluorescence analytical results are given in Tables 1–4.

Abundancia Formation) displays a transgressive character indicating general subsidence and a continuous evolution from continental to shallow marine conditions, which culminates in the formation of the Early Cretaceous marine backarc basin south of Copiapó.

Nothing precise can be said about the age of the Punta del Cobre Formation except that it occurs below beds attributed to the Late Valanginian–Early Hauterivian (Corvalán, 1974) and that ammonites indicate a Berriasian age for the upper part of the Algarrobos Member (Tilling, 1962). For this reason, usually a (Tithonian?)–pre-Late Valanginian age is assumed.

The basin formation correlates with a Late Jurassic–Early Cretaceous extensional event (Aguirre, 1985; Dalziel, 1986) recognized from southern Chile (Magellan Basin; Dalziel, 1981, 1986) to Peru (Huarmey Basin; Atherton et al., 1985 and references therein; Atherton and Webb, 1989). In central Chile, subsidence of the Early Cretaceous basin began in Berriasian times, as indicated by Berriasian to Hauterivian marine sedimentary rocks intercalated with

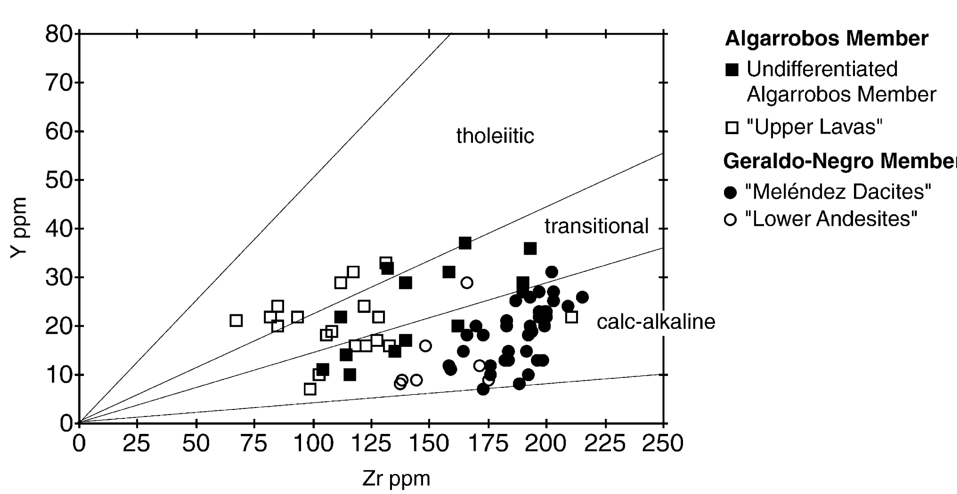

Fig. 14. A tendency towards more tholeiitic magmas are indicated for the top of the volcanic succession of the Punta del Cobre Formation by the Zr vs. Y discrimination diagram of MacLean and Barrett (1993). Selected whole rock X-ray fluorescence analytical results are given in Tables 1–3.

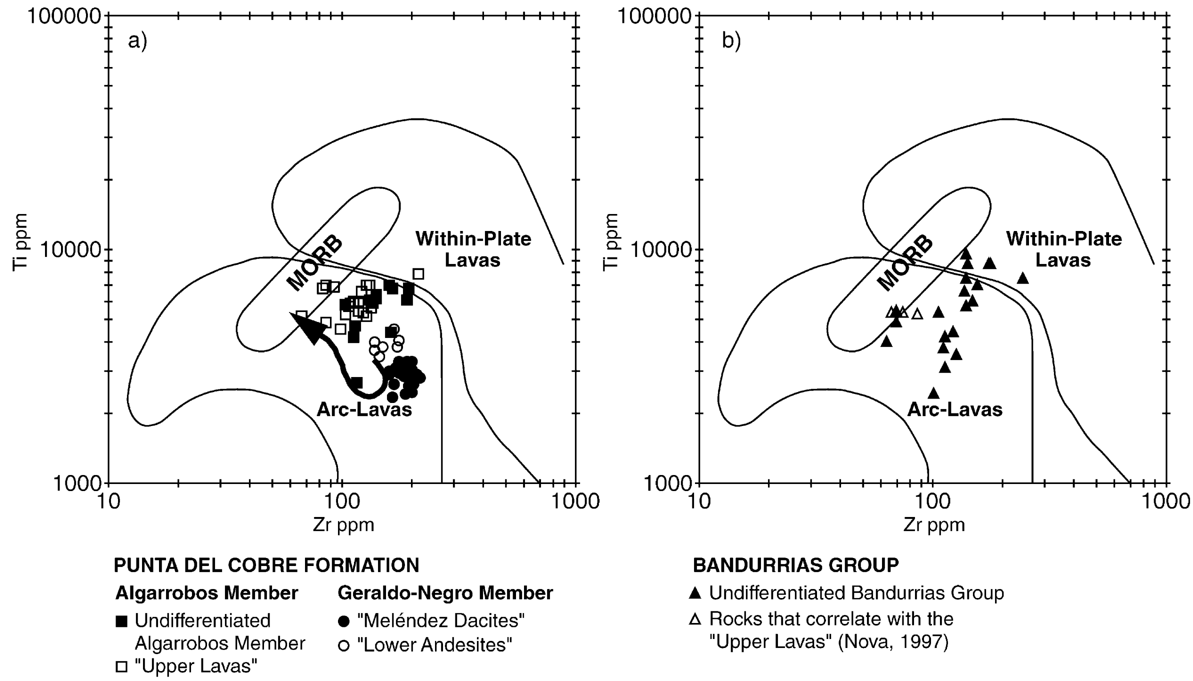

Fig. 15. (a) The arc-setting of the rocks of the Punta del Cobre Formation is confirmed by the Zr vs. Ti diagram (Pearce, 1982). The arrow represents the compositional evolution in time. Note that toward the upper part, the volcanic succession approaches, respectively, in parts even plots in the MORB field. (b) Rocks of the Bandurrias Group collected between 26°40′S and 28°50′S show affinities similar to those of the Punta del Cobre Formation. Selected whole rock X-ray fluorescence analytical results are given in Tables 1–4.

volcanic rocks unconformably overlying partly eroded Jurassic rocks (Åberg, et al., 1984; Aguirre, 1985), i.e. a similar period as in the Punta del Cobre–Candelaria area. By analogy with the observation in central Chile, the erosional unconformity above the Meléndez Dacites could be interpreted as a Late Jurassic paleosurface. However, in a tectonically active arc–backarc system under continental conditions, strong reliefs may be expected. Therefore, the Meléndez Dacites and the Lower Andesites could also be (Tithonian?)–Berriasian in age.

11.2. Petrologic implications

Trace element distribution and REE patterns indicate that the altered volcanic rocks of the Punta del Cobre Formation represent an original low-K to medium-K, calc-alkaline volcanic suite ranging from basalt to dacite. Towards the upper part of the sequence the REE patterns flatten, compositions approach the MORB field, and the volcanic rocks from Quebrada Rivera (Upper Lavas) even plot in the ocean-floor basalt (Fig. 13) and MORB fields (Fig. 15). The data suggest an evolution to primitive, less differentiated magmas towards the top of the volcanic succession, which may be an expression of the Late Jurassic–Early Cretaceous extension recognized along the margin of present-day South America (Åberg, et al., 1984; Aguirre, 1985; Atherton et al. 1985; Dalziel, 1986; Atherton and Webb, 1989). Recently, Nova (1997) and Lieben (2000) showed that basalts underlying carbonate rocks of the Nantoco Formation at Las Cañas (28°47′S 70°43′W) have primitive geochemical signatures similar to those of the Upper Lavas at Candelaria-Punta del Cobre.

The moderate slopes of the REE patterns of volcanic rocks of the Bandurrias Group can be compared to the patterns of the least-altered samples of the Lower Andesites and Meléndez Dacites (Fig. 16). The data presented show that there is no significant geochemical difference between the Punta del Cobre Formation and the Bandurrias Group.

Evidence for the presence of originally anomalous K-rich lavas, as suggested by Levi et al. (1988) for volcanic rocks of the Copiapó area, is not recognized. The less altered lavas show Na_2O and K_2O compositions typical for low to medium-K calc-alkaline basaltic andesites (e.g. PC 862, PC 904, PC 1074, PC 1082). The presented results are consistent, for instance, with those reported by Dostal et al. (1977) from Jurassic to Early Cretaceous volcanic rocks from an Andean transect between latitude 26 and 28°S. The described volcanic rocks (Group 1 of Dostal et al., 1977) also show flat REE patterns and low total REE contents and a trace element distribution indicating essentially low-K calc-alkaline island arc magmatism (Dostal et al., 1977). However, variations in geochemical compositions across the arc-backarc region, and time boundaries — as documented by, e.g. Vergara et al. (1995) and Vergara and Nyström (1996) for Early Cretaceous volcanic rocks of central Chile — cannot be excluded.

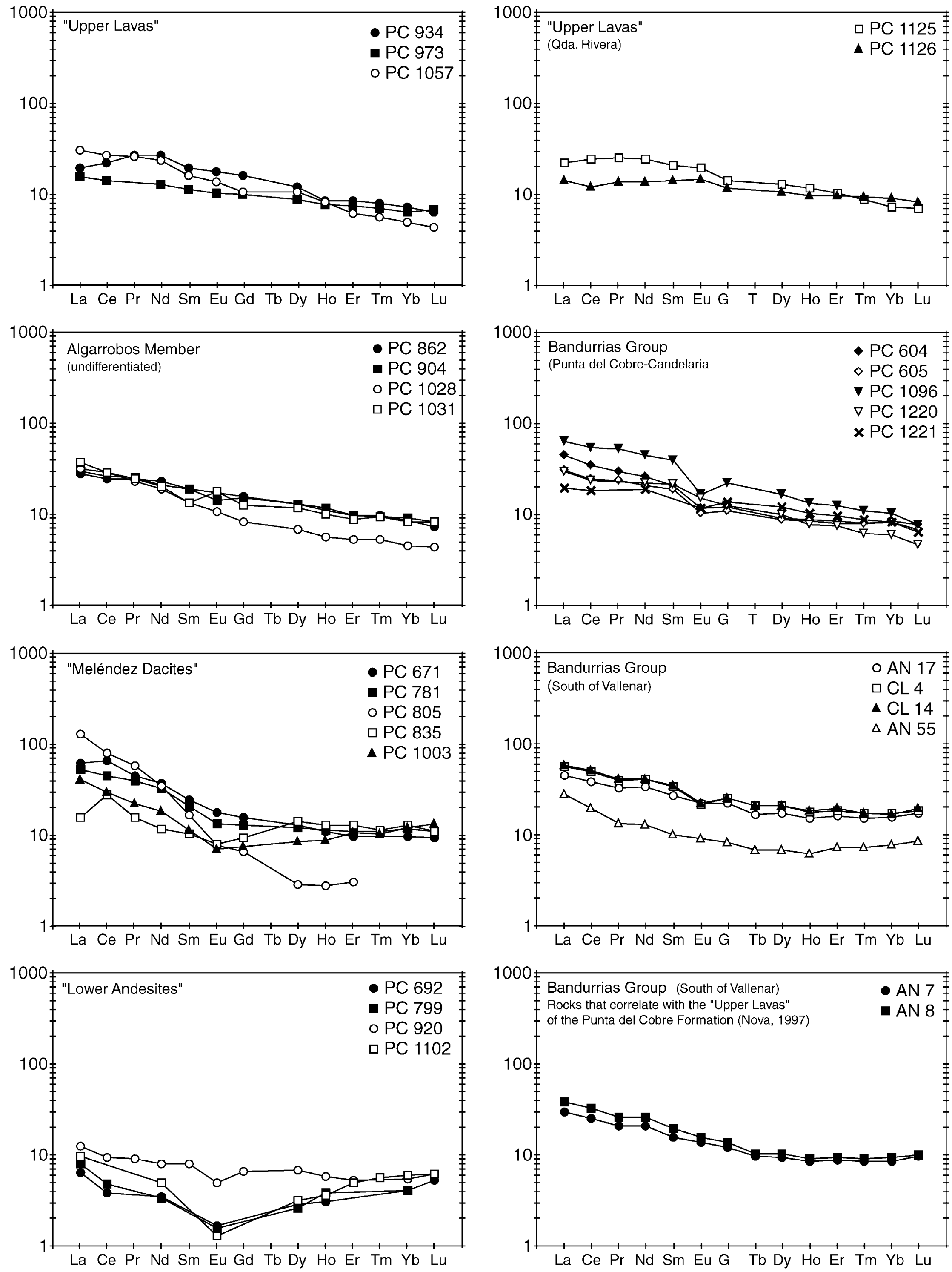

Fig. 16. Chondrite-normalized rare-earth element patterns of volcanic rocks of the Punta del Cobre Formation and Bandurrias Group. Rocks of the Upper Lavas at Quebrada Rivera show a flat REE pattern consistent with their MORB-like signature in the Zr vs. Ti diagram of Pearce (1982). See Table 5 for analytical results.

11.3. Stratigraphic correlation

Jurgan (1977a, p. 418) pointed out that the Punta del Cobre Formation might only be a lithologic variation of the Bandurrias Formation, respectively, Bandurrias Group. Indeed, our results confirm that the Punta del Cobre Formation could be considered as the lower part of the Bandurrias Group. The Punta del Cobre Formation underlies upper Valanginian–lower Hauterivian marine sediments of the Chañarcillo Group, i.e. units similar to those underlain by the lower part of the Bandurrias Group south of Chañarcillo (see Cisternas, 1986; Nova, 1997; Lieben, 2000). Both formations have similar lithologies and show a similar range of geochemical compositions and affinities of the volcanic rocks.

As stated above, the Bandurrias Group interfingers with all formations of the marine Chañarcillo Group and therefore represents the terrestrial–terrigenous time equivalent of the latter. The Abundancia Formation is interpreted to represent the interfingering of the Bandurrias Group with the lower part of the Nantoco Formation. Characteristics of this interfingering are the absence of continuous marker horizons, lateral and vertical changes in facies, and variations in thickness of the volcaniclastic sedimentary units, which decrease towards the interior of the marine basin. The difficulties we face in the area concerning stratigraphic correlation and the upper contact of the Punta del Cobre Formation are in part a result of these characteristics. These difficulties are amplified by the only local occurrence of volcanic units like the Meléndez Dacites or the volcanic flows of the Upper Lavas as well as by low-angle faulting (e.g. Ryan et al., 1995; Arévalo and Grocott, 1996).

12. Conclusions

The lower part of the Punta del Cobre Formation comprises over 300 m of basalt andesitic to andesitic rocks (Lower Andesites unit), locally succeeded by up to 200 m of dacites (Meléndez Dacites unit). Both units show calc-alkaline signatures. They were deposited in an arc environment, probably under terrestrial conditions. The age of the Lower Andesites and the Meléndez Dacites is Berriasian or pre-Berriasian (Tithonian?). Subsequent continental sedimentation of the Basal Breccia (up to 25 m) was followed by continental and near-shore shallow marine deposition of the Trinidad Siltstone (up to 60 m). The waterlain basalts to basaltic andesites of the Upper Lavas (up to 45 m, in the Punta del Cobre district), showing MORB affinity, form the upper part of the Punta del Cobre Formation.

The sedimentary record of the Trinidad Siltstone, and in particular by the Algarrobos Member (800 m), indicates a significant subsidence of the Punta del Cobre–Candelaria area during Berriasian to Valanginian. This is consistent with the geochemical signatures of more primitive, less differentiated magmas of the Upper Lavas. This evolution culminates in the formation of the Early Cretaceous marine backarc basin south of Copiapó and is probably an expression of the Late Jurassic–Early Cretaceous extensional event in the backarc region along the western margin of present-day South America. The Punta del Cobre Formation shows geochemical, lithologic, and paleogeographic features similar to the Bandurrias Group and could be included in the latter as its oldest unit.

Acknowledgements

We thank the geologists and managements of Cía. Contractual Minera Candelaria, Cía. Minera Copiapó/COMINOR, Cía. Minera Ojos del Salado S.A., Empresa Minera Mantos Blancos, Sociedad Contractual Minera Carola, Sociedad Punta del Cobre S.A. and Sali-Hochschild for the access to their properties and their collaboration. We are indebted to L. Alvaréz, P. Anguita, T. Balcu, C. Calderón, P. Calderón, O. Edelstein, C. Isache, R. Leveille, W. Martin, E. Nuñez, R. Nuñez, J. Ponce, R. Olivares, G. Oyarzún, and N. Pop for their collaboration and their constructive critizism. We particularly thank R. Zamora and his team and Empresa Minera Mantos Blancos for access to drill core SAU-7. Logistic support was obtained from the Instituto de Geología Económica Aplicada/Concepción and the Universidad de Atacama/Copiapó. We are very grateful to F. Bussy, F. Capponi, V. Dufresne, H.-R. Pfeifer, P. Thelin, and P. Voldet for analytical support and to P. Bengtson for preliminary identification of Berriasian ammonites. Constructive comments by M. Doppler, M. Dungan, T. Feeley, F. Lieben, and B. Singer are appreciated. We thank M. Brodtkorb and P. Jones for their suggestions for revisions. Earlier drafts of the manuscript benefited from suggestions by C. Arévalo, R. Astini, M.E. Cisternas, E. Godoy, J. Grocott, H. Lledó, C. Mpodozis, and V. Ramos. The project was supported by the SNSF grants 20-36397.92, 2000-040575.94, and 2000-047269.96 and the Deutsche Akademische Austauschdienst (DAAD).

References

Abad, E., 1977. Acerca de la paleogeografía Neocomiana en la región al sur de Copiapó (Prov. de Atacama-Chile). Revista de la Asociación Geológica Argentina 32, 24–33.

Abad, E., 1980. Cuadrángulo Estación Algarrobal Yerbas Buenas, Cerro Blanco, Merceditas y Tres Morros, Región de Atacama. Carta Geológica de Chile 38. Instituto de Investigaciónes Geológicas, Santiago de Chile, Scale 1:100 000.

Åberg, G., Aguirre, L., Levi, B., Nyström, J.O., 1984. Spreading-subsidence and generation of ensialic marginal basins: an example from the Early Cretaceous of central Chile. Volcanic and Associated Sedimentary and Tectonic Processes in Modern and Ancient Marginal Basins, Kokelar, B.P., Howells, M.F. (Eds.). Special Publication Geological Society of London 16, 185–193.

Aguirre, L., 1985. The Southern Andes. In: Nairn, A.E.M., Stehli, F.G., Uyeda, S. (Eds.). The Pacific Ocean. The Ocean Basins and Margins, vol. 7A. Plenum Press, New York, pp. 265–376.

Aguirre, L., Egert, E., 1965. Cuadrángulo Quebrada Marquesa, Provincia de Coquimbo. Carta Geológica de Chile, 15. Instituto de Investigaciónes Geológicas, Santiago de Chile 12 p.

Arévalo, C., 1994. Mapa Geológico del Cuadrángulo Los Loros. Documentos de Trabajo 6. SERNAGEOMIN, Santiago de Chile, Scale 1:100 000.

Arévalo, C., 1995. Mapa Geológico del Cuadrángulo Los Loros. Documentos de Trabajo 8. SERNAGEOMIN, Santiago de Chile, Scale 1:100 000.

Arévalo, C, 1999. The Coastal Cordillera — Precordillera boundary in the Copiapó area, northern Chile, and the structural setting of the

Candelaria Cu–Au ore deposit. Unpublished Ph.D. Thesis. Kingston University, Kingston-upon-Thames, UK, 244 p.

Arévalo, C., Grocott, J., 1996. Jurassic to Lower Eocene transtensional tectonics in the arc and backarc of the Atacama Region, Chile. III International Symposium of Andean Geodynamics, St. Malo, France. Abstracts, pp. 273–275.

Arévalo, C., Grocott, J., 1997. The tectonic setting of the Chañarcillo Group and the Bandurrias Formation: an Early–Late Cretaceous sinistral transpressive belt between the Coastal Cordillera and the Precordillera, Atacama Region, Chile. VIII Congreso Geológico Chileno (Antofagasta). Actas 3, 1604–1607.

Atherton, M.P., Webb, S., 1989. Volcanic facies, structure, and geochemistry of the marginal basin rocks of central Peru. Journal of South American Earth Sciences 2, 241–261.

Atherton, M.P., Warden, V., Sanderson, L.M., 1985. The Mesozoic marginal basin of central Peru: a geochemical study of within-plate-edge volcanism. In: Pitcher, W.S., Atherton, M.P., Cobbing, E.J., Beckinsale, R.D. (Eds.). Magmatism at a Plate Edge: The Peruvian Andes. Wiley, New York, pp. 47–58.

Barrett, T.J., MacLean, W.H., 1994. Chemostratigraphy and hydrothermal alteration in exploration for VHMS deposits in greenstones and younger volcanic rocks. Alteration and Alteration Processes Associated with Ore-forming Systems, Lentz, D.R. (Ed.). Short Course Notes, Geological Association of Canada 11, 433–467.

Berg, K., Breitkreuz, C., 1983. Mesozoische Plutone in der nordchilenischen Küstenkordillere: Petrogenese, Geochronologie, Geochemie und Geodynamik mantelbetonter Magmatite. Geotektonische Forschung 66, 1–107.

Biese-Nickel, W.A., 1942. La distribución del Cretácico Inferior al Sur de Copiapó. I Congreso Panamamericano de Ingeniería de Minas y Geología (Santiago) 2, 429–466.

Brüggen, J., 1934. Grundzüge der Geologie und Lagerstättenkunde Chiles. Akademie der Wissenschaften, Mathematik und Naturwissenschaftliche Klasse, Heidelberg, Abhandlungen 7.

Camus, F., 1980. Posible modelo genético para los yacimentos de Cobre del Distrito Minero Punta del Cobre. Revista Geológica de Chile 11, 51–76.

Camus, F., 1986. Los yacimientos estratoligados de Cu, Pb, Zn y Ag de Chile. In: Frutos, J., Oyarzun, R., Pincheira, M. (Eds.). Geología y Recursos Minerales de Chile, vol. 2. Editorial de la Universidad de Concepción, pp. 547–635.

Cisternas, M.E., 1986. Stratigraphische, fazielle und lithogeochemische Untersuchungen in der Unterkreide der Region Atacama: metallogenetische Bedeutung am Beispiel der Schichtgebundenen Eisenlagerstätte Bandurrias. Heidelberger Geowissenschaftliche Abhandlungen 2, 268 p.

Cisternas, M.E., Díaz, L.L., 1990. Geologic evolution of the Atacama Basin during the Lower Cretaceous. Stratabound Ore Deposits in the Andes, Fontboté, L., Amstutz, G.C., Cardozo, M., Cedillo, E., Frutos, J. (Eds.). Society for Geology Applied to Mineral Deposits, Special Publication 8, 495–504.

Corvalán, J., 1974. Estratigrafia del Neocomiano marino de la región al sur de Copiapó, Provincia de Atacama. Revista Geológica de Chile 1, 13–36.

Dallmeyer, R.D., Brown, M., Grocott, J., Taylor, G.K., Treloar, P.J., 1996. Mesozoic magmatic and tectonic events within the Andean plate boundary zone, 26°–27°30′S, north Chile: Constraints from $^{40}Ar/^{39}Ar$ mineral ages. Journal of Geology 104, 19–40.

Dalziel, I.W.D., 1981. Backarc extension in the southern Andes: A review and critical reappraisal. Philosophical Transactions of the Royal Society of London A300, 319–335.

Dalziel, I.W.D., 1986. Collision and Cordilleran Orogenesis: An Andean Perspective. Collision Tectonics, Coward, M.P., Ries, A.C. (Eds.). Geological Society of London, Special Publication 19, 389–404.

Dostal, J., Zentilli, M., Caelles, J.C., Clark, A.H., 1977. Geochemistry and origin of volcanic rocks of the Andes 26°–28°S. Contributions to Mineralogy and Petrology 63, 113–128.

Farrar, E., Clark, A.H., Haynes, S.J., Quirt, S.G., Conn, H., Zentilli, M., 1970. K–Ar evidence for the post Paleozoic migration of granitic intrusion foci in the Andes of northern Chile. Earth and Planetary Science Letters 10, 60–66.

Finlow-Bates, T., Stumpfl, E.F., 1981. The behavior of so-called immobile elements in hydrothermally altered rocks associated with volcanogenic submarine-exhalative ore deposits. Mineralium Deposita 16, 319–328.

Flores, H., 1938. Informe geológico del mineral de la Punta del Cobre, Atacama. Boletín Minas y Petroleo Chile 8, 136–146.

Floyd, P.A., Winchester, J.A., 1978. Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements. Chemical Geology 21, 291–306.

Gill, J.B., 1981. Orogenic Andesites and Plate Tectonics. Springer, Berlin 390 p.

Griem, W., 1994. Strukturgeologisch-petrographische und geochemische Untersuchungen an Ganggesteinen und deren magmatischen Äquivalenten im Andensegment bei 27° südlicher Breite (Region Atacama, Nordchile). Münstersche Forschungen zur Geologie und Paläologie 75, 139 p.

Hopf, S., 1987. Petrographische, mineralogische und geochemische Beobachtungen an der Cu-Lagerstätte Agustina/Distrikt Punta del Cobre/Chile, Diplomarbeit, Ruprechts-Karls Universität Heidelberg, 144 p.

Hopf, S., 1990. The Agustina mine, a volcanic-hosted copper deposit in northern Chile. Stratabound Ore Deposits in the Andes, Fontboté, L., Amstutz, G.C., Cardozo, M., Cedillo, E., Frutos, J. (Eds.). Society for Geology Applied to Mineral Deposits, Special Publication 8, 421–434.

Jurgan, H., 1977a. Zur Gliederung der Unterkreide-Serien in der Provinz Atacama. Chile. Geologische Rundschau 66, 404–434.

Jurgan, H., 1977b. Strukturelle und lithofazielle Entwicklung des andinen Unterkreide-Beckens im Norden Chiles (Provinz Atacama). Geotektektonische Forschung 52 138 p.

Levi, B., Aguirre, L., 1981. Ensialic spreading-subsidence in the Mesozoic and Paleogene Andes of central Chile. Journal of the Geological Society 138, 75–81.

Levi, B., Nyström, J.O., Thiele, R., Åberg, G., 1988. Geochemical trends in Mesozoic-Tertiary volcanic rocks from the Andes in central Chile, and tectonic implications. Journal of South American Earth Sciences 1, 63–74.

Lieben, F., 2000. Carbonate-hosted Pb–Zn ± Ag and Ba deposits in the Chañarcillo Group, northern Chile: multiple fluid types and genetic processes. Terre & Environnement, 22. Université de Genève 158 p.

Lino, S., 1984. Geología de la Mina Agustina, Comuna de Tierra Amarilla, Provincia de Copiapó, Region de Atacama. Memoria del Titulo, Universidad del Norte, Antofagasta, 161 p.

Lino, S., Rivera, S., 1985. Sobre el ambiente depositional de la formacion Punta del Cobre y sus implicaciones paleogeograficas. VIII Congreso Geológico Chileno (Antofagasta), Actas 1, 397–407.

MacLean, W.H., 1990. Mass change calculations in altered rock series. Mineralium Deposita 25, 44–49.

MacLean, W.H., Barrett, T.J., 1993. Lithochemical techniques using immobile elements. Journal of Geochemical Exploration 48, 109–133.

MacLean, W.H., Kranidiotis, P., 1987. Immobile elements as monitors of mass transfer in hydrothermal alteration Phelps Dodge massive sulfide deposit, Matagami, Quebec. Economic Geology 82, 951–962.

Marschik, R., 1996. Cretaceous Cu(–Fe) mineralization in the Punta del Cobre Belt, northern Chile. Terre & Environnement, 5. Université de Genève 200 p.

Marschik, R., Fontboté, L., 1994. Potassic and sodium alteration related to Cu-mineralization in the Punta del Cobre Formation, northern Chile. VII Congreso Geológico Chileno (Concepción) 2, 1591–1595.

Marschik, R., Fontboté, L., 1995. Superposed alteration and volcanic-hosted Cu(–Fe) mineralization in the Punta del Cobre Belt, northern Chile: a new type of intrusion related deposit? In: Pasava, J., Kríbek, B., Zák, K. (Eds.). Mineral Deposits: From Their Origin to Their Environmental Impacts. Proceedings of III Biennial SGA Meeting, Prague, August 1995 Balkema Publishers, Rotterdam, pp. 477–481.

Marschik, R., Fontboté, L., 1996. Copper(–iron) mineralization and superposition of alteration events at the Punta del Cobre belt, northern Chile. Economic Geology, Special Publication 5, 171–189.

Marschik, R., Singer, B., Munizaga, F., Tassinari, C., Moritz, R., Fontboté, L., 1997a. Age of Cu(–Fe) mineralization and thermal evolution of the Punta del Cobre district. Chile. Mineralium Deposita 32, 531–546.

Marschik, R., Chiaradia, M., Fontboté, L., 1997b. Intrusion-related Cu(–Fe)–Au mineralization of the Punta del Cobre belt, Chile: lead and sulfur isotopic constraints. In: Papunen, H. (Ed.). Mineral Deposits: Research and Exploration — Where do They Meet? Proc. IV Biennial SGA Meeting, Turku, August 1997 Balkema Publishers, Rotterdam, pp. 655–658.

Marschik, R., Fontboté, L., Chiaradia, M., 1997c. Cu(–Fe)– Au mineralization in the Punta del Cobre belt, Chile. VIII Congreso Geológico Chileno (Antofagasta), Actas 2, 1059–1062.

Marschik, R., Leveille, R.A., Martin, W., 2000. La Candelaria and the Punta del Cobre district, Chile: Early Cretaceous iron oxide Cu–Au(–Zn–Ag) mineralization. In: Porter, T.M. (Ed.). Hydrothermal Iron-Oxide Copper-Gold & Related Deposits: A Global Perspective, Adelaide, Australian Mineral Foundation, pp. 163–175.

Mayer, C., 1988. Ag- und Ag–Cu-Lagerstätten in der Region Atacama, Nordchile. Lagerstättenkundliche und geochemische Untersuchungen am Beispiel der Distrikte Chañarcillo (Ag– (Co–Ni–As)) und El Jardin (Ag–Cu). Heidelberger Geowissenschaftliche Abhandlungen 19, 290 p.

Moraga, A., 1977. Cuadrángulo Quebrada Desierto, Región de Atacama. Carta Geológica de Chile, 25. Instituto de Investigaciones Geológicas, Santiago de Chile 12 p.

Moscoso, R., Nasi, C., Salinas, Z., 1982. Hoja Vallenar y Parte Norte de La Serena. Carta Geológica de Chile, 55. SERNAGEOMIN, Santiago de Chile 100 p.

Nakamura, N., 1974. Determination of REE, Ba, Fe, Mg, Na, and K in carbonaceous and ordinary chondrites. Geochimica et Cosmochimica Acta 38, 757–775.

Nova, A.A., 1997. Estudio Petroquímico de las Volcanitas Neocomianas en el Sector Quebrada Las Cañas, III Región de Atacama, Chile. Memoria del Título, Universidad de Concepción, Chile 145 p.

Ortiz, F., Araya, R., Franqueza, F., Moraga, A., Zentilli, M., 1966. Informe Geológico del Distrito Minero de Punta del Cobre. Publicación Especial, 1. Instituto de Investigaciones Geológicas, Santiago de Chile.

Pearce, J.A., 1982. Trace element characteristics of lavas from destructive plate boundaries. In: Thorpe, R.S. (Ed.). Orogenic Andesites and Related Rocks. Wiley, Chichester, pp. 525–548.

Pearce, J.A., Cann, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis. Earth and Planetary Science Letters 19, 290–300.

Pérez, E., Cooper, M.R., Covacevich, V., 1990. Aptian ammonite-based age for the Pabellón Formation, Atacama Region, northern Chile. Revista Geológica de Chile 17, 181–185.

Pincheira, M., 1991. Mn–Fe–Mantos in "intra-arc" Becken des Unterkretazischen magmatischen Bogens Nordchile (Küstenkordillere, 27°–29°S): Tektonischer Rahmen, Petrographie und Geochemie von Erz und Nebengestein. Heidelberger Geowissenschaftliche Abhandlungen 46, 304 p.

Ruiz, C., 1940. Estudio Geológico y Económico de los Distritos de Ojancos y Punta del Cobre, Copiapó. Memoria del Título, Universidad de Chile, Santiago de Chile 239 p.

Ruiz, C., 1942. Estudio geológico de la region Ojancos-Punta del Cobre. I Congreso Panamericano de Ingeniería de Minas y Geología (Santiago) 3, 1186–1225.

Ryan, P.J., Lawrence, A.I., Jenkins, R.A., Matthews, J.P., Zamora, J.C., Marino, E., Urqueta, I., 1995. The Candelaria copper–gold deposit, Chile. In: Pierce, F.W., and Bolm, J.G. (Eds.). Porphyry Copper Deposits of the American Cordillera, Arizona Geological Society Digest. 20, pp. 625–645.

Schönfelder, H., 1990. Die Kupferlagerstätte Punta del Cobre, Nord-Chile: Eine Analyse der geochemisch-petrographischen Umwandlungszonierung und der vulkano-sedimentären Serie im Hangenden, Diplomarbeit, Ruprecht-Karls Universität Heidelberg, 109 p.

Segerstrom, K., 1960. Cuadrángulo Quebrada Paipote, Provincia de Atacama. Carta Geológica de Chile, 2(1). Instituto de Investigaciones Geológicas, Santiago de Chile 35 p.

Segerstrom, K., 1961. Facies change in the Neocomian rocks of the Teresita–Chulo area Atacama Province, Chile. US Geological Survey, Professional Paper 424-c, pp. 221–223.

Segerstrom, K., 1967. Geology and ore deposits of the central Atacama Province, Chile. Geological Society of America Bulletin 78, 305–318.

Segerstrom, K., 1968. Geología de las Hojas Copiapó y Ojos del Salado, Provincia de Atacama. Boletin, 24. Instituto de Investigaciones Geológicas, Santiago de Chile 58 p.

Segerstrom, K., Parker, R.L., 1959. Geología del Cuadrángulo Cerrillos, Provincia de Atacama. Carta Geológica de Chile, 1. Instituto de Investigaciones Geológicas, Santiago de Chile 33 p.

Segerstrom, K., Ruiz, C., 1962. Geología del Cuadrángulo Copiapó, Provincia de Atacama. Carta Geológica de Chile, 3. Instituto de Investigaciones Geológicas, Santiago de Chile 115 p.

Sepúlveda, P., Naranjo, J.A., 1982. Hoja Carrera Pinto, Región de Atacama. Carta Geológica de Chile, 53. SERNAGEOMIN, Santiago de Chile 60 p.

SERNAGEOMIN, 1982. Mapa Geológica de Chile Hoja 2/6 24°–30°30′ lat. S. SERNAGEOMIN, Santiago de Chile 1:1 000 000.

Shriver, N.A., MacLean, W.H., 1993. Mass, volume and chemical changes in the alteration zone at the Norbec mine, Noranda, Quebec. Mineralium Deposita 28, 157–166.

Tavera, J., 1956. Fauna del Cretáceo inferior de Copiapó. Universidad de Chile, Publicación 9, 205–216.

Tilling, R., 1962. Batholith Emplacement and Contact Metamorphism in the Paipote-Tierra Amarilla Area, Atacama Province, Chile. Unpublished Ph.D. Thesis. Yale University, New Haven CT USA, 195 p.

Tilling, R., 1963a. Batholith emplacement and contact metamorphism near Tierra Amarilla, Atacama Province, Chile [abstract]. Geological Society of America, Special Paper 76, 166–167.

Tilling, R., 1963b. Disequilibrium skarns of the Tierra Amarilla aureole, Atacama Province, Chile [abstract]. Geological Society of America, Special Paper 76, 167.

Tilling, R., 1976. El Batolito Andino cerca de Copiapó, Provincía de Atacama: Geología y Petrología. Revista Geológica de Chile 3, 1–24.

Vergara, M., Nyström, J.O., 1996. Geochemical features of Lower Cretaceous backarc lavas in the Andean Cordillera, Central Chile (31–34°S). Revista Geológica de Chile 23 (1), 97–106.

Vergara, M., Levi, B., Nyström, J.O., Cancino, A., 1995. Jurassic and Early Cretaceous island arc volcanism, extension and subsidence in the Coastal Range of Central Chile. Geological Society of America Bulletin 107, 1427–1440.

Whitehead, W.L., 1919. The veins of Chañarcillo, Chile. Economic Geology 14, 1–45.

Winchester, J.A., Floyd, P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology 20, 325–343.

Zentilli, M., 1974. Geological Evolution and Metallogenetic Relationships in the Andes of northern Chile Between 26° and 29°S. Unpublished Ph.D. Thesis. Queen's University, Kingston, Ont., Canada, 394 p.