Bulletin of the Geological Survey of Japan, vol. 35(11), p. 503–536, 1984 552. 311(83-17)

Plutonic Rocks of North-Central Chile

Shunso ISHIHARA*, Carlos E. ULRIKSEN**, Kohei SATO***, Shigeru TERASHIMA****, Taisei SATO*** and Yuji ENDO***

ISHIHARA, Shunso, ULRIKSEN, Carlos E., SATO, Kohei, TERASHIMA, Shigeru, SATO, Taisei and ENDO, Yuji (1984) Plutonic rocks of North-Central Chile. *Bull. Geol. Surv. Japan*, vol. 35(11), p. 503–536.

Abstract: Plutonic rocks in the North-Central Chile have been studied in three transect areas between 22°00′ and 34°00′ south. They are divided into late Paleozoic to early Mesozoic ilmenite-series of dominantly granite (coastal area) and granodiorite (interior) in composition, and middle Mesozoic to late Cenozoic magnetite-series granitoids of largely quartz diorite to granodiorite in composition. The former has magnetic susceptibility of $10–500 \times 10^{-6}$ emu/g while the latter varies from 100 to $2{,}000 \times 10^{-6}$ emu/g. Both series rocks exhibit an increasing tendency of the magnetic susceptibility toward the interior where porphyry copper belts are located. Even typical ilmenite-series biotite granite of the coast areas do not show typical S-type characteristics.

The Mesozoic-Cenozoic magnetite-series plutonic rocks are highly magnetic having high Fe_2O_3/FeO ratio, and contain abundant hematitized magnetite and hemo-ilmenite of both primary and secondary origins. These rocks are considered to have formed by oxidized magmas throughout the whole history. Chemically, the rocks are enriched in copper and depleted in sulfur, thus giving rise to high Cu/S ratio. The original high concentration of copper and high ratio of Fe_2O_3/FeO of the magmas are considered as the most fundamental reasoning to form the Cu-biased metallogeny. Porphyry copper related magmas may have been the most oxidized type; hence a large amount of sulfur has been concentrated around the intrusives as huge porphyry copper systems.

As compared with plutonic rocks of similar age in the West Pacific region, such as Japanese Islands where magnetite-series and ilmenite-series granitoids occur in approximately equal amount, the Chilean rocks are enriched in Al_2O_3, Na_2O, Fe_2O_3, Sr and Cu, and are depleted in FeO, S, Zn, Pb, Li and Sn. These characteristics are consistent with the general magnetite-series rock assemblages of relatively mafic compositions in the Chilean plutonic terrane. The Chilean rocks appear to have been originated in mafic source rocks with high Fe_2O_3/FeO ratio, and not interacted with or derived from the continental crust materials having a high carbon content.

Introduction

Chile, a country with a strong mining tradition, is now the world's second largest copper producer, with an output from the five operational porphyry copper deposits that exceeds 1×10^6 tons copper metal per year, some 15% of the world total, as well as 13,000 tons molybdenum and important amounts of gold and silver. The country also prossesses the world's largest identified resources of copper, perhaps 1.4×10^8 tons or 28% of the total for this reserve category, accompanied by up to 3×10^6 tons molybdenum (SILLITOE, 1981). The country has a large future potentiality for copper as indi-

* Research Planning Office, *** Mineral Deposits Department, **** Geochemistry & Technical Services Department, Geological Survey of Japan, Higashi 1-1-3, Yatabe, Tsukuba, Ibaraki, 305 Japan
** Servicio Nacional de Geología y Minería (SERNAGEOMIN), Casilla 10465, Santiago, Chile

cated by recent discovery of high-grade porphyry copper deposit at La Escondida (380 million tons of proved reserves with 2.2% Cu).

The Chilean porphyry deposits are present in several N–S sub-belts, younging in age generally continentward (*cf.*, Fig. 1); Upper Cretaceous in the coastal side, Paleocene in the middle zone and Upper Eocene-Lower Oligocene along the western foothill of the Andes Range and Miocene in further east Argentine. The coastal Cu (–Mo) belt carries local sub-belts of Fe (magnetite) and Au in its western part, and is flanked eastwards by polymetallic (Cu–Pb–Zn–Ag) belt.

Along the coastal areas, there occur also manto-type deposits which provide significant copper. The mineralization is controlled by bedding plane and fracture systems of host andesitic rocks, and its genetic relationship to plutonic activity may be controvertial (see T. SATO, 1984, this volume). However, intrusive rocks are always present at the footwall side or in the center of the deposits (*e.g.*, El Salado, Buena Esperanza and Mantos Blancos) and only minor ones (*e.g.*, Mantos Portales) occur in andesitic clastics without intrusive body among the studied ore deposits. Thus the mineralization appears to be genetically connected with nearby plutonism.

Considering the amount of ore metals precipitated in these various types of ore deposits, copper minerals occur predominantly in all the belts from the coast to the Andes. Lead and zinc are absent in the manto-type deposits and are very uncommon in the fringe-mineralized zones of porphyry copper deposits, and occur only as minor vein types between the major manto- and porphyry-type copper belts. In Japanese Islands of similar late Mesozoic-Cenozoic magmatic belts, on the contrary, Cu–Pb–Zn ratio in the magmatic-hydrothermal ore deposits is similar to that of the continental crust (ISHIHARA, 1978). The Chilean magmatic system is characterized by the strong Cu-biased metallogeney.

Both porphyry- and manto-type copper deposits are formed as a consequence of magnetite-series, calc-alkaline magmatism during its high-level emplacement. Whether any single plutonic body or province gives sign of the mineralization is a long-term task for economic geologists: so far no one appears to have successfully reached any simple conclusion. With the above in mind, several characteristics of the Chilean plutonic rocks are described and compared with those of Japanese plutonic rocks in this report. The studied areas are 22°00′–24°00′, 25°30′–28°00′ and 32°30′–34°00′S, and called the Antofagasta, Copiapo and Santiago transects in this paper.

Distribution, Bulk Composition and Rock Type

Plutonic rocks of the Chilean Andes are distributed continuously from the Peruvian coast batholiths (18°S) to the southern tip of South America (54°S) for more than 4,000 km (Fig. 2). They occupy about 30 percent of the total land area and occur as large batholiths to small intrusive plugs which may have brought the effusive equivalents to the surface along the Andean orogenic belt. Their exposure is seen in two lanes in the northern half (18–38°S); one along the coast while the other in the Andean Cordillera. But the southern half is somewhat different from the northern group (Fig. 2).

The plutonic rocks are divided into late Paleozoic group and Mesozoic to Cenozoic group. Recently, early Mesozoic age was found in late Paleozoic granitoids by whole-rock Rb–Sr method (SHIBATA *et al.*, 1984, this volume), but conventional classification is adopted in this paper. The late Paleozoic granitoids occur along the coast between Taltal and Traiguen (25°30′–38°13′) and are present sporadically in the interior (CORVALAN, 1968). RUIZ *et al.* (1965) pointed out that the late Paleozoic granitoids are generally coarse-grained biotite granite which is characterized by microcline.

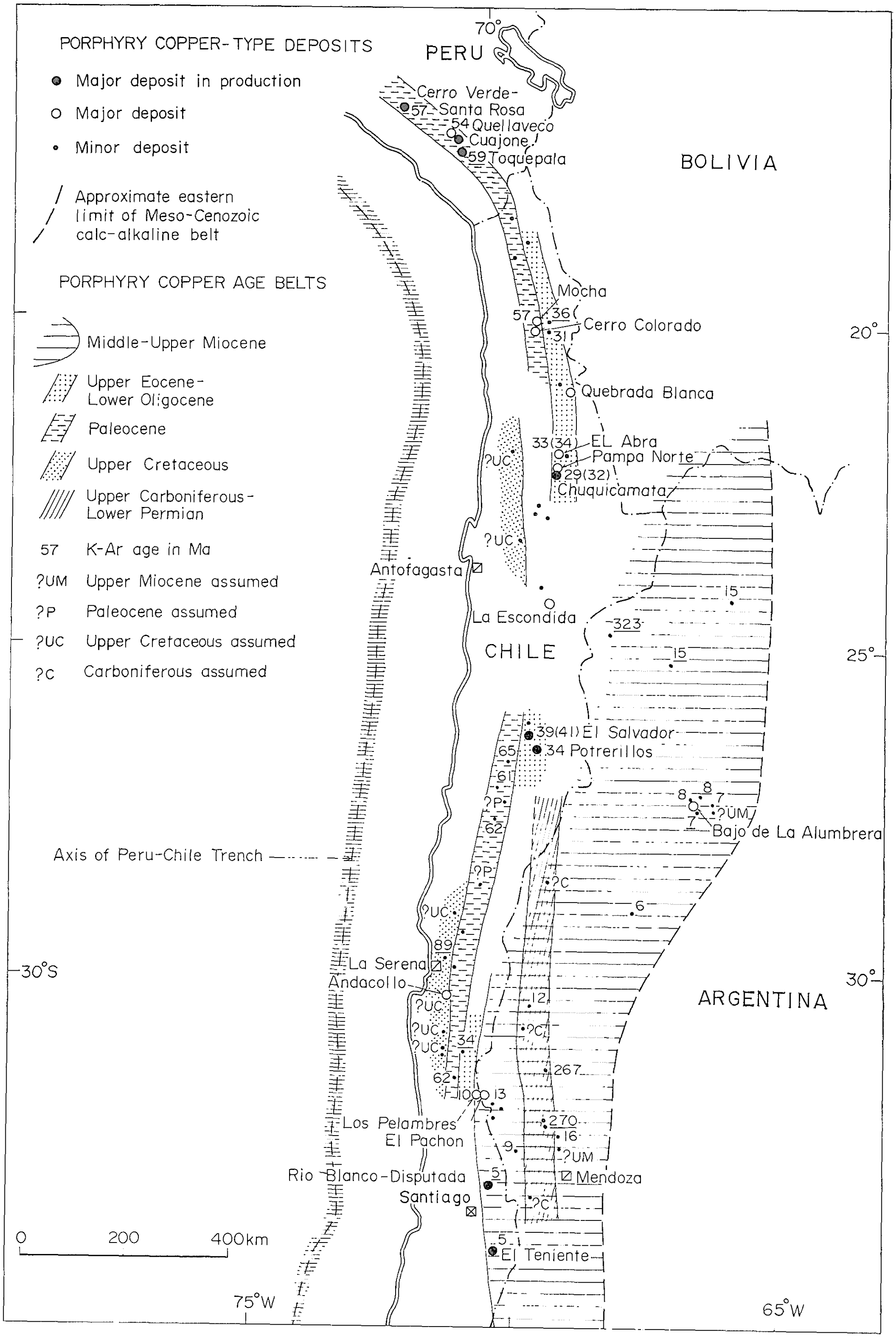
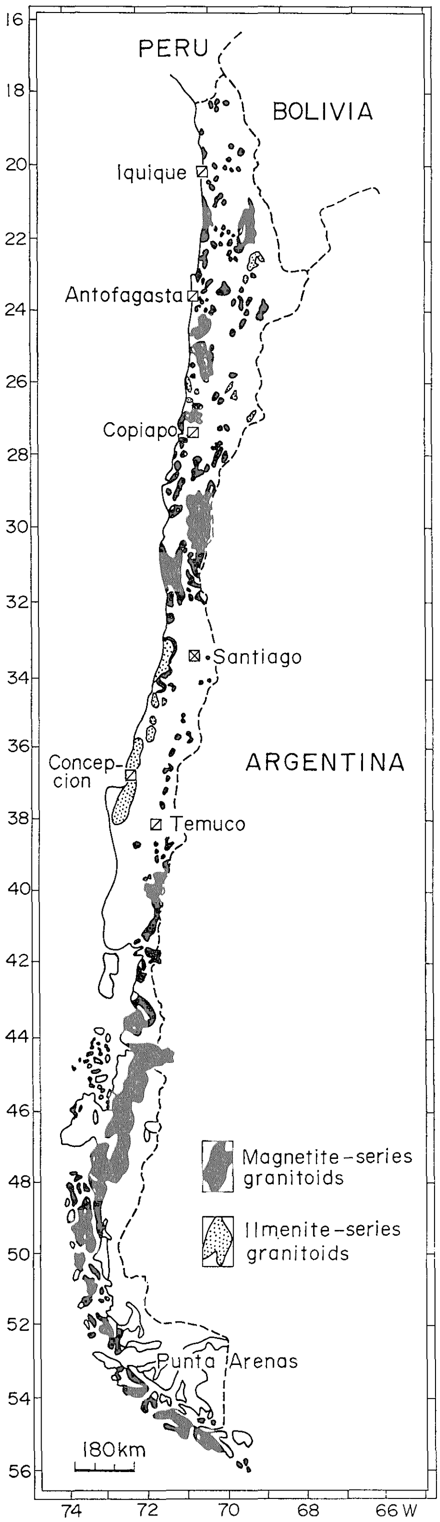


Fig. 1 Distribution of porphyry copper belts in the Andean orogenic zone. After SILLIOTE (1981) but partly revised.



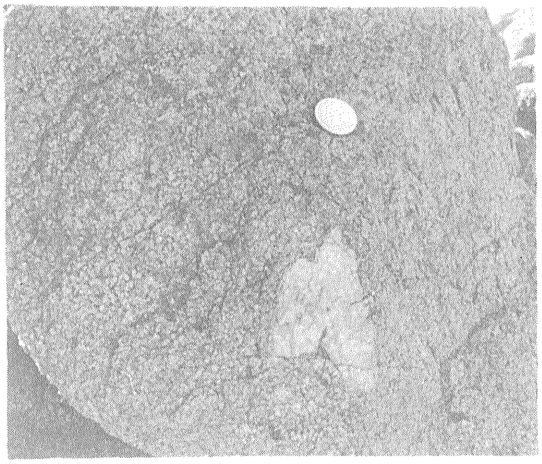


Fig. 3 Quartzitic meta-sedimentary xenolith occurring in late Paleozoic granite at road to Esmeralda (79SE14).

This may be so in the coastal batholiths, but those in the interior are more mafic in composition and a variety of composition may be seen (Table 2a). Late Paleozoic granitoids in Ci Funcho and Chañaral areas are typical massive biotite granite containing no mafic inclusion but metasedimentary xenolith (Fig. 3). Muscovite may be present especially in aplitic dike. In Santiago area, coarse-grained foliated granites occur near Viña del Mar. This may contain hornblende but again no primary muscovite. The granite may be katazonal, while those in the former areas are considered epizonal.

Granodiorite and more mafic rocks are common in late Paleozoic blocks to the east of El Salvador mine, south of Copiapo, and La Serena transect. Statistical analysis of modal analyses by Vistelius *et al.* (1970) indicates that ratio of granite among late Paleozoic plutonic rocks is 44%, by number of analysis, throughout the country (Table 1). A lower ratio of 30% is given in Fig. 3 of Aguirre (1983) for those occurring in the western flank of the Cordillera Frontal between 30°–33°S.

⇦
Fig. 2 Distribution of plutonic rocks in Chile. After Ishihara and Ulriksen (1980).

Table 1 Statistical analyses of bulk composition of Chilean plutonic rocks.

Composition	Late Paleozoic	Mesozoic-Cenozoic
Granite	44% (38%)	24% (26%)
Granodiorite	22% (34%)	22% (18%)
Quartz monzonite and Quartz monzodiorite	4% (1%)	29% (26%)
Tonalite and more mafic rocks	30% (27%)	24% (31%)

The orginal data taken from VISTELIUS *et al.* (1970). Percentages in parenthesis are taken from AGUIRRE (1983) for the Paleozoic and AGUIRRE *et al.* (1974) for the Mesozoic-Cenozoic.

The Mesozoic-Cenozoic granitoids occur extensively in the area to the east of the coastal late Paleozoic batholiths. AGUIRRE *et al.* (1974) studied them in the central part (30°–35°S) of the southern Andes, and stated that they belonged to calc-alkaline suite having quartz-monzodiorite and granodiorite composition in general, being associated with Fe, Cu, Zn and Mo mineralization. The plutonism was divided into Jurassic, Cretaceous and Tertiary cycles; each corresponding to major tectonic phases. FARRAR *et al.* (1970) and MCNUTT *et al.* (1975) found by K–Ar dating in the Taltal-Vallenear area (26°–29°S) that the locus of the plutonism shifted continentward at a rate increasing from 0.6 mm/yr in the Mesozoic to 1.0 mm/yr in the Cenozoic. The initial Sr ratio shows also spatial and temporal variations. It varies from 0.7043 to 0.7059 in the 195–128 Ma rocks of the coast and from 0.703 to 0.707 in the 128–10 Ma rocks in the interior (MCNUTT *et al.*, 1975). Porphyry copper related rocks are known so far to have low values as 0.704 (GUSTAFSON and HUNT, 1975; HALPERN, 1979; SHIBATA *et al.*, 1984).

The Mesozoic-Cenozoic plutonic rocks are characterized by predominance of mafic rocks such as tonalite, quartz diorite and diorite, and also of slightly alkaline suite rocks as quartz monzodiorite and quartz monzonite (Table 1). In the studied areas, most mafic rocks (SiO_2 48–55%) are present in Jurassic batholiths along the coast where equivalent volcanic rocks are seen as basaltic andesites of La Negro Formation. A majority of the other bodies are generally tonalite and granodiorite which sometimes contain mafic inclusions and rarely "obicular granite" (Plate IA, ISHIHARA, 1981a). Patchy xenolith of probably roof andesitic rocks are also seen locally in Tertiary stocks (Plate IB). Granite is very rare, much less than 24% (or 20%) given in Table 1, in our studied transects.

Modal opaque minerals give a clue to classify plutonic rocks in terms of oxygen fugacity. Magnetite-series and ilmenite-series granitoids of ISHIHARA (1977) are generally separated at 0.1 vol. percent of the opaque oxide minerals. Data by VISTELIUS *et al.* (1970) indicate that most of the late Paleozoic granitoids are plotted in the ilmenite-series field. The ilmenite-series are particularly predominant in the samples from the Maule (35°30′–36°00′S, M-series of VISTELIUS *et al.*, 1970) and Malleco (ca. 36°00′S, Mall-series) areas.

The Mesozoic-Cenozoic granitoids are generally of the magnetite-series on the modal composition and also on Fe_2O_3/FeO ratio taken from bulk chemical analysis of various authors (OYARZÚN and VILLALOBOS, 1969; MONTECINOS, 1979). Chemical analyses of SUAREZ (1977) on the Patagonian batholith of Jurassic to Tertiary ages (160–12 Ma), for example, indicate that only one out of 35 analyses has Fe_2O_3/FeO ratio lower than 0.5, which is the general boundary between the magnetite-series and the ilmenite-series granitoids.

In the studied areas, Jurassic quartz diorite and diorite occurring in Mejillones Peninsula and coastal area to the south of Chañaral contain sometimes no magnetite. These rocks may be deep facies of the Jurassic plutonic

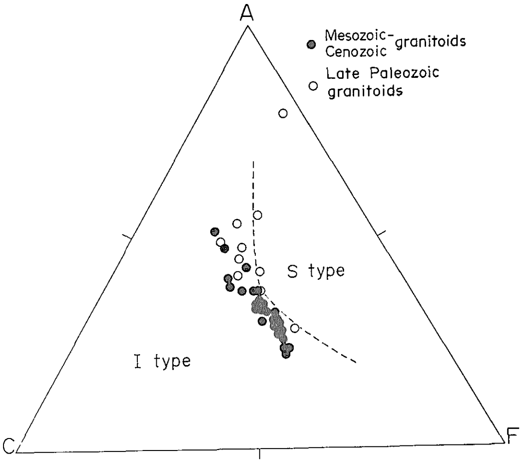


Fig. 4 ACF plot of the Chilean plutonic rocks indicating general I-type characteristics even on the ilmenite-series ones.

systems for the associated metamorphic rocks, size of plutons and grain size of the constituent minerals. Almost all the other Mesozoic-Cenozoic plutonic rocks contain abundant opaque oxide minerals and have high ratios of Fe_2O_3/FeO. Thus there is no doubt that these rocks belong to magnetite-series.

Mesozoic-Cenozoic plutonic rocks are hornblende bearing and must be I-type of CHAPPELL and WHITE (1974). Normative corundum that exceeds 1 wt.% is seen only on 2 samples out of 31 analyses (see Table 2). Late Paleozoic granitoids are examined on ACF diagram of TAKAHASHI *et al.* (1980). They fall mostly in I-type field (Fig. 4). About their normative corundum, all the foliated granites of Santiago area have the content less than 1%. But massive granites of Ci Funcho and Chañaral areas contain that more than 1%. Thus, these latter granites have somewhat S-type character. Xenolith of quartz aggregates which may be fragment of deformed quartzite in origin is indeed found in Ci Funcho-Esmeralda area (Fig. 3).

Magnetic Susceptibility

Measurement of magnetic susceptibility is a handy way to identify content of magnetite in plutonic rocks. The magnetite content appears to be proportionally related to oxygen fugacity during granitic emplacement. The higher oxygen fugacity provides the more favorable condition for the concentration of sulfide-forming components (ISHIHARA, 1981b). Thus magnetic susceptibility was measured in the studied area by a portable device in the way described by ISHIHARA (1979a). The results are shown in Figures 5 through 8.

Autofagasta Transect

In the Antofagasta-Chuquicamata region, late Paleozoic granitoids are seen sporadically, but Mesozoic ones occur widely with some Tertiary rocks in the interior (HALPERN, 1978; MONTECINOS, 1979). Magnetic susceptibility of late Paleozoic granitoids are generally as low as 20×10^{-6} emu/g (hereafter abbriviated as 20) which is a typical value for ilmenite-series. But some in Varillas area, south of Antofagasta, shown as late Paleozoic granitoids in the 1/250,000 sheet map have high values (*e.g.*, 79VA–3, 7, 250–660), thus dating is needed.

Mesozoic-Cenozoic plutonic rocks have high values equivalent to those of magnetite series (more than 100). Jurassic gabbro-granodiorite in the Coast Range ranges from 400 to 2000: some low values in the east of Tocopilla are resulted from break-down of magnetite by later alteration. Tertiary, Fortuna granodiorite at west of the Chuquicamata mine varies from 620 to 960 (Fig. 5), but Cretaceous-Tertiary, Andina tonalite further west yields 670–880. Many copper and some gold deposits of manto and vein types, and small porphyry-type copper deposit (Mantos Blancos) are known to occur in the Mesozoic granitic terrane (RUIZ *et al.*, 1965). Large porphyry copper deposits are associated with the Tertiary stocks.

Copiapo Transect

In the Chañaral-Copiapo region, late Paleozoic granitoids of the Coast Range between Taltal and Chañaral have magnetic susceptibility of the ilmenite-series. These granitoids are composed of medium-grained biotite

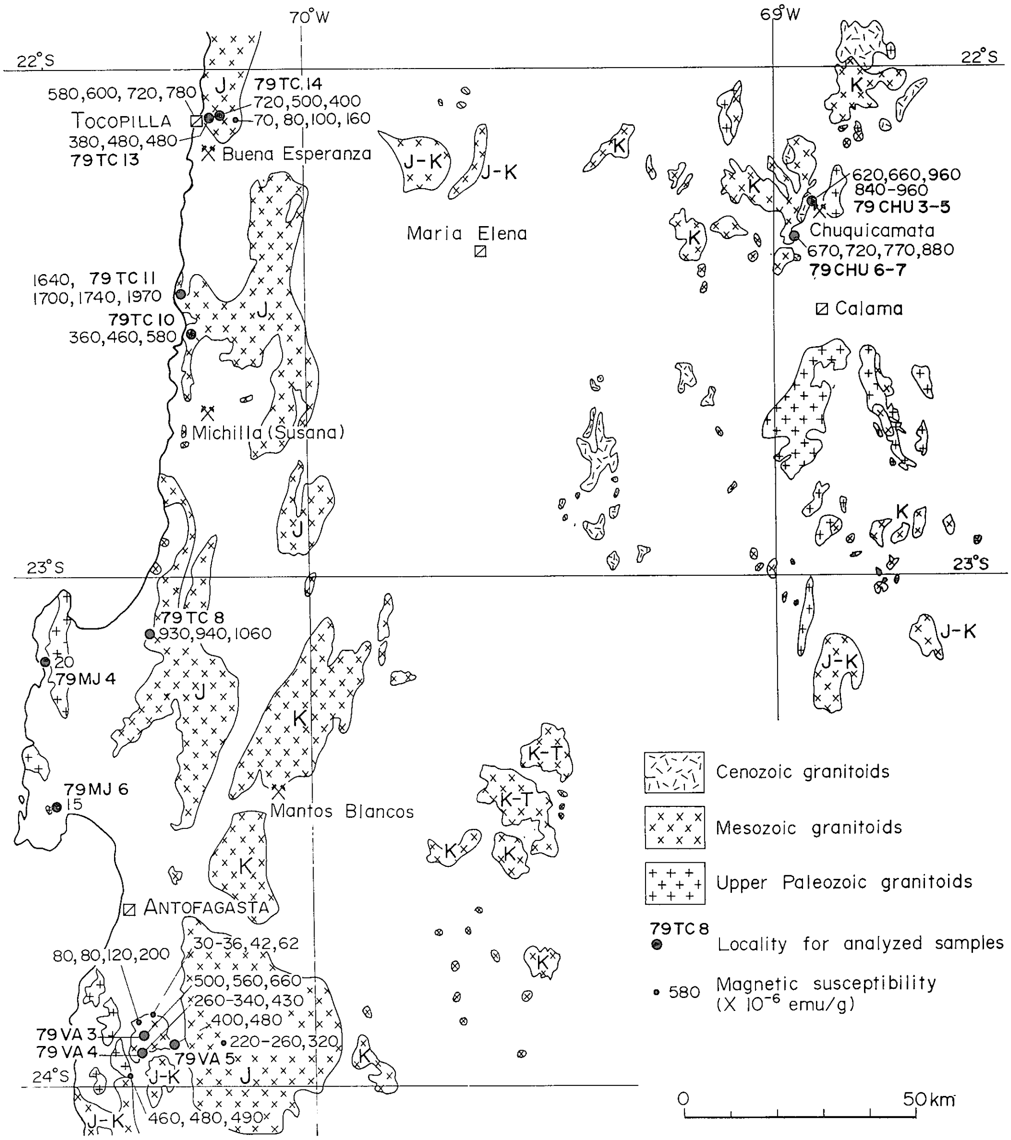


Fig. 5 Magnetic susceptibility of plutonic rocks and locality of the analyzed samples in the Antofagasta transect. Through Figs. 5–7, Rb–Sr age data are taken from SHIBATA *et al.* (1984). J, Jurassic; K, Cretaceous; T, Tertiary.

granites and small amount of dike-like intrusion of fine-grained two-mica granite. Isolated late Paleozoic blocks were examined at three localities in the Andean Cordillera. They are somewhat different from those of the coast in the magnetic susceptibility. No sulfide-mineralization is associated with these granites. Weak fluorite and topaz mineralization to the southeast of Vicuña may be related to this type of granitoids; the relationship observed everywhere in the West Pacific region (*e.g.*, SATO, 1980; ISHIHARA *et al.*, 1980).

The late Paleozoic granitoids (269 Ma, HALPERN, 1978) exposed to the east of El Salvador mine are more mafic than those occurring along the Coast Range, as the most dominant phase being hornblende-biotite granodiorite which is often foliated. The granodiorite has magnetic susceptibility lower than 100, while massive quartz diorite reveals a maximum of 300 (Fig. 6). Similarly, at the southeastern part of Salar de Maricunga, slightly foliated, coarse-grained granodiorite gives magnetic susceptibility of the ilmenite-series, while fine- to medium-grained quartz diorite and granite are more magnetic, ranging up to 430.

This general increasing tendency toward continental side may be related to the presence of late Paleozoic porphyry copper belt in Argentine side (Fig. 1). Since magnetite-series magmatism is a necessity of porphyry copper mineralization, real magnetite-series granitoids are expected to exist in Argentina. Thus, asymmetrical lateral variation common in Mesozoic-Cenozoic batholiths in the Circum-Pacific belt (ISHIHARA, 1981b), may indeed be present in the late Paleozoic granitic terrance.

The Mesozoic-Cenozoic granitoids are zonally arranged in age from Jurassic along the coast (180 Ma, FARRAR *et al.*, 1970) to Tertiary at El Salvador (40 Ma, GUSTAFSON and HUNT, 1975). These granitoids vary from quartz gabbro to granodiorite in composition, all containing hornblende and biotite. Biotite granite is rarely seen. They are strongly magnetic (Fig. 6). However, the Jurassic granitoids along the coast are not always strongly magnetic. Quartz gabbro, quartz diorite and tonalite around Caleta Obispo and south of Caldera, for example, give magnetic susceptibility below 140. These rocks are generally foliated. No mineralization is known related to the coastal plutonic rocks.

Magnetic susceptibility of Cretaceous and Tertiary granitoids are higher than 400. The Cretaceous ones occurring about 12 km south-southeast of Copiapo, however, have the values lower than 400. These are biotite granite which is generally less magnetic than, for example, granodiorite (ISHIHARA, 1979b). Unaltered "L" porphyry in tonalitic composition occurring at Inca level (8532 Dr. N, 3956 W) of the El Salvador mine gives magnetic susceptibility around 1,200. Magnetic susceptibility of the Mesozoic-Cenozoic granitoids in this region increase toward east. Copper deposits are widespread in the Cretaceous-Tertiary granitic terrane, but iron deposits of manto type including Cerro Iman are distributed in the Cretaceous granitic belt. Gold, silver and some lead-zinc deposits of vein types tend to occur further east, and porphyry copper deposits are seen along the easternmost part of the plutonic terrane (Fig. 6).

Santiago Transect

In the Santiago area, plutonic rocks divided by radiometric age data into Paleozoic (Devonian and Upper Carboniferous), Jurassic and Cretaceous on the Coast Range, and Tertiary (Miocene) granitoids in much interior of the Andean Cordillera. Magnetically, the granitoids are divisible into the Paleozoic and the Mesozoic-Cenozoic (Fig. 7).

The Paleozoic granitoids consist mainly of coarse-grained, weakly foliated, biotite granites. Those occurring in Viña del Mar and its north are weakly magnetic magnetite-series but some fall in the range of ilmenite series in their magnetic susceptibility. The Paleozoic granitoids assigned by CORVALAN (1968) and exposed to the east of Viña del Mar have been recently revised to Jurassic granitoids by VERGARA and DRAKE (1979). The tonalite and granodiorite are moderately magnetic to the level which is characteristic of Jurassic granitoids of other areas. Cretaceous granitoids occurring farther east are strongly magnetic and Tertiary stocks distributed in the western flank of the Andean Cordillera are moderately magnetic magnetite-series. Quartz diorite occurring just below the manto-type copper deposits at El Salado has lower (670) magnetic susceptibility than granodiorite of the Rio Blanco (Andina) porphyry copper deposit (960).

No mineralization is known related to late Paleozoic granitoids, but manto-type copper deposits prevail in the Cretaceous granitic

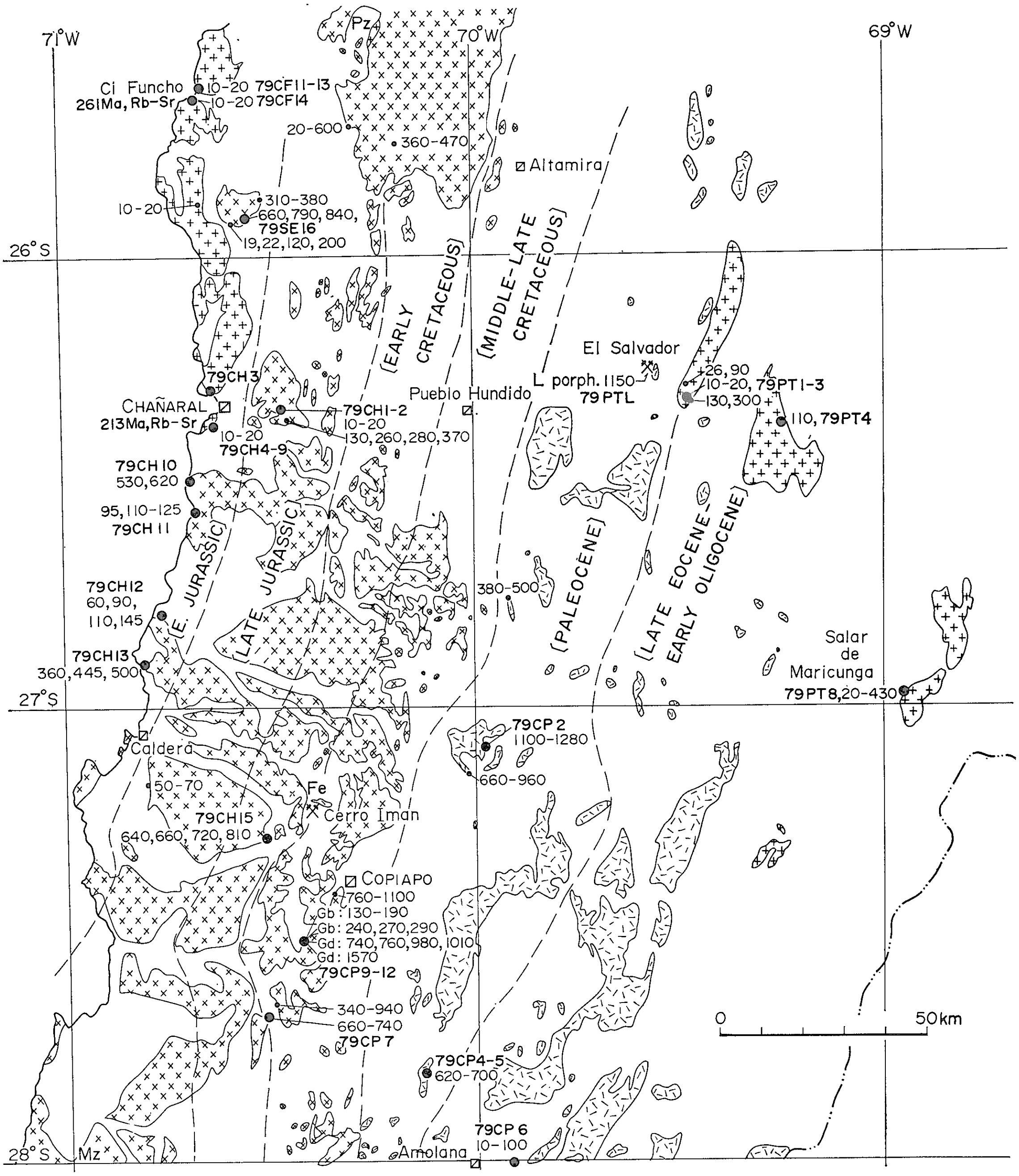


Fig. 6 Magnetic susceptibility of plutonic rocks and locality of the analyzed samples in the Copiapo transect. The age division is based mostly on MONTECINOS (1979). Gb, Biotite granite; Gd, granodiorite.

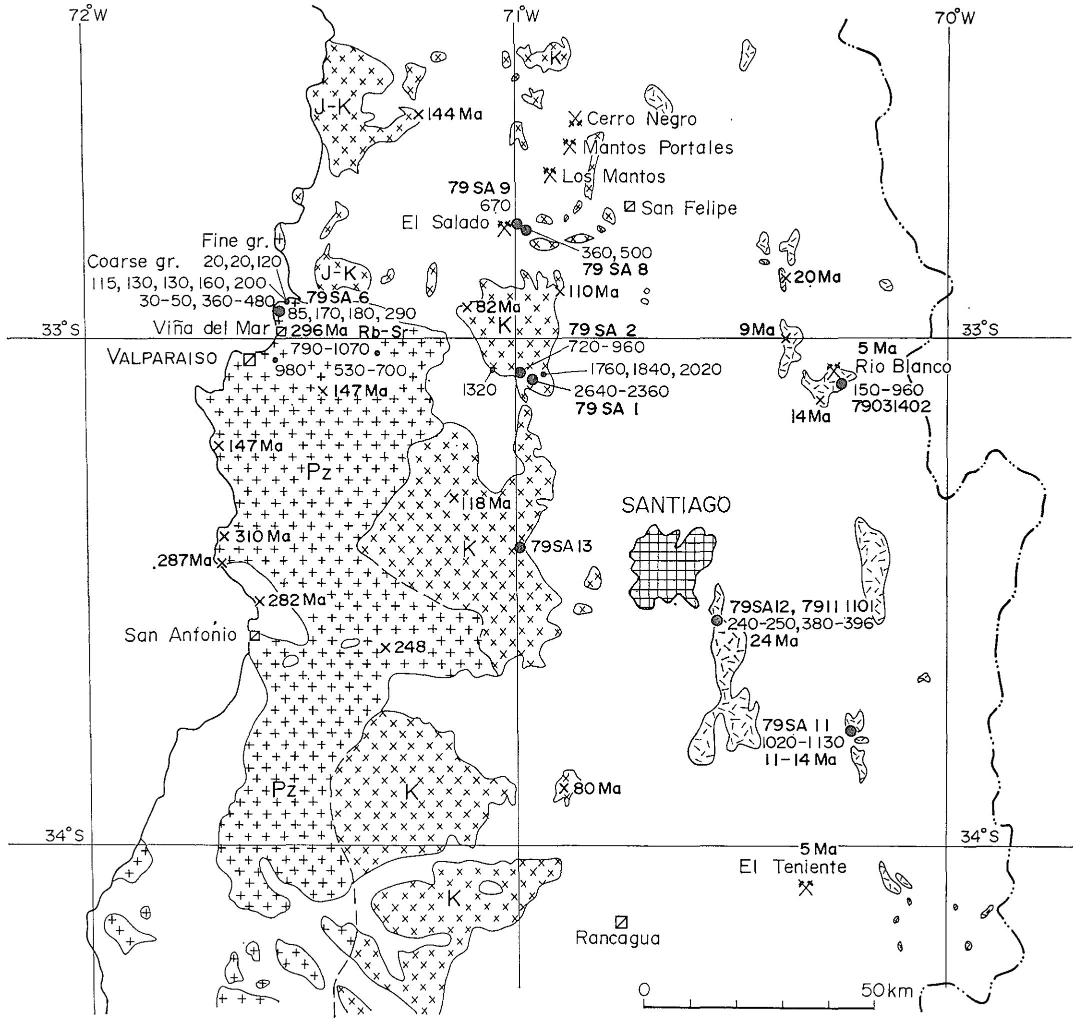


Fig. 7 Magnetic susceptibility of plutonic rocks and locality of the analyzed samples in the Santiago transect. K–Ar ages (Ma) compiled by VERGARA and DRAKE (1979) are also shown.

belt and porphyry copper deposits occur in the easternmost part of this plutonic terrane.

Summary

Magnetic susceptibility of Chilean plutonic rocks is generally higher than the range of ilmenite-series but varies areally being low along the coast plutonic terrane and high in the interior. It changes also with major composition. In the typical magnetite-series granitic terrane of Southwest Japan, it is highest at a tonalitic composition; the Chilean rocks exhibit similar trend (Fig. 8).

In the magnetic susceptibility vs. CaO diagram, Cenozoic granitoids are plotted in the field of the typical magnetite-series granitoids of the Sanin district of Southwest Japan. Cretaceous granitoids have lower values than Cenozoic ones, and Jurassic granitoids are much lower; many plotted below the field of the typical magnetite series. Since the age of the plutonism becomes younger eastward, it can be concluded that magnetic susceptibility increases toward the same direction.

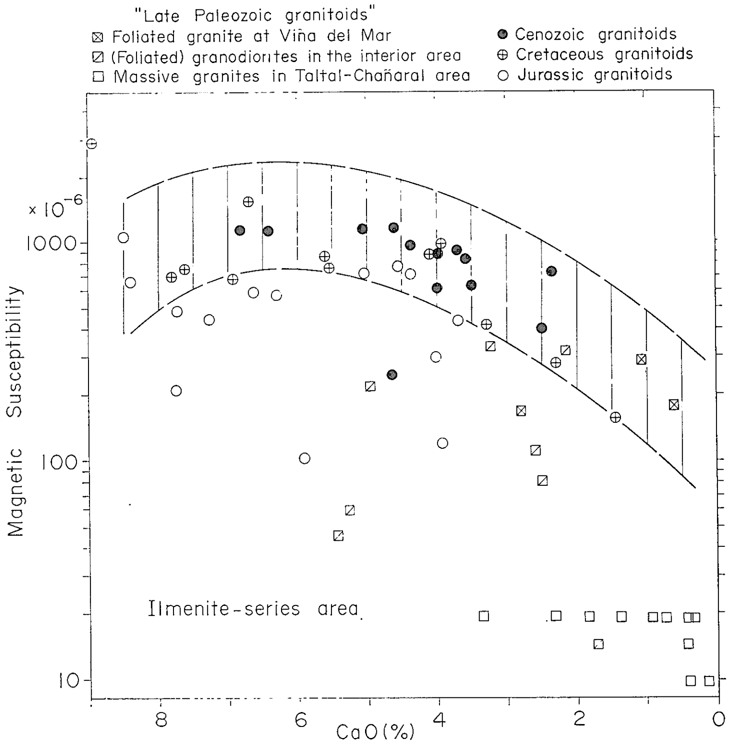


Fig. 8 Magnetic susceptibility vs. CaO content of the Chilean plutonic rocks. Shaded is the area of typical magnetite-series granitoids in Southwest Japan.

Among late Paleozoic granitoids, foliated granites at the north of Viña del Mar, which are dated at 296 Ma (upper Carboniferous, SHIBATA *et al.*, 1984), and partly foliated granitoids of the interior area have intermediate values between those of typical magnetite-series and ilmenite-series granitoids in Japan. In the Carboniferous granitoids, the less calcic rocks have higher magnetic susceptibility than the more calcic rocks. This is sometimes observed in biotite granite areas at north of the typical ilmenite-series granitic terrane of Southwest Japan and is considered to indicate increasing of fO_2 at the final stage of the magmatic differentiation. Massive granites of Taltal-Chañaral area, which are dated at 261 and 213 Ma (SHIBATA *et al.*, 1984) have typical values for ilmenite series and are considered as the most reduced type in the studied region.

Opaque Mineralogy

As shown on the large variation of magnetic susceptibility, the Chilean plutonic rocks contain various amounts of magnetite. Opaque minerals were studied on 38 polished sections from 30 localities (ISHIHARA *et al.*, 1982), and described in the following paragraphs.

Late Paleozoic Granitoids

Ci Funcho-Chañaral ($\chi \leqq 20 \times 10^{-6}$ emu/g, 79CF13, 79CH5, 7, 8): The rocks are biotite granite which may contain colorless amphibole (79CF13) and muscovite (79CH5, 7, 8). The amphibole and muscovite are considered to have formed by subsolidus reaction, but hydrothermal alterations over plagioclase and biotite are weak. Opaque minerals are negligible in amount. Ilmenite (0.2 mm in length) is most common occurring in biotite. It is hematitized, then converted to goethite in dike rock (79CH7). Magnetite is hardly seen but minute grain in the muscovite-bearing rock has hematite lamellae, indicating oxidation at the latest stage of crystallization of this granite. Very minute grains of chalcopyrite>pyrite may be seen.

Viña del Mar (χ=80–290, 79SA6A, B, C): The rocks are biotite granite which are stressed and recrystallized. Hydrothemal alteration is almost nil. Opaque minerals are very small in amount. Magnetite is polygonal to irregular in shape occurring in biotite and very rarely in plagioclase. Ilmenite is not visible except for secondary one occurring with sphene. Sulfides are tiny grains of pyrite and chalcopyrite but 79SA6A specimen contains rather abundant pyrite>chalcopyrite.

Jurassic Granitoids

Tocopilla (χ=480–720, 79TC8, 10, 13, 14): The rocks are pyroxene-hornblende diorite to hornblende-biotite tonalite. Magnetite is medium-grained (0.5 mm) and is euhedral-subhedral occurring in mafic silicates or along grain boundary between mafic and salic silicates (Plate IC). Magnetite of relatively unaltered 79TC8 and 10, whose plagioclase is weakly altered to sericite, coexists often with homogenous ilmenite of anhedral form, and contains no (79TC8) or some (79TC10) ilmenite lamellae. Few chalcocite-covellite grains are observed in this rock.

Magnetite of two sericitized and epidotized samples (79TC13, 14) from the Tocopilla township where the manto-type copper deposit of Buena Esperanza and other copper veins are distributed, is strongly oxidized, as shown by crossed lamellae of hematite. This oxidation which is possibly due to hydrothermal alteration is consistent with intense hematitization and epidotization observed over the intruded andesitic rocks nearby plutonic bodies. Ilmenite is also hematitized and isolated grains of hemo-ilmenite are seen associated with the ilmenite. Whole rock sulfur isotopic ratio of the altered rocks (79TC13) is magmatic value as high as +9.1‰, while nearby ore sulfur of Buena Esperanza mine gives −0.3‰ δ^{34}S. Mantos Blancos ore yields similarly −0.1 and −1.5‰ δ^{34}S (SASAKI *et al.*, 1984, this volume).

South of Chañaral (χ=100–570, 79CH10, 11, 12, 13): The rocks range from biotite-pyroxene tonalite (79CH13) to biotite-hornblende granodiorite. Magnetite is coarse-grained (up to 1.5 mm), euhedral-subhedral and occurs associated with mafic silicates. The mineral often contains ilmenite lamellae and hematite crystals (Plate IIA). Cross-lamellae of hematite is also developed in some magnetites. Ilmenite is composed of homogeneous crystals attached with magnetite, while the others with hematite lamellae. Also recognized are small crystals of hemo-ilmenite and hematite, especially in rocks altered moderately (*e.g.*, 79CH10). Sulfides are only few grains of very minute crystals of chalcopyrite and pyrite whose ratio is about 3:1.

Cretaceous Granitoids

Copiapo (χ=160–770, 79CH15, 79CP7, 9A, 9B, 11): The rocks range from biotite-hornblende tonalite to granodiorite, but locally to biotite granodiorite and granite (79CP9A, B). Tonalite contains generally homogeneous magnetite whose margin is only slightly hematitized; the hematitization is strong on 79CH15 specimen. Ilmenite and hemo-ilmenite are rarely seen, except for 79CP11 (Plate IIA). Chalcopyrite (20 μm) occurs commonly filling negative crystals in magnetite. The whole rock sulfur isotopic ratio is +4.2‰ (79CH15) and ore sulfur of Cerro Iman manto-type iron deposits is −0.1‰ (SASAKI *et al.*, 1984). Felsic facies (79CP9A, B) contains small amount of fine-grained magnetite. Illmenite is again rare. Lath-shaped hematite may be pseudomorph after ilmenite.

El Salado (χ=680–920, 79SA8, 9): The rocks occur just below the manto-type copper deposit at El Salado (hornblende diorite, 79SA9) and its vicinity (biotite-bearing hornblende tonalite, 79SA8). These rocks are hydrothermally altered; plagioclase is strongly sericitized, mafic silicates are converted to epidote-group minerals and chlorite to a moderate degree. Magnetite of 79SA8 contains almost always cross-lamellae of hematite, and ilmenite is sometimes surrounded by sphene. Hemo-ilmenite is present and is associated also with sphene. The footwall diorite is slightly different from the tonalite. Magnetite is more strongly hematitized along the margin and ilmenite is more often converted to sphene, and sulfides (chalcopyrite > pyrite) are commonly seen in the interstices of silicates and in quartz. $\delta^{34}S$ is $+2.2‰$ for 79SA8 and $+5.0‰$ for 79SA9, but ore sulfur of El Salado mine gives $-1.3‰$ $\delta^{34}S$.

Tertiary Granitoids

East of Copiapo ($\chi=620$–1190, 79CP2, 4, 5): The rocks range from biotite-hornblende-pyroxene quartz monzodiorite to biotite-hornblende granodiorite. They are often porphyritic and myrmekite is common indicating a high level of intrusion. Primary epidote is rare but is seen (79CP2).

Magnetite is coarse-grained (up to 1.5 mm) and subhedral-rounded occurring mostly in mafic silicates and rarely in plagioclase, and it contains inclusions of silicates. Magnetite has generally cross-lamellae of hematite. Ilmenite is common; anhedral-homogeneous ones are intimately related to magnetite with irregular boundary, euhedral-stubby ilmenite and hemo-ilmenite are also present. Chalcopyrite grains filling negative crystals in magnetite is not uncommon in magnetite (Plate IIB).

The epidote-bearing rock is unique: hematite in the hematitized magnetite is seen as rectangular or granular crystals, and chalcopyrite is abundant. Large chalcopyrite grain occurs in mafic silicates but droplet is seen mostly in salic minerals.

El Salvador ($\chi=1150$, 79PT-L, "L porphyry"): L porphyry is least altered among X, K and L porphyries related to the El Salvador porphyry copper mineralizations. The rock is biotite tonalite having Z′ color of biotite of pale brown, which may be a color of hydrothermal biotite, but successive alterations (sericite ≒ calcite > chlorite) are observed only slightly in the specimens.

Magnetite is abundant and is euhedral to subhedral with no ilmenite lamellae in general. Its margin is slightly hematitized. Ilmenite is mostly hemo-ilmenite having irregular coexisting boundary. Some crystals occurring in the interstices of silicates as irregular form (Plate IID) may be secondary in origin for the mode of occurrence and alteration products contained in it. Chalcopyrite (up to 0.05 mm) and pyrite (0.05 mm), with the ratio of approximately 10:1, occur as irregular rod shape in all the silicates and along grain boundary of salic minerals. Pyrite is also seen along cracks without any hydrothermal alterations. Bornite (?) may be present. Whole rock sulfur of L porphyry is $+5.9‰$ $\delta^{34}S$ and is quite different from ore sulfur of the main orebody, which varies from -3 to $-9‰$ on pyrite (FIELD and GUSTAFSON, 1976).

Chuquicamata ($\chi=900$–960, 79CHU3, 4, 5, 6): The granitoids here are composed of Andina tonalite (79CHU6) and Fortuna granodiorite (79CHU3–5). The Andina tonalite is unaltered, pyroxene-bearing biotite-hornblende tonalite, in which pyroxene occurs as relict in hornblende. The opaque mineralogy is similar to that of the Fortuna granodiorite, but sphene is seen around ilmenite-magnetite crystals.

The Fortuna granodiorite is characterized by euhedral sphene. It is sphene-bearing hornblende-biotite granodiorite with nil alteration. Magnetite is coarse-grained (up to 1 mm). Coarse crystals tend to occur with mafic silicates, but small ones are associated with salic minerals. Magnetite often has hematite blades along the margin. Euhedral ilmenite occurring in biotite is homogenous. Sphene occurs abundantly not particularly associated with ilmenite but together with all the other rock-forming minerals (Plate ID). Hemo-ilmenite with a high percentage of hematite molecule is also common (Plate IIC) and is considered as secondary in origin for dusty hydrothermal minerals contained in the crystal. Sulfides are very rare, although sulfur contents of these rocks are relatively high (Fig. 14). The rock sulfur yields magmatic value of +4.0‰, while related ore sulfur is −4.7‰ $\delta^{34}S$ (SASAKI *et al.*, 1984).

Rio Blanco mine (χ=630, 79031402): The rock is biotite-hornblende granodiorite. Hydrothermal alteration is weak. Magnetite is coarse-grained (up to 1 mm) being associated with irregular intergrowth of ilmenite and occurs generally with mafic silicates. Ilmenite has very strong anisotropism. Some large crystals of chalcopyrite (up to 0.1 mm) is present in tourmaline. The rock sulfur gives +6.1‰, while related ore sulfur yields −1.3‰ $\delta^{34}S$ (SASAKI *et al.*, 1984).

Summary

Late Paleozoic granitoids have only little of opaque minerals with a simple mineralogy. Mesozoic-Cenozoic ones, on the other hand, contain abundant opaque minerals of mostly magnetite. Majority of the magnetite are seen associated with mafic silicates as euhedral to subhedral grains, generally 0.05 to 0.5 mm but occasionally up to 1.5 mm in diameter, but subhedral magnetite may be seen along grain boundaries of salic minerals, especially in rocks with high magnetic susceptibility. Small euhedral magnetites of 5 to 20 μm size may occur in plagioclase core, suggesting an early stage crystallization of the mineral. The textural evidence indicates, however, that almost all of magnetite crystallized after plagioclase but prior to mafic silicates.

Magnetite grains are commonly associated with or intergrown with various amounts of ilmenite. The mineral is very small in amount in rocks of Viña del Mar and Copiapo areas. These rocks may belong to the magnetite type of TAINOSHO (1982). All the other magnetite-series rocks are of his co-existing type, in which fairly large amount of ilmenite crystallizes together with magnetite.

Ilmenite occurs also as thin lamellae in some magnetite, indicating subsolidus oxidation of primary Ti-bearing magnetite. Magnetite is almost always replaced by hematite along (111) plane in various degrees. The amount of hematite is estimated to be 2 to 20% of host magnetite, the extreme case of which is seen usually as cross-lamellae or rectangular crystals of hematite (*e.g.*, 79CP2). The textural relationship indicates that the hematitization took place after exsolution of the ilmenite lamellae in magnetite.

Ilmenite also contains hematite lamellae of less than 1 μm in width, which is considered to have formed by subsolidus oxidation. Hemo-ilmenite, which is believed to have crystallized in highly oxidized condition of solidifying magmas, is seen universally in the Mesozoic-Cenozoic granitoids. However, the mineral is contained less in fresh rocks of Jurassic and Cretaceous ages (*e.g.*, Tocopilla, 79TC11; Copiapo, 79CP7, 11), but much more in Tertiary stocks (*e.g.*, Chuquicamata and east of Copiapo), and also in altered rocks (*e.g.*, Tocopilla, El Salado, Chañaral, 79CH10). There seem to be at least two generations of hemo-ilmenite; primary, clean one crystallized in magmatic stage and secondary, dusty one formed during deuteric stage. The strongly oxidized environment throughout the magmatic history is characteristic feature of the Chilean rocks and is similar to the history of typical magnetite-series granitoids in Southwest Japan.

The other diagonostic feature observed in the Chilean rocks is low content of sulfides but very high ratio of copper/iron sulfides. Sulfide minerals are chiefly chalcopyrite and subordinately pyrite, which are generally 10 to 20 μm in size occurring in salic minerals rarely in magnetite. Bornite, chalcocite and pyrrhotite(?) may be present but precise identification is needed. The chalcopyrite occurring in magnetite may be an early crystallized phase of magmatic Cu–Fe sulfide, but most of sulfides appear to be crystallized in the late stage. Whole rock sulfur isotopic ratios of +2.2 to +9.1‰ indicate that sulfur of fresh and even moderately altered rocks is magmatic in origin. Sulfides are occasionally surrounded and replaced by goethite, indicating oxidation during much later stages.

In fresh rocks, chalcopyrite is always more abundant than pyrite, having the ratio by number of grain about 3 (*e.g.,* Chañaral and Copiapo). In the case of Tertiary stocks to the east of Copiapo, the ratio goes up to 7. In mineralized areas, there are two types in the mode of occurrence: Tertiary Fortuna granodiorite (fresh) in the Chuquicamata area contains no visible sulfides. The same is true in Jurassic least altered diorite-tonalite in the Tocopilla area and Tertiary fresh granodiorite in the Rio Blanco mine. Copper sulfides may have been expelled out of the magmatic systems to ore deposits. L porphyry at El Salvador, on the other hand, contains abundant sulfides mostly of pyrite. This rock occurs within the porphyry copper system and has received biotitization, but later hydrothermal alterations such as sericitization, carbonatization and chloritization are only slight; thus the pyrite is considered to be of magmatic origin, which is supported by whole rock $\delta^{34}S$ of +5.9‰ (SASAKI *et al.*, 1984).

Chemical Compositions

Chemical analyses were made on 66 samples and listed in Table 2. Their localities are shown in Figures 5–7. The results were processed by GEOCAPS (GEOChemical data Analysis Program System) of YOSHII and SATO (1983) for normative calculation and graphic presentation.

General Remarks—Comparison with Japanese Granitoids

Analytical results are plotted on the HARKER's diagram and compared with the average composition of Japanese granitoids of ARAMAKI *et al.* (1972) for major components and of ISHIHARA *et al.*, (unpublished) for minor elements (Fig. 9). The Chilean rocks are grouped into late Paleozoic, Mesozoic (Jurassic and Cretaceous) and Tertiary granitoids.

Among major components, those enriched in the Chilean rocks are Al_2O_3, Na_2O and Fe_2O_3 K_2O is not much different from that of the Japanese average. Fe_2O_3/FeO ratio is definitely higher in the Chilean rocks, because the Japanese rocks are composed roughly equal amount of magnetite-series and ilmenite-series granitoids, while the Chilean rocks are predominantly of magnetite-series ones. Among the Chilean magnetite-series granitoids, Tertiary ones are more potassic and oxidized (higher Fe_2O_3/FeO) and less calcic than the Mesozoic rocks.

Minor components show clear difference in the two regions. Total carbon, which appear to imply CO_2 carbon, is much lower in the Chilean rocks. This is truely observed in the microscopic studies mentioned before that carbonates are rarely seen but sericite is most popular everywhere and that epidote is diagonostic in the Mesozoic granitoids related to manto-type copper deposits. Sulfur is low even in ilmenite-series granitoids of late Paleozoic age, which is quite different from most of ilmenite-series granitoids in Japan, but zinc, lead, lithium and tin contents are low in the Chilean rocks. Within the Chilean magnetite-series granitoids, the Tertiary ones are higher in content of nearly all the elements as total C, Cu, Zn, Pb, Li, Rb, Sr and Be than the Mesozoic ones.

Alkali Ratio

Alkali ratio of igneous rock is often found to change across continental margin magmatic belt. The ratio of the analyzed rocks were examined in K_2O–Na_2O–CaO diagram (Fig. 10). Late Paleozoic granitoids are divided into two groups: those of Viña del Mar (SA in Fig. 10), El Salvador (PT) and Ci Funcho (CF) areas are faintly more potassic than the Japanese average, whereas those of Chañaral (CH) area are quite sodic. The former group has initial Sr ratio of 0.70637–0.70641, while the latter has 0.70455 (SHIBATA *et al.*, 1984). Thus there is a positive correlation between K_2O/Na_2O and initial Sr ratios. Altered granitoids at south of Copiapo and east of El Salvador are most potassic, because of sericitization over plagioclase.

Mesozoic-Cenozoic granitoids have K_2O/Na_2O ratio more or less lower than that of the Japanese average. In the Chuquicamata area,

Table 2a List of analyzed plutonic rocks: so-called Paleozoic granitoids (serial nos. 1-22).
Note for Tables 2a and 2b: Ferromagnesian minerals are listed in increasing order of abundance. (J) Jurassic, (K) Cretaceous, and (T) Tertiary in age. T. C, total carbon but mostly carbonate carbon; Kai, magnetic susceptibility in emu/g, $\times 10^{-6}$. * Weakly, ** strongly altered rock. Ser, sericite; cc, calcite; epd, epidote; sph, sphene. n. d., not determined.

Serial No.	1	2	3	4	5	6	7	8
Sample No.	79SA6A	79SA6B	79SA6C	79SA6D	79CF11	79CF13	79CF14	79CF12
SiO_2	68.78	71.34	75.82	73.89	n.d.	66.75	70.04	75.63
TiO_2	.35	.34	.13	.05	n.d.	.46	.31	.05
Al_2O_3	14.36	14.72	12.46	13.91	n.d.	16.34	15.58	13.26
Fe_2O_3	1.44	1.15	.84	.64	n.d.	.87	.63	.52
FeO	2.80	1.51	.61	.25	n.d.	2.23	1.80	.54
MnO	.09	.06	.02	.16	n.d.	.05	.05	.04
MgO	.86	.57	.10	.14	n.d.	1.35	.79	.06
CaO	2.72	2.53	1.08	.61	.42	3.36	2.30	.70
Na_2O	3.58	3.90	2.69	3.88	2.76	3.78	3.72	3.78
K_2O	3.75	3.04	5.17	5.63	1.46	2.78	3.25	4.42
P_2O_5	.15	.07	.04	.02	n.d.	.11	.08	.02
H_2O+	.21	.21	.32	.25	n.d.	.96	.67	.19
H_2O-	.36	.20	.22	.20	n.d.	.26	.32	.26
Total	99.45	99.64	99.50	99.63	4.64	99.30	99.54	99.47
T.C	0	4	5	100	410	9	70	270
S	140	3	2	20	30	4	10	20
Cu	7	4	3	3	11	13	8	5
Zn	51	31	13	2	30	44	35	36
Pb	16	15	15	32	12	21	22	40
Li	24	22	14	1	14	54	59	8
Rb	125	106	161	203	64	110	150	141
Sr	140	129	138	20	68	328	185	51
Sn	1.5	1.2	1.0	1.1	1.5	3.3	4.4	2.1
Be	2.0	1.9	.9	5.2	1.2	2.5	2.4	1.5
Kai	170	80	290	180	20	20	20	20
Q	25.41	30.32	37.92	28.25	—	23.99	29.01	34.94
C	—	.58	.57	.37	—	1.27	1.95	1.03
or	22.16	17.97	30.55	33.27	—	16.43	19.21	26.12
ab	30.29	33.00	22.76	32.83	—	31.99	31.48	31.99
an	12.04	12.09	5.10	2.90	—	15.95	10.89	3.34
wo–di	.20	—	—	—	—	—	—	—
en–di	.08	—	—	—	—	—	—	—
fs–di	.13	—	—	—	—	—	—	—
en–hy	2.07	1.42	.25	.35	—	3.36	1.97	.15
fs–hy	3.41	1.37	.25	.14	—	2.71	2.37	.55
mt	2.09	1.67	1.22	.93	—	1.26	.91	.75
hm	—	—	—	—	—	—	—	—
il	.66	.65	.25	.09	—	.87	.59	.09
ap	.35	.16	.09	.05	—	.25	.19	.05
Others	.57	.41	.54	.45	—	1.22	.99	.45
Total	99.45	99.64	99.50	99.63	—	99.30	99.54	99.47
Q+or+ab	77.86	81.29	91.24	94.35	—	72.40	79.69	93.05

Santiago area: 79SA 6. 71°33.3′—32°57.4′, A~C. Biotite granite, stressed, D. Aplite dikelet.
Ci Funcho area: 79CF 11, 13. 70°38.7′—25°39.6′, 11. Biotite-sericite-quartz schist; 13. Hornblende-bearing biotite granite*(ser); 14. 70°39.7′—25°40.2′, Biotite granite*(ser); 12. 70°38.7′—25°39.6′, Same as 14.

Table 2a (Continued)

Serial No. Sample No.	9 79CH3	10 79CH4	11 79CH5	12 79CH2	13 79CH7	14 79CH8	15 79CH9	16 79PT1
SiO_2	n.d.	n.d.	73.08	73.53	74.54	n.d.	n.d.	n.d.
TiO_2	n.d.	n.d.	.21	.22	.06	n.d.	n.d.	n.d.
Al_2O_3	n.d.	n.d.	14.79	12.47	14.49	n.d.	n.d.	n.d.
Fe_2O_3	n.d.	n.d.	.75	.67	.60	n.d.	n.d.	n.d.
FeO	n.d.	n.d.	.97	1.15	.79	n.d.	n.d.	n.d.
MnO	n.d.	n.d.	.06	.04	.05	n.d.	n.d.	n.d.
MgO	n.d.	n.d.	.46	.87	.24	n.d.	n.d.	n.d.
CaO	.42	.34	1.78	1.34	.90	.38	.10	5.23
Na_2O	.94	7.25	4.76	3.00	4.78	4.56	4.54	2.88
K_2O	3.76	2.48	2.42	5.04	2.54	3.60	3.72	2.10
P_2O_5	n.d.	n.d.	.10	.07	.08	n.d.	n.d.	n.d.
H_2O+	n.d.	n.d.	.38	.69	.62	n.d.	n.d.	n.d.
H_2O-	n.d.	n.d.	.04	.16	.18	n.d.	n.d.	n.d.
Total	5.12	10.07	99.80	99.25	99.87	8.54	8.36	10.21
T.C	415	20	3	230	120	40	30	560
S	20	1340	80	10	60	30	30	60
Cu	5	5	4	4	3	4	2	13
Zn	20	80	31	14	21	10	32	65
Pb	6	9	11	17	12	13	4	17
Li	15	20	18	22	28	4	8	28
Rb	114	43	68	229	73	96	215	118
Sr	32	35	163	74	100	31	18	270
Sn	3.9	1.6	1.4	1.9	.6	.7	3.3	n.d.
Be	1.7	1.1	1.2	2.3	2.1	1.1	.3	2.0
Kai	15	20	20	20	20	10	10	60
Q	—	—	31.49	32.35	34.52	—	—	—
C	—	—	1.34	—	2.43	—	—	—
or	—	—	14.30	29.78	15.01	—	—	—
ab	—	—	40.28	25.38	40.45	—	—	—
an	—	—	8.18	5.67	3.94	—	—	—
wo–di	—	—	—	.22	—	—	—	—
en–di	—	—	—	.13	—	—	—	—
fs–di	—	—	—	.08	—	—	—	—
en–hy	—	—	1.15	2.04	.60	—	—	—
fs–hy	—	—	.93	1.19	.95	—	—	—
mt	—	—	1.09	.97	.87	—	—	—
hm	—	—	—	—	—	—	—	—
il	—	—	.40	.42	.11	—	—	—
ap	—	—	.23	.16	.19	—	—	—
Others	—	—	.42	.85	.80	—	—	—
Total	—	—	99.80	99.25	99.87	—	—	—
Q+or+ab	—	—	86.07	87.52	89.98	—	—	—

Chañaral area : 79CH 3. 70°37.5′—26°17.9′, Biotite-sericite-quartz slate; 4, 5. 70°37.2′—26°22.8′, 4. Sericite-biotite-hornblende diorite**(ser>cc); 5. Biotite granite*(ser); 2. 70°29.7′—26°21.7′, Biotite granite (218 Ma)*(ser); 7. 70°39.6′—26°23.3′, Muscovite-biotite granite; 8, 9. 70°39.6′—26°23.3′, 8. Biotite-muscovite aplite dikelet; 9. biotite-muscovite aplite dike.

Potrerillos area : 79PT 1. 69°27.3′—26°18.3′, Biotite-hornblende granodiorite**(ser≫epd>cc).

Table 2a (Continued)

Serial No. Sample No.	17 79PT3	18 79PT4	19 79PT8	20 79CP6A	21 79CP6B	22 79CP6C	23 79MJ6	24 79MJ4
SiO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
TiO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Fe_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
FeO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MgO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CaO	4.94	2.64	1.70	5.40	3.21	2.16	13.50	3.36
Na_2O	3.13	3.76	3.37	2.90	2.75	2.47	2.28	3.72
K_2O	3.15	2.83	4.06	2.79	4.56	5.30	.37	1.75
P_2O_5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H_2O+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H_2O-	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	11.22	9.23	9.13	11.09	10.52	9.93	16.15	8.83
T.C	1000	140	50	110	100	70	1540	1600
S	310	10	40	40	40	30	90	1000
Cu	18	4	4	25	12	5	68	30
Zn	82	30	37	68	48	35	37	56
Pb	20	15	22	19	23	24	14	19
Li	31	22	59	32	40	34	14	39
Rb	96	108	150	138	173	192	8	66
Sr	292	350	154	316	292	281	282	281
Sn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Be	1.4	2.4	2.4	1.6	1.4	1.2	.6	2.7
Kai	220	110	15	45	340	320	25	10
Q	—	—	—	—	—	—	—	—
C	—	—	—	—	—	—	—	—
or	—	—	—	—	—	—	—	—
ab	—	—	—	—	—	—	—	—
an	—	—	—	—	—	—	—	—
wo–di	—	—	—	—	—	—	—	—
en–di	—	—	—	—	—	—	—	—
fs–di	—	—	—	—	—	—	—	—
en–hy	—	—	—	—	—	—	—	—
fs–hy	—	—	—	—	—	—	—	—
mt	—	—	—	—	—	—	—	—
hm	—	—	—	—	—	—	—	—
il	—	—	—	—	—	—	—	—
ap	—	—	—	—	—	—	—	—
Others	—	—	—	—	—	—	—	—
Total	—	—	—	—	—	—	—	—

Potrerillos (Maricunga) area : 79PT 3. 69°27.3′—26°18.3′, Biotite-hornblende granodiorite**(ser>cc>epd), less altered than 79PT–1; 4. 69°15.9′—26°20.4′, Biotite granite; 8. (Maricunga)68°58.2′—26°59.4′, Same as 4*(ser).

South of Copiapo : 79CP 6A~C. 69°58.7′—28°01′; A. Hornblende-biotite granodiorite**(ser>epd); B. Biotite-hornblende granodiorite**(ser>epd>sph); C. Biotite-epidote (secondary) granite dikelet**(epd>ser>sph).

Northern Region (22°—24° S), Mejillones Peninsula : 79MJ 6. 70°35.4′—23°26.7′, Hornblende gabbro, no opaques (Paleozoic?)*(ser>cc>epd); 4. 70°32.4′—23°11.4′, Pegmatitic biotite granite, vein 7cm wide in biotite gneiss, no opaques (Paleozoic?)*(ser>cc>epd).

Table 2b List of analyzed plutonic rocks: Mesozoic-Cenozoic granitoids (serial nos. 23–66).

Serial No. Sample No.	25 79VA3	26 79VA4	27 79VA5	28 79TC11	29 79TC8	30 79TC13	31 79TC10	32 79TC14
SiO_2	n.d.	n.d.	n.d.	48.30	54.22	n.d.	56.22	62.81
TiO_2	n.d.	n.d.	n.d.	.83	.84	n.d.	.67	.66
Al_2O_3	n.d.	n.d.	n.d.	17.29	17.53	n.d.	16.46	15.23
Fe_2O_3	n.d.	n.d.	n.d.	3.94	3.11	n.d.	2.03	2.52
FeO	n.d.	n.d.	n.d.	6.54	6.07	n.d.	5.28	3.27
MnO	n.d.	n.d.	n.d.	.21	.21	n.d.	.17	.10
MgO	n.d.	n.d.	n.d.	8.02	4.37	n.d.	4.45	2.08
CaO	6.63	3.98	3.71	11.62	8.50	8.42	7.74	4.40
Na_2O	3.38	4.38	4.47	2.24	3.67	3.89	3.52	3.86
K_2O	2.27	2.25	2.40	.26	.54	1.07	1.52	2.86
P_2O_5	n.d.	n.d.	n.d.	.02	.10	n.d.	.17	.16
H_2O+	n.d.	n.d.	n.d.	.26	.21	n.d.	1.30	1.45
H_2O-	n.d.	n.d.	n.d.	.28	.28	n.d.	.04	.12
Total	12.28	10.61	10.58	99.81	99.65	13.38	99.57	99.52
T.C	230	90	100	130	50	130	60	100
S	220	50	100	20	30	50	50	30
Cu	111	78	27	18	105	38	83	237
Zn	63	43	45	75	80	27	85	38
Pb	9	8	10	14	11	11	15	9
Li	19	24	16	12	10	23	12	9
Rb	95	60	45	7	12	32	60	166
Sr	356	402	398	324	332	368	271	262
Sn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Be	1.2	1.6	1.6	.4	.6	.8	1.0	1.2
Kai	590	300	440	1740	1060	655	480	720
Q	—	—	—	—	5.45	—	6.63	17.04
C	—	—	—	—	—	—	—	—
or	—	—	—	1.54	3.19	—	8.98	16.90
ab	—	—	—	18.95	31.05	—	29.78	32.66
an	—	—	—	36.35	29.76	—	24.62	15.78
wo–di	—	—	—	8.84	4.91	—	5.29	2.09
en–di	—	—	—	5.89	2.77	—	3.05	1.25
fs–di	—	—	—	2.29	1.93	—	1.99	.73
en-hy	—	—	—	10.23	8.11	—	8.03	3.93
fs–hy	—	—	—	3.98	5.65	—	5.24	2.29
mt	—	—	—	5.71	4.51	—	2.94	3.65
hm	—	—	—	—	—	—	—	—
il	—	—	—	1.58	1.60	—	1.27	1.25
ap	—	—	—	.05	.23	—	.39	.37
Others	—	—	—	.54	.49	—	1.34	1.57
Total	—	—	—	95.96	99.65	—	99.57	99.52
Q+or+ab	—	—	—	20.49	39.69	—	45.40	66.60

Northern region (22°—24°), Varillos: 79VA 3. 70°22.2′—23°53.4′, Pyroxene-hornblende-biotite quartz mozodiorite, stressed (J?); 4. 70°23.9′—23°57.3′, Hornblende-biotite granodiorite (J?)*(ser >chl); 5. 70°18.3′—23°55.2′, Hornblende-biotite granodiorite (J?)*(ser).

Tocopilla area: 79TC 11. 70°15.8′—22°18.8′, Pyroxene diorite (J); 8. 70°20.4′—23°08.4′, Hornblende-biotite-pyroxene quartz diorite (J); 13. 70°17.7′—23°06.8′, Pyroxene-bearing hornblende diorite (J)**(ser>epd); 10. 70°14.4′—22°26.2′, Biotite-hornblende quartz diorite (J)*(ser); 14. 70°10.5′—22°06.2′, Pyroxene-biotite-hornblende tonalite**(ser>epd).

Table 2b (Continued)

Serial No.	33	34	35	36	37	38	39	40
Sample No.	79CHU7	79CHU6	79CHU3	79CHU5	79CHU4	79CHU11	79CHU12	80MZH3
SiO_2	59.24	62.22	64.02	64.17	n.d.	55.30	71.18	62.70
TiO_2	.74	.77	.44	.50	n.d.	.99	.35	.61
Al_2O_3	17.36	16.31	17.42	16.92	n.d.	18.83	14.57	17.25
Fe_2O_3	2.76	3.31	2.51	2.27	n.d.	3.47	1.31	2.12
FeO	3.20	2.01	1.40	1.51	n.d.	4.17	1.22	2.66
MnO	.12	.11	.07	.04	n.d.	.13	.06	.06
MgO	3.12	2.09	1.42	1.55	n.d.	2.48	.76	2.54
CaO	5.55	4.10	4.36	4.00	3.68	6.82	2.35	5.08
Na_2O	3.91	3.85	4.82	4.33	4.49	3.88	3.25	3.42
K_2O	2.61	3.82	2.39	3.04	2.95	1.43	3.74	2.51
P_2O_5	.22	.19	.22	.19	n.d.	.32	.07	.16
H_2O+	.92	.77	.60	.74	n.d.	1.44	.63	.68
H_2O-	.02	.06	.04	.14	n.d.	.14	.09	.02
Total	99.77	99.61	99.71	99.40	11.12	99.40	99.58	99.81
T.C	210	70	160	100	90	100	150	190
S	30	470	20	440	370	130	30	50
Cu	82	21	12	46	115	36	16	48
Zn	72	62	40	26	20	63	27	44
Pb	14	16	13	10	8	10	12	14
Li	23	23	22	15	12	19	9	20
Rb	118	182	84	103	91	52	130	107
Sr	546	404	702	603	631	380	182	412
Sn	n.d.	n.d.	1.0	.9	1.1	n.d.	n.d.	n.d.
Be	1.5	2.3	1.8	1.4	1.6	1.4	.6	1.3
Kai	770	880	960	900	920	1130	730	510
Q	10.26	14.52	16.29	17.12	—	8.74	31.68	17.96
C	—	—	—	—	—	—	1.07	.05
or	15.42	22.57	14.12	17.97	—	8.45	22.10	14.83
ab	33.09	32.58	40.79	36.64	—	32.83	27.50	28.94
an	22.11	15.94	18.84	17.75	—	29.74	11.20	24.16
wo–di	1.66	1.32	.57	.35	—	.84	—	—
en–di	1.15	1.14	.49	.30	—	.51	—	—
fs–di	.38	—	—	.01	—	.28	—	—
en–hy	6.62	4.07	3.05	3.56	—	5.67	1.89	6.33
fs–hy	2.21	—	—	.13	—	3.12	.69	2.24
mt	4.00	4.60	3.46	3.29	—	5.03	1.90	3.07
hm	—	.13	.12	—	—	—	—	—
il	1.41	1.46	.84	.95	—	1.88	.66	1.16
ap	.51	.44	.51	.44	—	.74	.16	.37
Others	.94	.83	.64	.88	—	1.58	.72	.70
Total	99.77	99.61	99.71	99.40	—	99.40	99.58	99.81
Q+or+ab	58.77	69.68	71.20	71.72	—	50.02	81.28	61.73

Chuquicamata area: 79CHU 7. 68°58.5′—22°21.3′, Hornblende-biotite-pyroxene tonalite (Andina, K–T); 6. 68°57.3′—22°20.8′, Pyroxene-bearing biotite-hornblende tonalite (Andina, K–T); 3, 5, 4. 68°56.1′—22°16.2′, 3. Sphene-bearing biotite-hornblende granodiorite (Fortuna, 36 Ma); 5. Hornblende-biotite granodiorite (Fortuna, T); 4. Biotite-hornblende tonalite (*do.*, T)*(chl).

North of Chuquicamata: 11(K). 68°42′—21°42′, Biotite-hornblende tonalite (T); 12 (T). 68°45′—21°35′, Hornblende-biotite granodiorite (T).

Interior of Arica: 80MZH 3. Biotite-hornblende granoriorite (T).

Table 2b (Continued)

Serial No. Sample No.	41 79SE16	42 79CH1	43 79CH13	44 79CH10	45 79CH12	46 79CH15	47 79CH11	48 79CP7
SiO_2	n.d.	n.d.	58.19	n.d.	61.55	n.d.	66.94	n.d.
TiO_2	n.d.	n.d.	.81	n.d.	.85	n.d.	.40	n.d.
Al_2O_3	n.d.	n.d.	17.15	n.d.	16.83	n.d.	16.60	n.d.
Fe_2O_3	n.d.	n.d.	1.51	n.d.	1.59	n.d.	1.43	n.d.
FeO	n.d.	n.d.	4.99	n.d.	4.35	n.d.	1.87	n.d.
MnO	n.d.	n.d.	.13	n.d.	.10	n.d.	.07	n.d.
MgO	n.d.	n.d.	4.07	n.d.	3.00	n.d.	1.64	n.d.
CaO	4.55	7.76	7.28	6.30	5.88	5.05	3.92	7.80
Na_2O	4.22	3.09	3.40	3.30	3.54	3.54	4.49	3.36
K_2O	2.22	1.32	1.40	1.48	1.56	2.38	1.61	1.48
P_2O_5	n.d.	n.d.	.14	n.d.	.13	n.d.	.14	n.d.
H_2O+	n.d.	n.d.	.31	n.d.	.42	n.d.	.36	n.d.
H_2O-	n.d.	n.d.	.14	n.d.	.02	n.d.	.14	n.d.
Total	10.99	12.17	99.52	11.08	99.82	10.97	99.61	12.64
T.C	420	290	80	1160	100	180	80	210
S	190	70	30	50	150	50	40	50
Cu	166	54	53	34	17	12	9	116
Zn	81	49	62	62	60	52	48	50
Pb	16	15	12	13	11	9	12	11
Li	32	14	21	22	33	22	21	13
Rb	106	68	51	58	46	66	44	40
Sr	280	281	272	224	265	425	374	768
Sn	n.d.	1.4	1.4	1.6	2.3	.9	1.6	.9
Be	1.2	1.1	1.0	1.1	1.0	1.5	1.1	1.2
Kai	790	260	440	570	100	710	120	700
Q	—	—	10.36	—	16.42	—	23.43	—
C	—	—	—	—	—	—	.68	—
or	—	—	8.27	—	9.22	—	9.51	—
ab	—	—	28.77	—	29.95	—	37.99	—
an	—	—	27.40	—	25.42	—	18.53	—
wo–di	—	—	3.26	—	1.21	—	—	—
en–di	—	—	1.86	—	.67	—	—	—
fs–di	—	—	1.25	—	.49	—	—	—
en–hy	—	—	8.28	—	6.80	—	4.08	—
fs–hy	—	—	5.57	—	4.96	—	1.72	—
mt	—	—	2.19	—	2.31	—	2.07	—
hm	—	—	—	—	—	—	—	—
il	—	—	1.54	—	1.61	—	.76	—
ap	—	—	.32	—	.30	—	.32	—
Others	—	—	.45	—	.44	—	.50	—
Total	—	—	99.52	—	99.82	—	99.61	—
Q+or+ab	—	—	47.41	—	55.60	—	70.94	—

Taltal-Copiapo Region (25°30′—28° S): 79SE-16. 70°31.5′—25°54.3′. Biotite-hornblende granodiorite(J)**(ser≫chl>sph, cc); 79CH 1. 70°26.2′—26°21.4′, Pyroxene-bearing biotite-hornblende quartz diorite (J); 13. 70°47.7′—26°54.6′, Biotite-pyroxene tonalite (J, 187 Ma); 10. 70°41.7′—26°30.6′, Biotite-hornblende tonalite (J)**(ser>cc>epd, chl); 12. 70°45.6′—26°17.7′, Biotite-hornblende tonalite (J); 15. 70°30.3′—27°17.4′, Same as 12 (K, 123 Ma); 11. 70°41.4′—26°35.7′, Hornblende-biotite granodiorite (J, 191 Ma); 79CP 7. 70°29.4′—27°27.6′, Biotite-hornblende tonalite (K)*(ser>epd).

Table 2b (Continued)

Serial No. / Sample No.	49 / 79CP11	50 / 79CP12	51 / 79CP10	52 / 79CP9A	53 / 79CP9B	54 / 79CP2	55 / 79CP5	56 / 79CP4	57 / 79PTL
SiO_2	54.76	n.d.	64.18	71.79	74.50	60.38	63.83	66.03	58.70
TiO_2	.59	n.d.	.34	.17	.13	.67	.57	.50	1.03
Al_2O_3	19.42	n.d.	17.45	15.04	13.71	17.40	16.50	16.03	18.80
Fe_2O_3	3.56	n.d.	2.63	1.24	1.00	3.06	2.30	1.99	3.48
FeO	3.52	n.d.	1.72	.75	.43	2.44	2.16	1.80	2.62
MnO	.22	n.d.	.16	.04	.03	.10	.09	.08	.03
MgO	3.61	n.d.	1.40	.57	.26	2.77	2.24	1.68	2.27
CaO	7.62	6.70	4.94	2.31	1.43	4.58	4.03	3.61	5.05
Na_2O	3.94	3.84	4.24	3.40	2.96	4.00	3.87	3.64	5.00
K_2O	1.10	1.20	1.79	3.76	4.92	3.55	3.43	3.80	1.62
P_2O_5	.19	n.d.	.17	.08	.03	.21	.15	.12	.33
H_2O+	.82	n.d.	.49	.29	.27	.52	.71	.51	.45
H_2O-	.36	n.d.	.12	.18	.09	.04	.02	.02	.28
Total	99.71	11.74	99.63	99.62	99.76	99.72	99.90	99.81	99.66
T.C	140	200	270	50	60	150	110	130	460
S	60	180	10	30	20	110	40	20	4840
Cu	44	12	13	76	21	160	75	24	53
Zn	60	47	48	11	4	67	64	38	25
Pb	10	9	8	7	7	17	22	11	9
Li	15	16	26	15	11	21	37	32	17
Rb	29	30	48	88	88	144	143	172	53
Sr	550	558	518	290	207	500	423	345	745
Sn	.9	1.0	.9	.8	.6	1.8	1.9	1.3	.9
Be	1.0	1.0	1.1	1.0	1.0	2.1	1.6	1.5	1.4
Kai	760	1570	980	280	160	1190	620	840	1150
Q	6.09	—	20.17	31.98	35.09	10.21	16.38	20.17	10.01
C	—	—	—	1.37	.99	—	—	—	.43
or	6.50	—	10.58	22.22	29.08	20.98	20.27	22.46	9.57
ab	33.34	—	35.88	28.77	25.05	33.85	32.75	30.80	42.31
an	32.05	—	23.29	10.94	6.90	19.04	17.52	16.18	22.90
wo–di	1.88	—	.04	—	—	.97	.62	.40	—
en–di	1.30	—	.03	—	—	.75	.46	.29	—
fs–di	.43	—	.01	—	—	.11	.11	.07	—
en–hy	7.69	—	3.46	1.42	.65	6.15	5.12	3.89	5.65
fs–hy	2.53	—	.71	.15	—	.92	1.19	.92	.29
mt	5.16	—	3.81	1.80	1.11	4.44	3.33	2.88	5.05
hm	—	—	—	—	.24	—	—	—	—
il	1.12	—	.65	.32	.25	1.27	1.08	.95	1.96
ap	.44	—	.39	.19	.07	.49	.35	.28	.76
Others	1.18	—	.61	.47	.36	.56	.73	.53	.73
Total	99.71	—	99.63	99.62	99.76	99.72	99.90	99.81	99.66
Q+or+ab	45.93	—	66.62	82.97	89.21	65.03	69.39	73.43	61.89

Copiapo area: 79CP 11, 12. 70°25.8′—27°31.8′, Biotite-hornblende tonalite (K); 12 is weakly altered*(epd, chl, sph); 79CP 10. 70°25.8′—27°31.8′, Hornblende-biotite tonalite (K); 9A. 70°25.8′—27°31.5′, 9A. Biotite granodiorite (K); 9B. Allanite-bearing biotite granite (K); 79CP 2. 69°54.6′—27°05.4′, Biotite-hornblende-pyroxene granodiorite, myrmekitic (T); 5, 4. 70°12.6′—27°49.2′, 5. Biotite-hornblende quartz monzodiorite (T); 4. Biotite-hornblende granodiorite, porphyritic (T).

El Teniente mine: 79PT-L, Inca adit, Dr 8532N-3956W, Biotite tonalite (T, 40 Ma).

Table 2b (Continued)

Serial No. Sample No.	58 79SA1	59 79SA2	60 79SA9	61 79SA8	62 79SA13	63 79111101	64 79SA12	65 79SA11	66 79031402
SiO_2	51.44	57.03	54.58	65.53	61.18	70.82	59.69	56.35	65.91
TiO_2	.96	1.05	1.12	.43	.64	.34	.63	.94	.53
Al_2O_3	18.04	18.12	16.03	15.87	16.88	14.07	18.15	18.41	15.65
Fe_2O_3	5.73	2.27	2.99	1.79	3.15	1.23	2.87	2.87	1.87
FeO	4.46	4.06	5.64	1.98	2.08	1.62	2.62	4.24	1.76
MnO	.14	.11	.14	.07	.07	.06	.12	.13	.06
MgO	4.29	2.99	3.45	1.23	2.35	.92	2.05	3.08	1.70
CaO	8.96	5.57	6.92	3.33	4.98	2.51	4.67	6.42	3.48
Na_2O	3.84	4.24	3.53	4.15	4.09	3.69	3.33	4.16	4.47
K_2O	.85	3.18	3.48	3.84	2.86	3.56	4.04	2.16	3.10
P_2O_5	.34	.31	.57	.16	.22	.08	.29	.31	.15
H_2O+	.77	.57	1.28	1.03	.67	.34	1.10	.56	.43
H_2O-	.06	.10	.08	.08	.26	.16	.18	.16	.24
Total	99.88	99.60	99.81	99.49	99.43	99.40	99.74	99.79	99.35
T.C	90	80	130	110	40	70	300	370	180
S	60	80	110	50	1820	10	130	90	30
Cu	28	76	272	18	95	18	62	80	12
Zn	38	69	26	19	40	35	79	86	31
Pb	13	18	9	5	8	14	30	19	8
Li	2	10	5	3	34	28	23	24	5
Rb	14	76	108	95	97	128	147	84	84
Sr	563	460	332	291	726	182	674	550	485
Sn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Be	1.0	1.7	1.5	1.1	1.4	1.2	2.4	1.5	1.5
Kai	2900	850	680	420	n.d.	400	250	1100	630
Q	3.00	3.83	2.30	17.92	13.63	28.65	11.88	5.55	18.66
C	—	—	—	—	—	—	.50	—	—
or	5.02	18.79	20.57	22.69	16.90	21.04	23.87	12.76	18.32
ab	32.49	35.88	29.87	35.12	34.61	31.22	28.18	35.20	37.82
an	29.48	21.02	17.62	13.33	19.25	11.31	21.27	25.18	13.48
wo–di	5.32	1.92	5.42	.89	1.68	.26	—	1.94	1.17
en–di	4.00	1.17	3.01	.56	1.40	.15	—	1.19	.87
fs–di	.80	.64	2.20	.29	.07	.10	—	.64	.19
en–hy	6.69	6.28	5.58	2.51	4.46	2.14	5.11	6.48	3.37
fs–hy	1.33	3.41	4.09	1.29	.22	1.41	1.62	3.47	.73
mt	8.31	3.29	4.33	2.59	4.57	1.78	4.16	4.16	2.71
hm	—	—	—	—	—	—	—	—	—
il	1.82	1.99	2.13	.82	1.22	.65	1.20	1.79	1.01
ap	.79	.72	1.32	.37	.51	.19	.67	.72	.35
Others	.83	.67	1.36	1.11	.93	.50	1.28	.72	.67
Total	99.88	99.60	99.81	99.49	99.43	99.40	99.74	99.79	99.35
Q+or+ab	40.52	58.50	52.74	75.73	65.14	80.92	63.93	53.51	74.81

Santiago Region: 79SA 1. 70°59.1′—33°04.5′, Sphene-pyroxene-bearing hornblende diorite (K)**; 2. 71°09′—33°04.2′, Pyroxene-bearing hornblende-biotite monzodiorite (K)*(ser); 9. 70°59.1′—32°55.4′, Hornblende diorite (K)**(ser); 8. 70°58.8′—32°57.9′, Biotite-bearing hornblende tonalite (K)**(ser>epd); 13. 70°57′—33°25′, Same as 8 (K); 79111101. 70°31.2′—33°35.6′, Biotite-hornblende granodiorite (T); 79SA 12. *do.* La Obra, Same as 1 (T, 24 Ma); 11. 33°45′—70°15′, Pyroxene-biotite-hornblende granodiorite (T, 14 Ma).

Rio Blanco mine (Andina Div. CODELCO): 79031402. Biotite-hornblende granodiorite (T, 4 Ma).

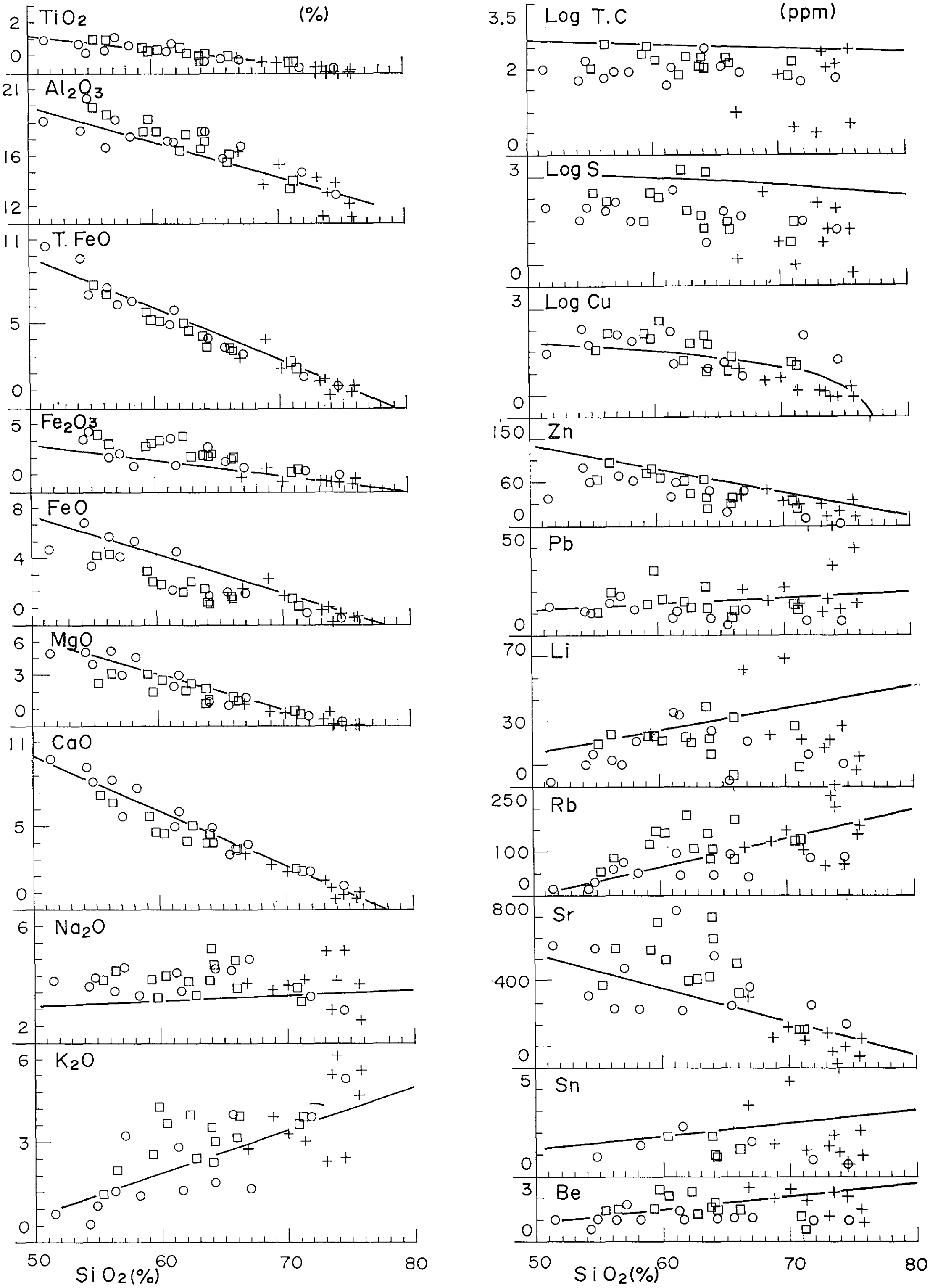


Fig. 9 Major (wt.%) and minor (ppm) components plotted against SiO_2 content (wt.%). + Late Paleozoic, ○ Mesozoic and □ Tertiary granitoids. T.C, total carbon. Solid line, trend of average composition of Japanese granitoids (ARAMAKI *et al.*, 1972; ISHIHARA *et al.*, unpublished data).

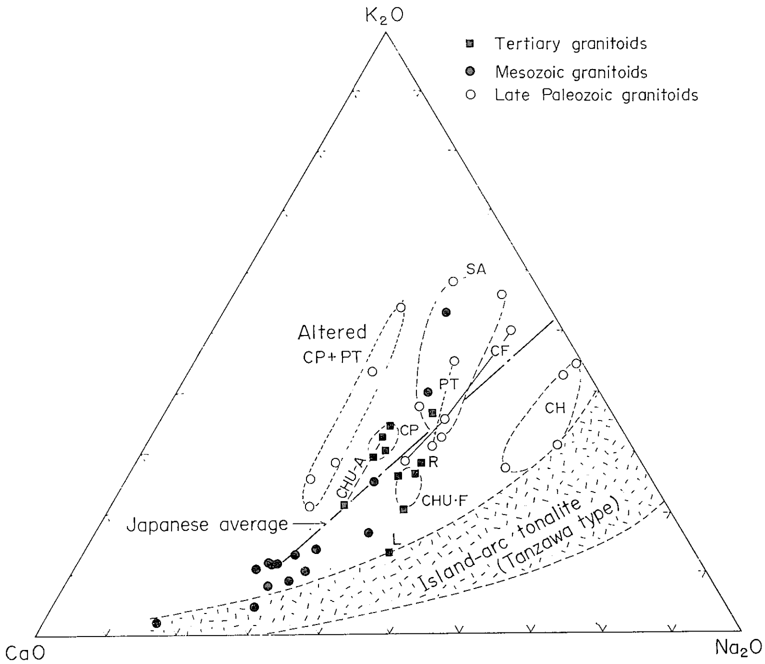


Fig. 10 K_2O–Na_2O–CaO diagram for Chilean plutonic rocks.
CF, Ci Funcho; CH, Chañaral; CHU-A, Chuqicamata, Andina tonalite; CHU-F, Fortuna granodiorite; CP, Copiapo; L, L porphyry at El Salvador; PT, Portrerillos; R, Rio Blanco mine; SA, Santiago.

Tertiary "Fortuna" granodiorite (CHU-F) is more sodic than Cretaceous-Tertiary "Andina" tonalite (CHU-A, Fig. 10). Quartz diorite in the Rio Blanco mine (R) and L porphyry in the El Salvador mine (L) are also sodic. Thus Tertiary granitoids are generally more sodic than Mesozoic ones, except for those to the east of Copiapo (CP). Similar characteristics of K_2O/Na_2O ratio varying in time is also observed between Jurassic and Cretaceous granitoids in the Copiapo transect, although they are not shown by different symbols in Figure 10.

Figure 11 illustrates normative quartz-orthoclase-plagioclase diagram. If unaltered and least altered rocks are concerned, late Paleozoic and Mesozoic granitoids have a trend from the plagioclase corner to monzogranite clan. Tertiary ones of the Chuquicamata, Rio Blanco and east of Copiapo areas, however, are plotted toward quartz-depleted but orthoclase-enriched area from this trend within quartz monzodiorite clan. Thus most of Tertiary granitoids appear to have sub-alkaline trend evolving from quartz monzodiorite to monzogranite.

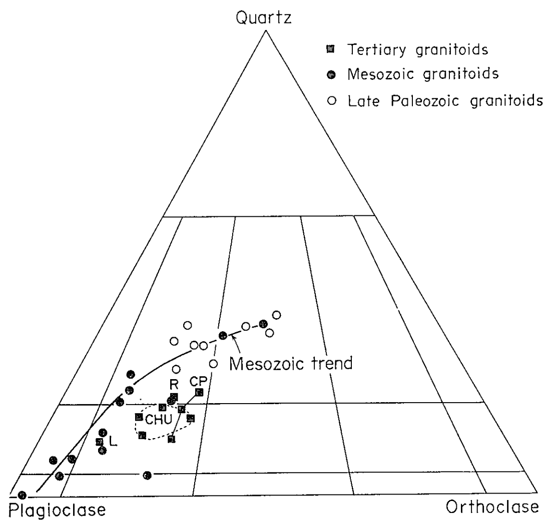


Fig. 11 Normative plagioclase-orthoclace-quartz diagram for Chilean plutonic rocks. CHU, CP, L and R, same as in Fig. 10.

Table 3 XRF analyses of some magnetite-series granitoids from the Antofagasta transect, northern Chile.

Sample No.	SiO_2 (%)	MnO (%)	Y (ppm)	Zr (ppm)	Zr/Y
79 CHU 5 (Fortuna)	64.2	0.04	9	123	13.7
79 CHU 3 (*do.*)	64.0	0.07	9	93	10.3
79 CHU 6 (Andina)	62.2	0.11	25	211	8.4
79 CHU 7 (*do.*)	59.2	0.12	18	174	9.7
79 TC 10 (Tocopilla)	56.2	0.17	27	68	2.5
79 TC 8 (*do.*)	54.2	0.21	15	41	2.7

SiO_2 and MnO from Table 2. Y and Zr analyzed by O. UJIKE.

Yttrium and Manganese Ratio

BALDWIN and PEARCE (1982) found in the Chilean porphyry copper belts that productive intrusions are depleted in Y and MnO, relative to non-productive intrusions, by an early separation of these components into mafic silicates. Their samples to represent the productive porphyries are very much dependent upon L porphyry at El Salvador, because fresh porphyries are not generally available in the Chilean porphyry copper deposits. At Chuquicamata, they chose East and West porphyries, and Elena granodiorite, all of which have been altered to various degrees.

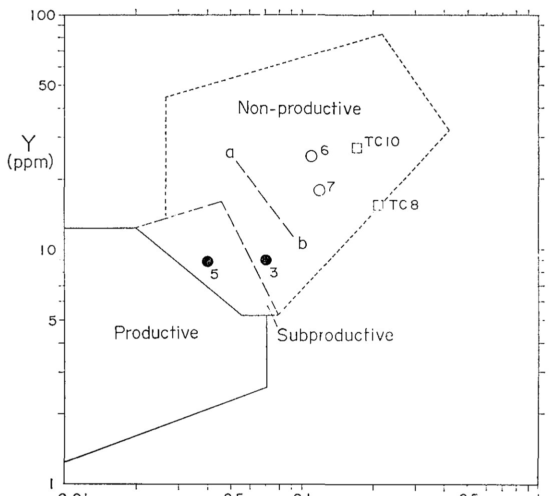


Fig. 12 Yttrium and manganese plot of some Chilean plutonic rocks with the division of productive, sub-productive and non-productive porphyries by BALDWIN and PEARCE (1982). Numerals are the last digits of the sample numbers listed in Table 3. Broken line a–b is the discriminant boundary for intrusions of Pacific arcs.

Six unaltered granitoids from the Antofagasta transect were examined for Y and Zr by XRF analysis. The results are listed in Table 3 and are plotted, together with MnO content given in Table 2, in Figure 12.

The examined rocks are grouped into three in the Y–MnO diagram. Jurassic granitoids of Tocopilla coast (TC series), which occur in a zone of manto-type copper deposits, are most enriched in Y and MnO, being plotted in the non-productive area. Andina tonalite of the Chuquicamata area has similar abundance but Fortuna granodiorite of the same area is least enriched in these components.

In the Chuquicamata area, the studied rocks were taken from the area just west of the West Fissure, and the Fortuna granodiorite crops out right next to the Chuquicamata orebody. Thus the proposal of BALDWIN and PEARCE (1982) appears to be valid on the studied rocks, although the discriminant boundary between the porphyry copper productive and non-productive porphyry line is shifted to the boundary for their Pacific arc type (broken line with a–b, Fig. 12).

Sulfur and Copper Contents

As is shown in Figure 9, Chilean granitoids have characteristic feature on sulfur and copper contents. Figure 13 indicates more detailed distribution pattern of these elements of fresh and least altered rocks (** of Table 2 is excluded). Sulfur is much lower than the average composition of Japanese granitoids, except for the Chuquicamata rocks and L porphyry. Copper content of late Paleozoic granitoids are consistently lower than that of the Japanese granitoids, but Mesozoic-Cenozoic rocks have a large variation on this element being generally rich in copper. Thus, Chilean rocks are characterized by low S/Cu ratios as compared with the Japanese granitoids (Fig. 14).

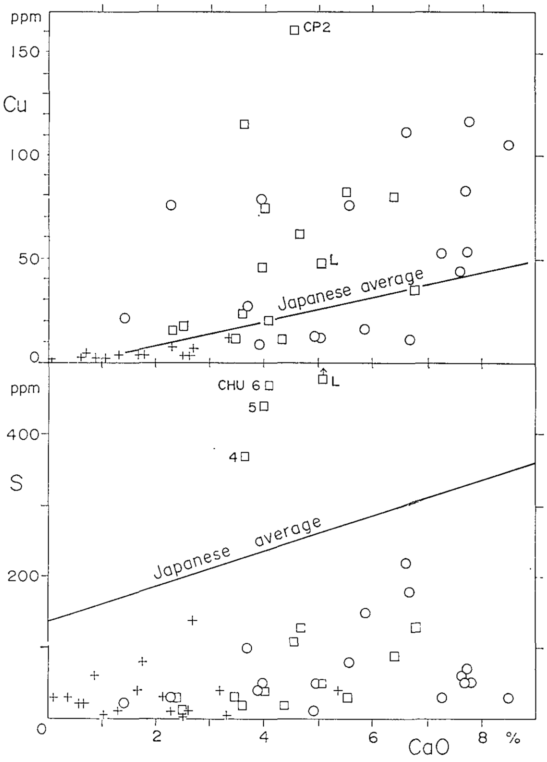


Fig. 13 Copper and sulfur contents vs. CaO content for Chilean plutonic rocks. + Late Paleozoic, ○ Mesozoic, □ Tertiary granitoids. CHU–4, 5, 6, Chuquicamata; CP–2, East of Copiapo; L, L porphyry at El Salvador.

In Japanese Islands, both magnetite-series and ilmenite-series granitoids have S/Cu ratio higher than that of chalcopyrite, which is consistent with microscopic observation that either pyrrhotite (in ilmenite-series) or pyrite (in magnetite-series) are much more common than chalcopyrite in both the series (ISHIHARA *et al.*, 1983; TERASHIMA and ISHIHARA, 1983, 1984). In the Chilean rocks, however, many unaltered granitoids of magnetite series have the ratios of bornite and chalcocite (Fig. 14). Although chalcocite was found in one altered rocks, the mineral is very uncommon in the studied rocks.

In porphyry copper mineralized areas of southwestern United States, BANKS (1982) reported distribution of copper and sulfur in non-sulfide rock-forming minerals of granitic rocks that copper is contained in vermiculite(?) up to 10 wt.% and chlorite up to a few thousands ppm, and sulfur is present mostly in apatite (average 640 ppm) and biotite (avg. 200 ppm). The Chilean rocks with low S/Cu ratios may have possibility of the copper contained in the fringe alteration products of biotite, because sulfides are not found abundantly. Similarly, bulk sulfur of felsic granitoids with a low level of sulfur content, in which sulfides are not visible, may have their source in the biotite, although detailed studies are needed in future.

Table 4 gives a list of average compositions of selected components from different areas.

Table 4 Average compositions of selected components from different areas.

Area	Age & mineralization	SiO_2	S	Cu	Fe_2O_3/FeO	x
Chañaral (79 CH 11,12,13)	Jurassic; barren	62.2%	73ppm	26ppm	0.48	220
Tocopilla (79 TC 8,10)	*do.* ; Cu (manto)	55.2	40	94	0.45	770
Copiapo (79 CP 9 A,10,11)	Cretaceous; Fe, Cu (*do.*)	63.6	33	44	1.40	673
E. Copiapo (79 CP 2,4,5)	Tertiary; Cu, Au (vein)	63.4	57	86	1.14	631
Chuquicamata (79 CHU 3,5,6,7)	*do.* ; Cu, Mo (porphyry)	62.4	240	40	1.45	878
Average, Japan (n=572)	Mesozoic-Cenozoic	62.5	277	28	0.45	441

Gabbro and granite are excluded. Fresh and least altered rocks are averaged. Used sample numbers are given in parethesis. x, magnetic susceptibility in emu/g, $\times 10^{-6}$.

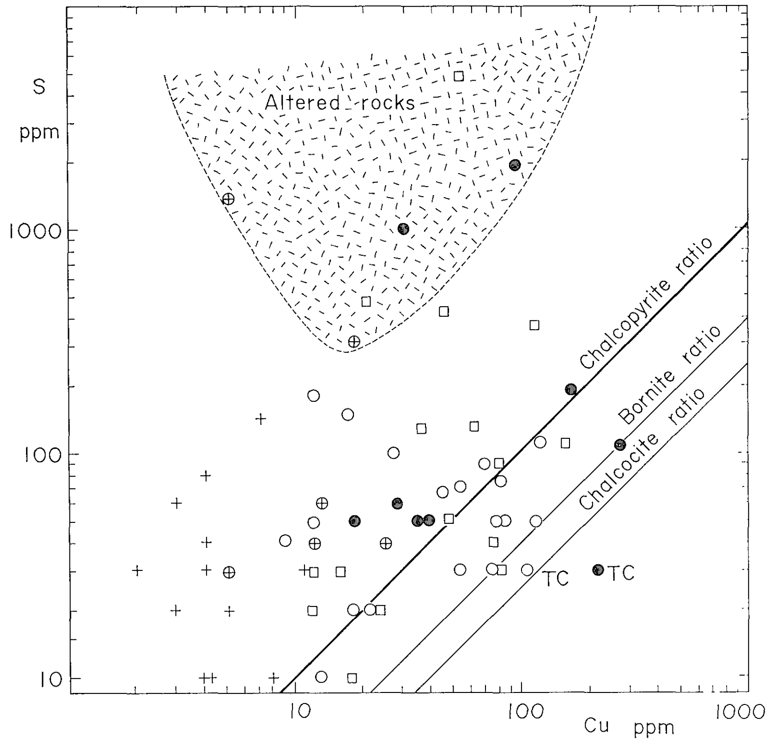


Fig. 14 Sulfur vs. copper diagram for Chilean plutonic rocks. + Late Paleozoic (⊕ altered), ○ Mesozoic (● altered) and □ Tertiary (■ altered) granitoids. TC, Tocopilla.

A minority of rock types such as gabbro and granite and altered rock are excluded. Thus the averages reveal characteristics of the Chilean rocks studied. Mineralizations dominantly with copper are seen throughout the four areas, except for the Chañaral coast; copper is very strongly concentrated as porphyry type in the Chuquicamata area, magnetite-hematite deposits of manto type is diagonostic with the Cretaceous Copiapo rocks, and manto-type copper deposit is distinct in the Tocopilla area. Granitic rocks of the mineralized areas have generally low initial strontium ratios indicating a primitive source material (SHIBATA *et al.*, 1984), and their S/Cu ratios are consistent with those of the related ore deposits, *i.e.*, low in the manto-type and high in the porphyry-type mineralized areas.

Characteristics of rocks from mineralized areas, as compared with those of barren granitoids, are high values of copper content,

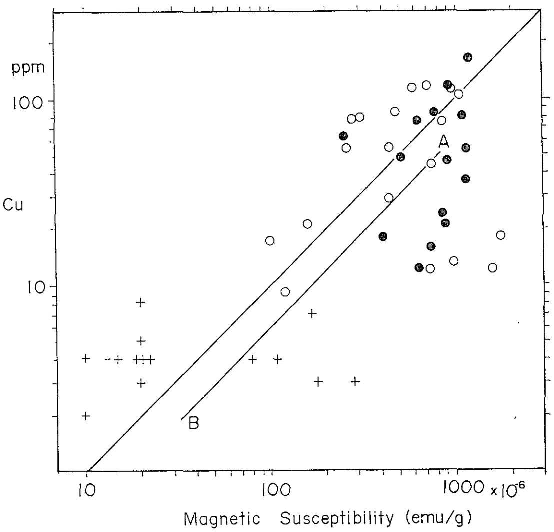


Fig. 15 Copper vs. magnetic susceptibility diagram for Chilean plutonic rocks. + Late Paleozoic, ○ Mesozoic, and ● Tertiary granitoids. Line A–B, average Japanese granitoids (50–77.5% SiO_2).

Fe_2O_3/FeO ratio and magnetic susceptibility. Apparent low value of Fe_2O_3/FeO on the Tocopilla rocks have to be considered with their low silica content (55%). Similarly, copper content and magnetic susceptibility of the same rocks need to be reduced when they are compared with other rocks with 62–63% SiO_2. Among the granitoids related to mineralizations, those from the Chuquicamata porphyry copper area have highest S/Cu and Fe_2O_3/FeO ratio indicating that this type of mineralization is resulted from granitic magmas with a high fO_2 and fS_2.

Concluding Remarks

The Chilean plutonic rocks studied fall into two distinct categories: one ranging in age from late Paleozoic to early Mesozoic being composed predominantly of ilmenite-series which are low in their magnetic susceptibility and copper content, whereas the other varying in age from middle Mesozoic to late Cenozoic being almost solely composed of magnetite-series, which are characterized by high magnetic susceptibility and copper content (Fig. 14). The magnetite-series plutonic rocks are associated with manto-type copper and iron deposits in the western half, while huge porphyry copper deposits in the eastern half of the Andean plutonic belt. This copper-rich metallogeny relative to the Japanese one depend upon basically high concentration of copper in the original magmas.

The magnetite-series rocks contain almost always hematitized magnetite and hemo-ilmenite of both primary and secondary in origin. These rocks appear to have crystallized under an oxidized condition throughout the magmatic stage and even in the deuteric stage. This satisfies one of the most basic requirement for the formation of sulfide deposits. The oxidized characteristics may have resulted from the original high Fe_2O_3/FeO ratio. Source rocks involving altered ocean floor basalts are most pausible for the Chilean magnetite-series magmatism. The presence of magnetite-series rocks with a moderate degree of the initial strontinum ratio indicates relatively low carbon content in the Chilean continental crust.

Very low contents of sulfides in the Chilean plutonic rocks suggest that copper in rocks and ore deposits were contained in magmas not only as sulfide melt—but also in the silicate melt. These coppers were concentrated into the top of pluton by fractional crystallization of magmas and circulation of magmatic waters. Magmas in the manto-type deposit area were originally low in sulfur; thus formed low S/Cu ore deposits of the manto-type. Higher values in sulfur content and Fe_2O_3/FeO ratio of porphyry copper related rocks, relative to rocks close to manto-type deposits, indicate that the porphyry copper related magmas were originally rich in sulfur and highly oxidized. Thus insoluble oxidized species of sulfur was moved out from the magmas and formed high S/Cu ore deposits of the porphyry type.

Acknowledgement: The authors with to express their sincere gratitude to Ms. Maria TERESA C. P., Mr. Raúl SALAS, O., Mr. V. MAKSAEV, SERNAGEOMIN, and staff members of the Corparacion Nacional del Cobre de Chile (CODELCO) for their hospitality during the visit of GSJ members to Chile. XRF analysis of our colleague, Dr. Osamu UJIKE, is also appreciated.

References

AGUIRRE, L. (1983) Granitoids in Chile. *Geol. Soc. America, Mem.* 19, p. 293–316.

————, CHARRIER, R., DAVIDSON, J., MPODOZIS, A., RIVANO, S., THIELE, R., TIDY, E., VERGARA, M. and VICENTE, J. C. (1974) Andean magmatism: its paleogeographic and structural setting in the central part (30°–35°S) of the southern Andes. *Pacific Geol.*, no. 8, p. 1–38.

ARAMAKI, S., HIRAYAMA, K. and NOZAWA, T. (1972) Chemical composition of Japanese granites, Part 2. Variation trends and average composition of 1,200 analyses. *Jour. Geol. Soc. Japan*, vol. 78, p. 39–49.

BALDWIN, J. A. and PEARCE, J. A. (1982) Discrimination of productive and nonproductive porphyritic intrusions in the Chilean Andes. *Econ. Geol.*, vol. 77, p. 664–674.

BANKS, N. G. (1982) Sulfur and copper in magma and rocks: Ray porphyry copper deposit, Pinal County, Arizona. *Advances in Geology of the Porphyry Copper Deposits, Southwestern North America* (S. R. TITLEY ed.), Univ. Ariz. Press, p. 227–257.

BANKS, N. G. and PAGE, N. J. (1980) Some observations that bear on the genesis of porphyry-copper deposits. *Proc. 5th IAGOD Symp.*, vol. 1, p. 49–73. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, p. 49–73.

CHAPPELL, B. W. and WHITE, A. J. R. (1974) Two contrasting granite types. *Pacific Geol.*, no. 8, p. 173–174.

CORVALAN, J. D. (1968) *Mapa geologico de Chile.* Scale 1/1,000,000, Inst. Inv. Geol., Santiago.

FIELD, C. W. and GUSTAFSON, L. B. (1976) Sulfur isotopes in the porphyry copper deposit at El Salvador, Chile. *Econ. Geol.*, vol. 71, p. 1533–1548.

FARRAR, E., CLARK, A. H., HAYNES, S. J. QUIRT, G. S., CONN, H. and ZENTILLI, M. (1970) K–Ar evidence for the post-Paleozoic migration of granitic intrusive foci in the Andes of northern Chile. *Earth Planet. Sci. Lett.*, vol. 10, p. 60–66.

GUSTAFSON, L. B. and HUNT, J. P. (1975) The porphyry copper deposit at El Salvador, Chile. *Econ. Geol.*, vol. 70, p. 857–912.

HALPERN, M. (1978) Geological significance of Rb–Sr isotopic data of northern Chile crystalline rocks of the Andean orogen between latitudes 23° and 27° South. *Geol. Soc. America, Bull.*, vol. 89, p. 522–532.

——— (1979) Strontium isotope composition of rocks from the Disputada copper mine, Chile. *Econ. Geol.*, vol. 74, p. 129–130.

ISHIHARA, S. (1977) The magnetite-series and ilmenite-series granitic rocks. *Mining Geol.*, vol. 27, p. 293–305.

——— (1978) Metallogenesis in the Japanese island-arc system. *Jour. Geol. Soc. London*, vol. 135, p. 389–406.

——— (1979a) Kappameter KT–3 and its application for some volcanic rocks in Japan. *Bull. Geol. Surv. Japan*, vol. 30, p. 513–519.

——— (1979b) Lateral variation of magnetic susceptibility of the Japanese granitoids. *Jour. Geol. Soc. Japan*, vol. 85, p. 509–523.

——— (1981a) Obicular granitoids of Chile. *Chishitsu News*, vol. 326, p. 1–4.

——— (1981b) The granitoid series and mineralization. *75 Anniv. Vol., Econ. Geol.*, p. 458–484.

——— and ULRIKSEN, C. E. (1980) The magnetite-series and ilmenite-series granitoids in Chile. *Mining Geol.*, vol. 30, p. 183–190.

———, SAWATA, H., SHIBATA, K., TERASHIMA, S., ARRYKUL, S. and SATO, K. (1980) Granites and Sn–W deposits of Peninsular Thailand. *Mining Geol. Spec. Issue*, no. 8, p. 223–241.

———, ENDO, Y. and ULRIKSEN, C. E. (1982) Granitoids in Chile: Chemistry and opaque minerals (abst). *Mining Geol.*, vol. 32, p. 167–168.

———, KANISAWA, S. and TERASHIMA, S. (1983) Sulfur and sulfides in the Cretaceous, magnetite-series granitoids of the Kitakami Mountains, Japan. *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, vol. 78, p. 1–10.

LOPEZ-ESCOBAR, L., FREY, F. A. and OYARZÚN, J. (1979) Geochemical characteristics of central Chile (33°–34°) granitoids. *Contrib. Mineral. Petrol*, vol. 70, p. 439–450.

MCNUTT, R. H., CROCKET, J. H., CLARK, A. H., CAELLES, J. C., FARRAR, E., HAYNES, S. J. and ZENTILLI, M. (1975) Initial $^{87}Sr/^{86}Sr$ ratios of plutonic and volcanic rocks of the central Andes between latitudes 26° and 29° South. *Earth Planet. Sci. Lett.*, vol. 27, p. 305–313.

MONTECINOS, P. C. (1979) Plutonismo durante et ciclo tectonico Andino en el norte de Chile, entre los 18°–29° lat. *Sur. II Cong. Geol. Chileno*, vol. 3, p. 89–109.

OYARZÚN, J. and VILLALOBOS, J. (1969) Recopilacion de analisis quimicos de rocas chilenas. *Dept. Geol., Univ. Chile*, Publ. no. 33, p. 47.

RUIZ, C. F., AGUIRRE, L., CORVALAN, J., KLOHN, C., KLOHN, E. y LEVI, B. (1965) *Geologia y yacimientos metaliferos de Chile.* Inst. Inv. Geol., Chile, 305p.

SASAKI, A., ULRIKSEN, C. E., SATO, K. and ISHIHARA, S. (1984) Sulfur isotope reconnaissance of porphyry copper and manto type deposits in Chile and the Philippines. *Bull. Geol. Surv. Japan*, vol. 35, p. 615–622.

SATO, Kohei (1980) Distribution of fluorite deposits in Japanese Islands. *Mineral. De-*

posita, vol. 15, p. 327–334.

SATO, Takeo (1984) Manto-type copper deposits in Chile—A review. *Bull. Geol. Surv. Japan*, vol. 35, p. 565–582.

SHIBATA, K., ULRIKSEN, C. E. and ISHIHARA, S. (1984) Rb–Sr ages and initial $^{87}Sr/^{86}Sr$ ratios of late Paleozoic granitic rocks from northern Chile. *Bull. Geol. Surv. Japan*, vol. 35, p. 537–545.

SILLITOE, R. H. (1981) Regional aspects of the Andean porphyry copper belt in Chile and Argentina. *Trans. Instn. Min. Metall.*, Sect. B, vol. 90, p. 15–36.

SUAREZ, M. D. (1977) Notas geoquimicas preliminares del batolito Patagonico al sur de Tierra del Fuego, Chile. *Revista Geol. Chile*, no. 4, p. 15–33.

TAINOSHO, Y. (1982) Fe–Ti oxide minerals of the late Mesozoic to early Tertiary granitic rocks in eastern Chugoku and Kinki districts, Southwest Japan. *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, vol. 77, p. 387–402.

TAKAHASHI, M., ARAMAKI, S. and ISHIHARA, S. (1980) Magnetite-series/ilmenite-series vs. I-type/S-type granitoids. *Mining Geol. Spec. Issue*, no. 8, p. 13–28.

TERASHIMA, S. and ISHIHARA, S. (1983) Copper, lead, zinc, arsenic and sulfur of the Japanese granitoids: (1) Kitakami Mountains and Abukuma Highland. *Bull. Geol. Surv. Japan*, vol. 34, p. 443–453.

——— and ——— (1984) *ditto*; (2) Inner Zone of Southwest Japan. *ditto*, vol., 35, p. 127–145.

VERGARA, M. M. and DRAKE, R. (1979) Eventos magmaticos-plutonicos en los Andes de Chile central. *II Cong. Geol. Chileno*, vol. 1, p. 19–30.

VISTELIUS, A. B., IVANOV, D. N. KURODA, Y. and RUIZ, C. F. (1970) Variations of modal composition of granitic rocks in some regions around the Pacific. *Mathem. Geol.*, vol. 2, p. 63–80.

YOSHII, M. and SATO, T. (1983) An outline of GEOCAPS, a geochemical data analysis program system in BASIC. *Geological Data Processing. Japanese Society for Geological Data Processing*, no. 8, p. 21–40.

チリ中北部の深成岩類

石原舜三・C. E. ウルリクセン・佐藤興平・寺島　滋・佐藤岱生・遠藤祐二

要　　旨

チリ中北部の深成岩類をアントファガスタ (22°00′–24°00′S)，コピアポ (25°30′–28°00′)，サンティアゴ (32°30′–34°00′) の3横断面を中心として調査した．深成岩類は古生代後期—中生代初期のチタン鉄鉱系を主とするもの，および中生代中期—新生代後期のほとんど磁鉄鉱系のみからなるものに分けられる．前者は主に花崗岩（海岸地帯）と花崗閃緑岩（内陸部）からなり，後者は主に石英閃緑岩—花崗閃緑岩である．岩石の帯磁率は前者で $10\text{–}500 \times 10^{-6}$emu/g，後者で $100\text{–}2000 \times 10^{-6}$emu/g の値を示す．両系列共に，その帯磁率は内陸のポーフィリーカッパー鉱床帯へ向けて増加する傾向がみられる．海岸地帯の典型的なチタン鉄鉱系においても S タイプの性格は顕著ではない．

中生代—新生代磁鉄鉱系深成岩類に関係して海岸側にマント型銅（および鉄）鉱床が，内陸のアンデス山麓にポーフィリー型銅鉱床がみられる．深成岩類は全般的に高い帯磁率と Fe_2O_3/FeO 比を示し，ヘモイルメナイトや赤鉄鉱化した磁鉄鉱を含み，これらがマグマ期から後マグマ期において酸化的な環境にあったことを示す．岩石中の硫化物は一般に少ないが黄銅鉱が普遍的に認められる．岩石中の銅含有量は高いが硫黄は少なく，したがって Cu/S 比は高い．

チリの磁鉄鉱系岩石を形成したマグマは本来銅に富んでいたものと思われ，それが高い酸素フュガシティのもので浅所貫入岩の頂部に濃集し，マント型・鉱脈型などの銅に富む鉱床区を生成したものと考えられる．ポーフィリー型銅鉱床に関係する貫入岩の S/Cu 比は高いが，これにはマグマの fO_2 が非常に高く貫入岩体頂部への硫黄集積率が高かったか，あるいはマグマの硫黄原濃度が高かったの2点が考

えられる．S/Cu 比が高い巨大なポーフィリー型鉱床はこれらの相乗効果により形成されたと思われる．

チリとほぼ同じ年代を持つ日本の花崗岩類の平均値と比較すると，チリの中生代―新生代磁鉄鉱系深成岩類は，Al_2O_3, Na_2O, Fe_2O_3, Sr, Cu などに富み，FeO, S, Zn, Pb, Li, Sn などに乏しい．これらの特徴は，チリの岩石がほぼ磁鉄鉱系のみから構成されることと調和的である．これら岩石を形成した原マグマは，Fe_2O_3/FeO 比が高い大洋底地殻のような苦鉄物質から生成されたものと考えられる．一部には大陸地殻から発生したかそれを同化したマグマも考えられるが，生成岩石が酸化的であることからチリの大陸地殻は一般に炭素に乏しいことが推察される．

（受付：1984年8月20日；受理：1984年9月25日）

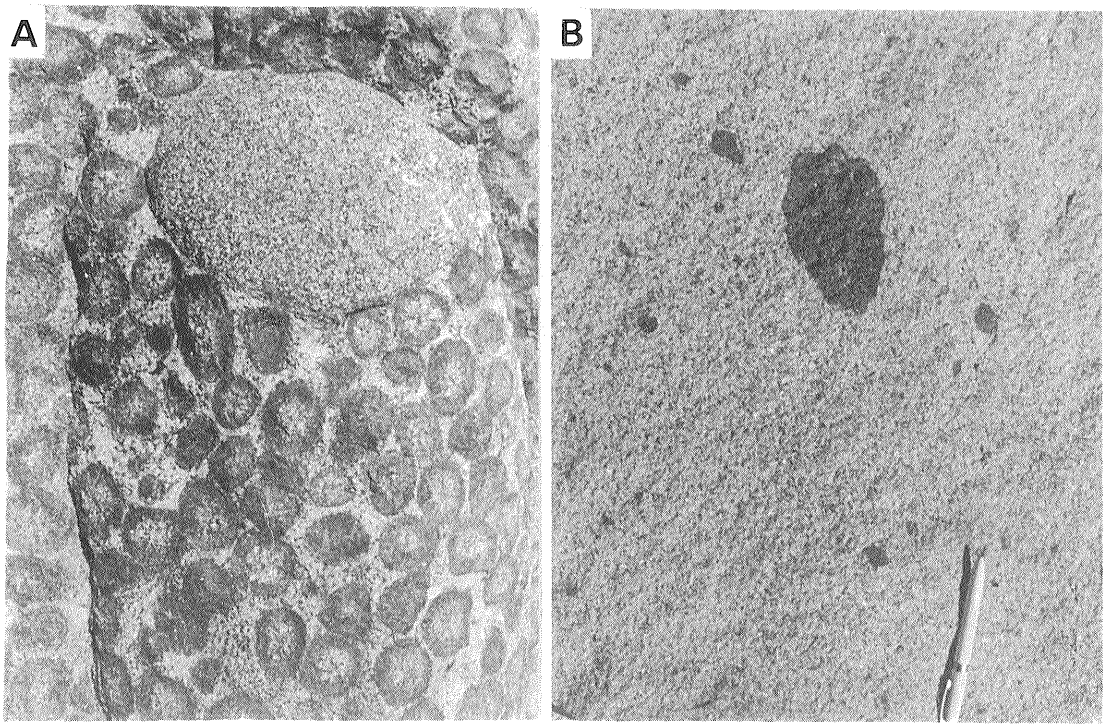


Plate I A–B Mafic xenoliths: A, Dioritic rocks, which is common in the Jurassic granitoids along the Chañaral coast, occurring in a pegmatitic obicular granodiorite at north of Caldera. Size of the obicular is most commonly 6–8 cm in diameter. B, Poorly digested, fragmental xenolith of andesite in Tertiary stock at east of Santiago (79111101).

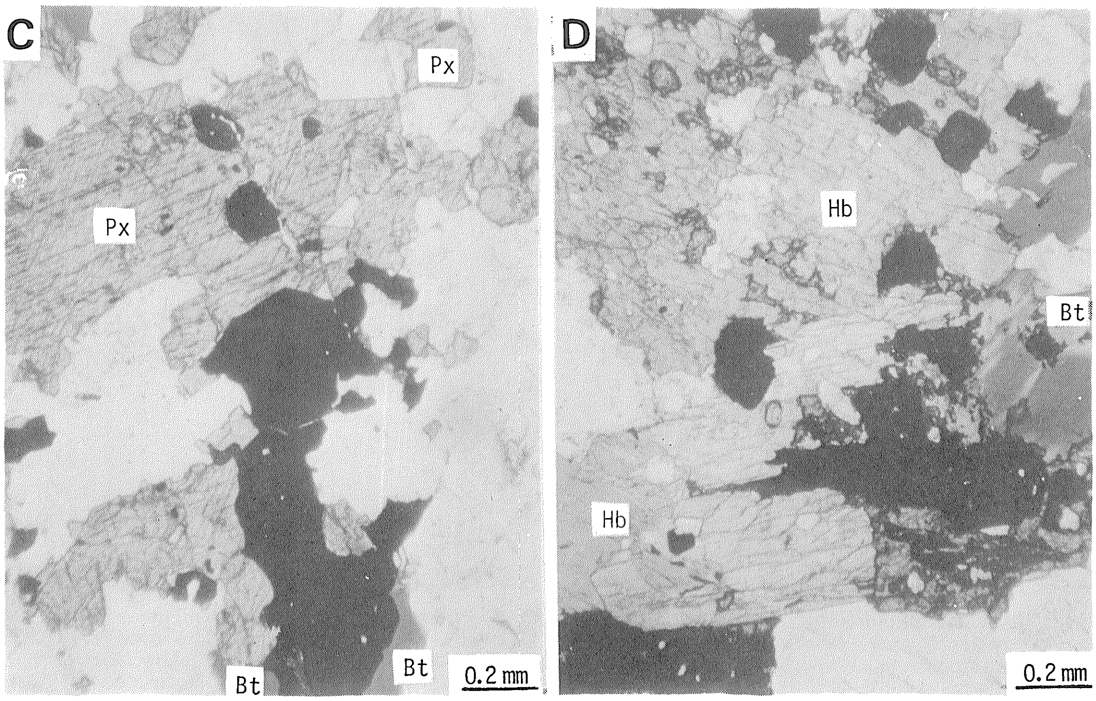


Plate I C–D Photomicrographs under transmitted light. C, Euhedral-subhedral magnetite (black) occurring with pyroxene (Px) and biotite (Bt) (79TC8). D, Euhedral magnetite (black) occurring with sphene (gray, high relief), hornblende (Hb) and biotite (Bt) (79CHU5).

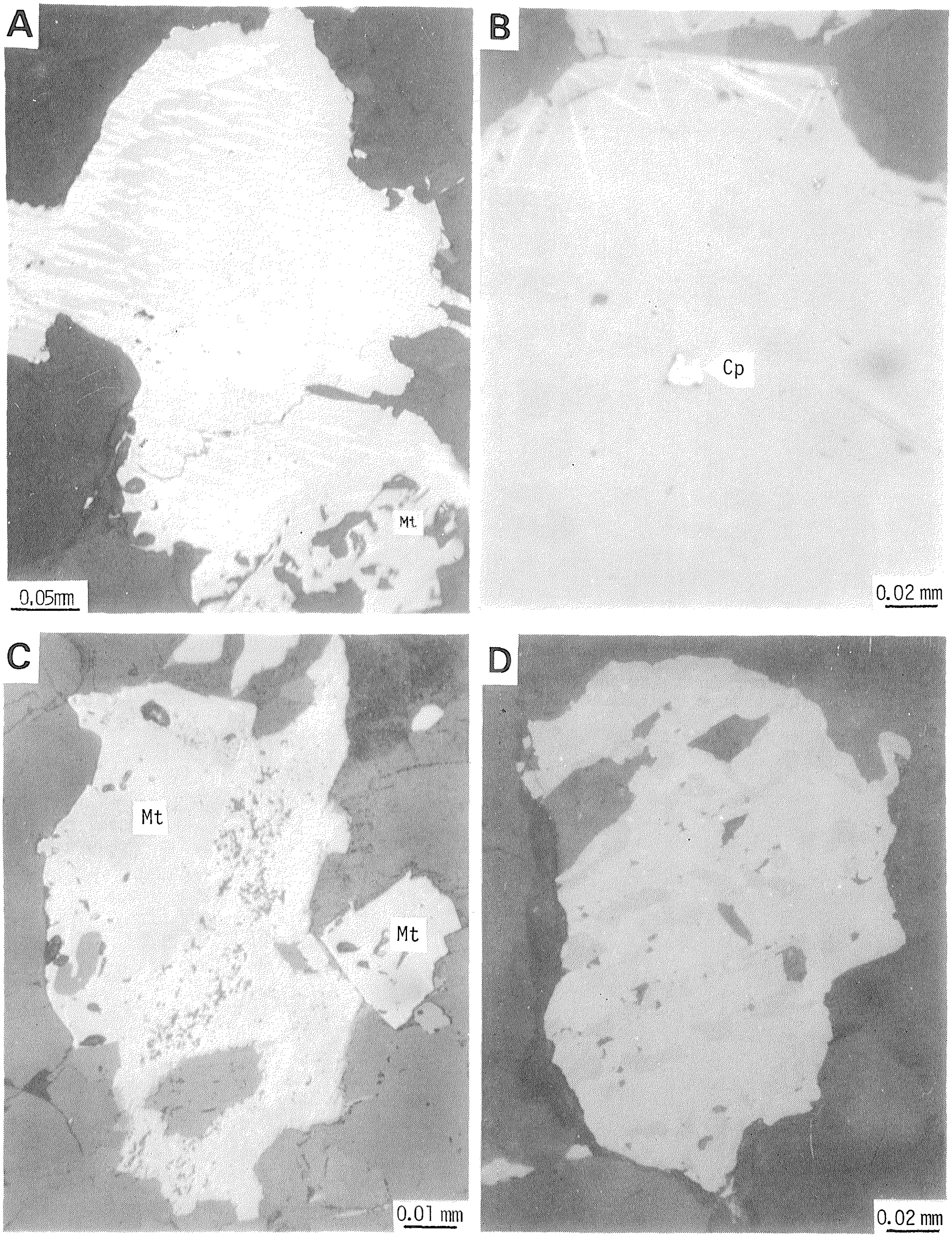


Plate II Photomicrographs under reflected light. A, Primary hemo-ilmenite (hematite white, ilmenite gray) occurring with magnetite (Mt) (79CP11). B, Chalcopyrite (Cp) occurring in magnetite. White blade at margin of magnetite is hematite (79CP4). C, Secondary hemo-ilmenite containing dusty hydrothermal minerals. Mt, magnetite (79CHU5). D, Secondary hemo-ilmenite occurring in the interstices of salic minerals in L porphyry (79PT-L).