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The Magnetite-series and Ilmenite-series Granitoids in Chile

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Abstract: Paleozoic and Mesozoic-Cenozoic granitoids of the Chilean Andes were studied magnetically in the area between Latitude 22–35°S. The Paleozoic granitoids are found to be composed of the ilmenite-series and weakly magnetic magnetite-series, whereas all the Mesozoic-Cenozoic ones appear to be the magnetite-series. Lack of significant sulfide deposits in the Paleozoic terrains may have been resulted from the reducing nature of the granitic magmatism.

Within the magnetite-series terrains of Mesozoic-Cenozoic age, magnetic susceptibility of the granitoids seems to increase continentward. Granitoids related to porphyry copper deposits in the Andean Cordillera have higher magnetic susceptibility than those occurring in the Coast Range which could be genetically associated with manto-type deposits. The different styles of mineralization may possibly be in consequence of the different oxidation status of the granitic magmatism.

Introduction

Granitoids in 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. These granitoids range in composition, from quartz diorite to granite, and show different mode of occurrence, from catazonal to epizonal. Some of the epizonal granitoids are associated with well-known prophyry copper and manto-type ore deposits.

The magnetite-series and ilmenite-series granitoids (ISHIHARA, 1977) have an important bearing on genesis of the metallic mineralizations (ISHIHARA, 1980). Thus, a brief examination of the Chilean granitoids in terms of this classification have been made on the basis of magnetic susceptibility and microscopic modal analyis data. This paper deals with the distribution of the two series granitoids and their relationship to the mineralization . The studied areas are shown in Figure 1.

Granitoids in Chile

Granitoids of Chile 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 (see Fig. 7).

The Paleozoic granitoids occur mostly along the western coast between Taltal and Traiguen (25°30′–38°13′S) and are present sporadically in the interior (CORVALAN, 1968). RUIZ et al. (1965) pointed out that the Paleozoic granitoids are generally coarse-grained biotite granite which is characterized by microcline. The Paleozoic granitoids are often foliated and mylonitized. Only weak fluorite and topaz mineralizations are known in the granitoids exposed to the southeast of Vicuña.

The Mesozoic-Cenozoic granitoids occur extensively in the area to the east of the coastal Paleozoic batholiths. AGUIRRE et al. (1974) studied them in the central part (30°–35°S) of the southern Andes, and stated that they belong to calc-alkaline suite having quartz-monzo-

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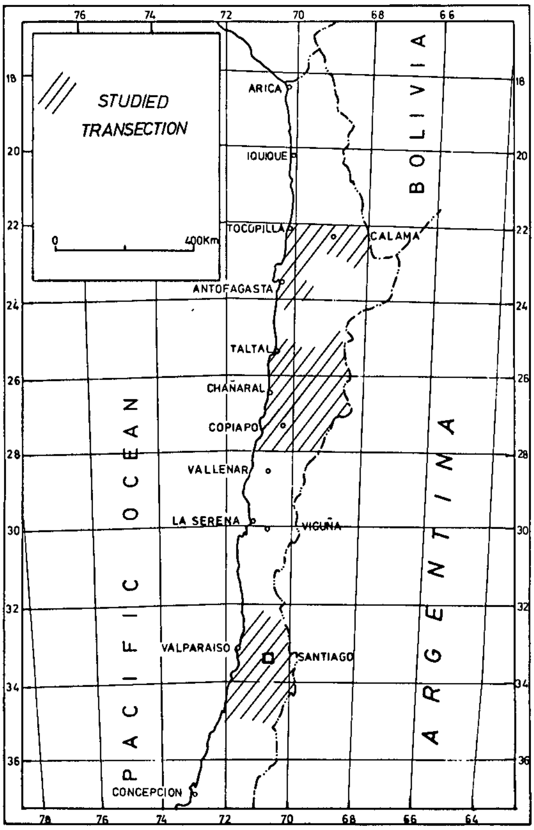

Fig. 1 Locality map of the studied areas.

Table 1 Percentage of various granitoids depending upon their age. Modal analyses of VISTELIUS et al. (1970) plotted in Fig.2. were converted to percentage and are compared with those by AGUIRRE et al. (1974) which are shown in parenthesis.

Composition	Paleozoic	Mesozoic Cenozoic
Granite	44%	24% (26%)
Granodiorite	22%	22% (18%)
Tonalite and quartz diorite	30%	24% (31%)
Quartz monzodiorite and quartz monzonite	4%	29% (26%)

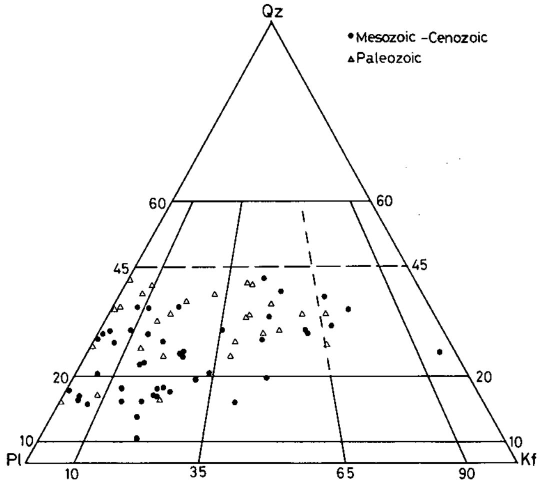

Fig. 2 Modal feldspars and quartz composition of the Chilean granitoids. Data of VISTELIUS et al. (1970) were classified into Paleozoic and Mesozoic-Cenozoic by referring their locality to the geological map of Chile (CORVALAN, 1968), and then plotted. Some of the Paleozoic granitoids may belong to the Mesozoic-Cenozoic, according to recent age determination (see text).

diorite and granodiorite composition in general and 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-Vallenar 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.

Table 1 and Figure 2 are a summary of modal composition of the Paleozoic and Mesozoic–Cenozoic granitoids studied in regional scale by VISTELIUS et al. (1970) and AGUIRRE et al. (1974). The Paleozoic granitoids are dominantly granitic, whereas the Mesozoic–Cenozoic ones are characterized by predominance of slightly alkaline suites such as quartz monzodiorite and quartz monzonite. These granitoids have been magnetically studied in the areas along the following three transections.

Magnetic Susceptibility

Magnetic susceptibility was measured along three transections, tentatively named as the Santiago, Copiapo and Antofagasta transections, by a portable device in the way described in ISHIHARA (1979a). The results are shown in Figures 3 to 5.

In the Santiago transection (32°30′–35°00′), the granitoids are divided by radiometric age data into Paleozoic (Devonian and Upper Carboniferous), Jurassic and Cretaceous on the

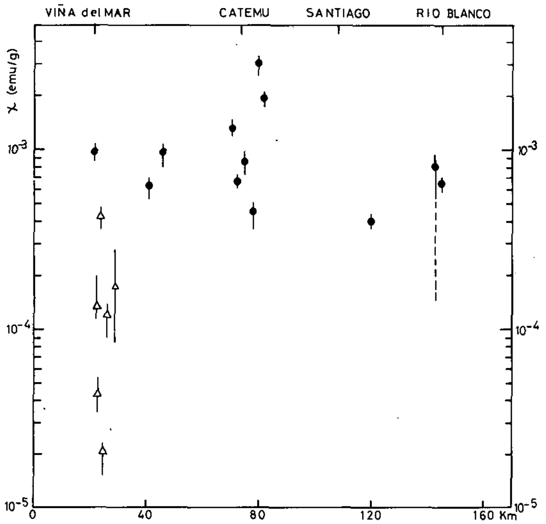

Fig. 3 Magnetic susceptibility of granitoids at the Santiago transection (32°45′–33°30′S). Triangle, Paleozoic granitoids; solid circle, Mesozoic-Cenozoic granitoids. Mean values of 3–5 measurements are plotted with bar indicating the range for one outcrop. Broken line is range of hydrothermally altered rocks.

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. 3).

The Paleozoic granitoids consist mainly of coarse-grained, weakly foliated, biotite granites. Those occurring in Viña del Mar and its north are weakly magnetic and some show magnetic susceptibility of the ilmenite-series (χ below 100×10^{-6} emu/g). The Paleozoic granitoids assigned by CORVALAN (1968) 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 (670×10^{-6} emu/g) magnetic susceptibility than granodiorite of the Andina (Rio Blanco) porphyry copper deposit (960×10^{-6} emu/g).

In the *Copiapo transection* (25°30′–28°00′) where the plutonic rocks become also younger toward east (FARRAR et al., 1970), the 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 granites and small amount of dike-like intrusion of fine-grained two-mica granite. Isolated Paleozoic blocks were examined at three localities in the Andean Cordillera. They are also weakly magnetic as follows.

The 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 then 100×10^{-6} emu/g, while massive quartz diorite reveals a maximum of 300×10^{-6} emu/g (Fig. 4). 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

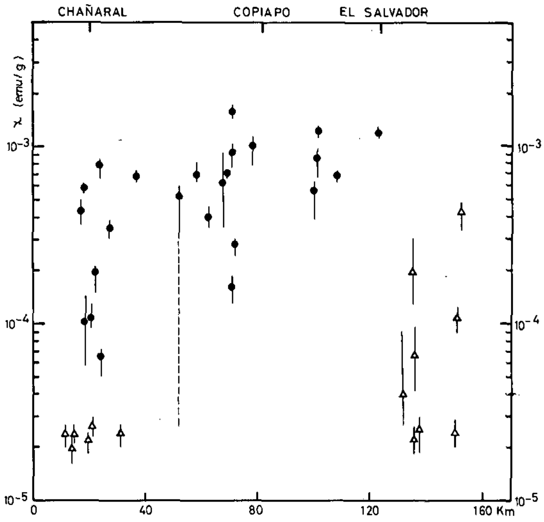

Fig. 4 Magnetic susceptibility of granitoids at the Copiapo transection (25°30′–28°00′S). The results from the northern part (north of Chañaral, 26°22′S) are plotted at E–W but those from the southern part at N75°W profiles. For symbols, see Fig. 3.

diorite and granite are more magnetic, ranging up to 450 × 10^{-6} emu/g.

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. 4). 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 × 10^{-6} emu/g. These rocks are generally foliated.

Magnetic susceptibility of Cretaceous and Tertiary granitoids are higher than 400 × 10^{-6} emu/g. The Cretaceous ones occurring about 12 km south-southeast of Copiapo, however, have the values lower than 400 × 10^{-6} emu/g. These are biotite granite which is generally less magnetic than, for example, granodiorite (ISHIHARA, 1979b). Unaltered "L" porphyry in monzodioritic composition occurring at Inca level (8532 Dr. N, 3956 m W) of the El Salvador mine gives magnetic susceptibility around 1,200 × 10^{-6} emu/g. Magnetic susceptibility of the Mesozoic-Cenozoic granitoids along this transection seems to increase toward east.

Granitoids of the Antofagasta transection have been least studied geochronologically. Available data (HALPERN, 1978; MONTECINOS, 1979) suggest, however, that a lateral viration of Jurassic granitoids in the Coast Range to Tertiary granodiorite of the Chuquicamata area may also exist along this transection. These granitoids have generally quartz diorite to granodiorite composition, all having magnetic susceptibility of the magnetite-series.

In the Coast Range, quartz gabbro and granodiorite of the Varillas area, south of Antofagasta, have lower magnetic susceptibility than quartz diorite and granodiorite of the Antofagasta-Tocopilla area (Fig. 5). These Jurassic granitoids have an average of 500 × 10^{-6} emu/g, while the Tertiary granodiorite at the Chuquicamata mine is measured around 800 × 10^{-6} emu/g. Thus, here again, magnetic susceptibility of these magnetite-series granitoids seems to increase continentward.

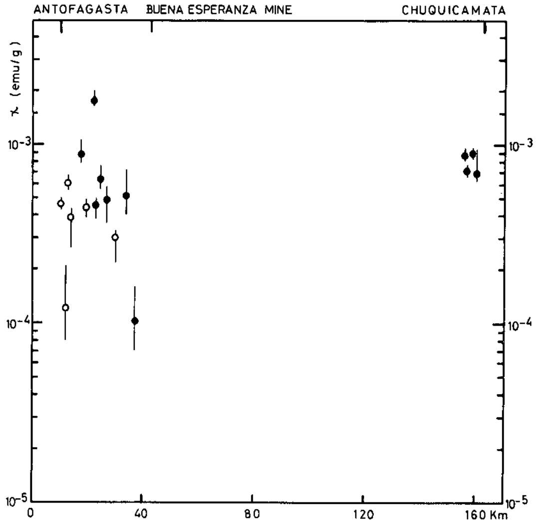

Fig. 5 Magnetic susceptibility of granitoids at the Antofagasta transection (22°00′–24°00′S). The Coast Range graniotids are divided into those occurring north (solid circle) and south (open circle) of Antofagasta.

Distribution of the Magnetite-Series and Ilmenite-Series Granitoids

From the descriptions in the previous chapter, it is clear that the Paleozoic granitoids have generally magnetic susceptibility of the ilmenite-series, whereas the Mesozoic-Cenozoic ones are all with the values of the magnetite-series. VISTELIUS et al. (1970) made a detailed description of opaque minerals in the Chilean granitoids. The magnetite-series and ilmenite-series granitoids are usually separated at 0.1 vol. percent of the opaque oxide minerals (ISHIHARA, 1977). Thus their data are re-examined in Figure 6, in which most of the 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 gen-

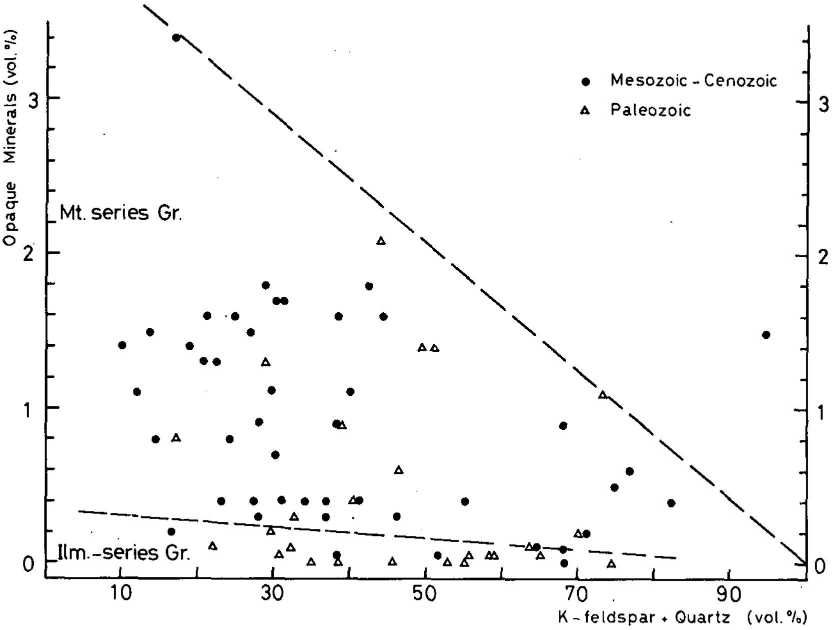

Fig. 6 Opaque minerals–K-feldspar + quartz diagram of the Chilean granitoids. Data from Vistelius et al. (1970) treated in the same way as in Fig. 2. Broken line is the general boundary of the Japanese magnetite-series and ilmenite-series of Ishihara (1977).

erally of the magnetite-series on the modal composition and also on Fe_2O_3/FeO ratio taken from bulk chemical analyses of various authors (Oyarzun 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.

Distribution of the two series of granitoids thus determined is shown in Figure 7. The Chilean granitoids are dominantly composed of the magnetite-series.

Lateral Variation

There is a tendency observed on the Copiapo transection that the magnetic susceptibility of both Paleozoic and Mesozoic-Cenozoic granitoids may increase continentward (Fig. 4). The Paleozoic granitoids of this transection, however, are more mafic in the Andean Cordillera than in the Coast Range. The compositional difference may have some influence in this low range of magnetic susceptibility. In addition, the coastal Paleozoic granitoids of the Santiago transection are biotite granite and are slightly magnetic. Thus additional study is required to determine regional variation of magnetic susceptibility of the Paleozoic granitoids.

The Mesozoic-Cenozoic granitoids, on the other hand, appear to be quartz gabbro to granodiorite in the coastal side and quartz monzodiorite-granodiorite in the Andean Cordillera. A low magnetic susceptibility was obtained from Jurassic granitoids along each transection. Thus, the Jurassic granitoids seem to have least content of magnetite among the products of the magnetite-series magmatism in the Andean orogeny. This least magnetic character at the westernmost zone is the same tendency as that observed across the Sierra Nevada batholith (Ishihara, 1979b).

Aguirre et al. (1974) and Lopez-Escobar et al. (1979) described that Tertiary granitoids are more alkalic than the Cretaceous granitoids.

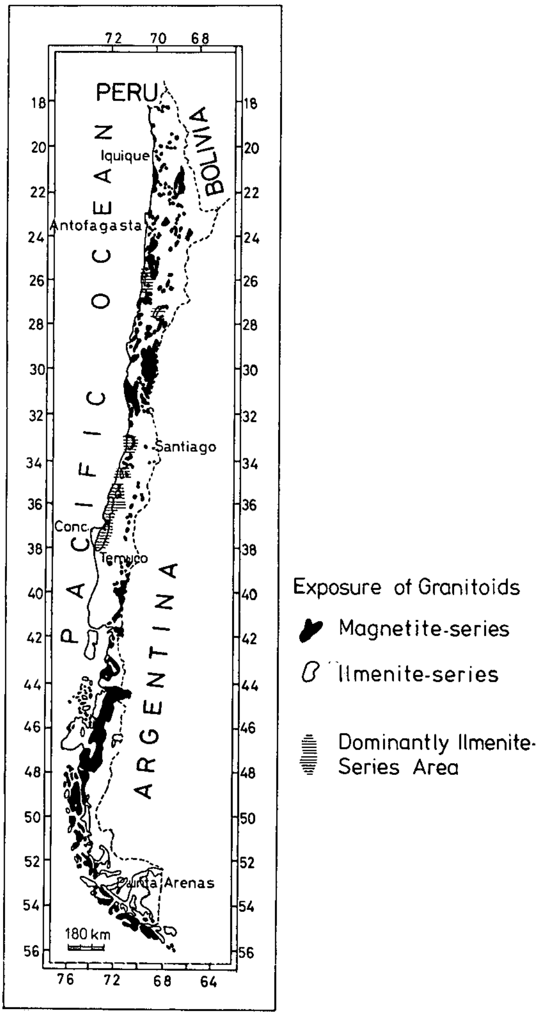

Fig. 7 Assumed distribution of the magnetite-series and ilmenite-series graniotids in Chile.

Alkaline granitoids in orogenic belt are generally more magnetic than typical calc-alkaline granitoids (Kanaya and Ishihara, 1973; Kanaya, 1975). It may be possible to conclude that the magnetic susceptibility increases continentward across the Chilean magnetite-series belt.

Relation to Mineralization

In the Paleozoic granitoids terrains, only weak mineralization including Au (34–40°S), Pb-Zn (46–56°S) and Fe–Mn (38–40°S) are known (Ruiz et al., 1965). However, genetic link of these deposits to the granitic magmatism is unclear. Indeed, all the Fe–Mn and a large part of the Au mineralizations seem to be not related to the Paleozoic granitoids. It is probably justified to say that the Paleozoic granitoids are practically free of sulfide mineralization.

The Paleozoic granitoids often occur associated with metamorphic rocks, indicating that a deep level of batholiths is presently seen. However, in some other areas, Taltal-Chañaral for example, the granitoids are massive biotite granite having fine-grained muscovite-bearing variety, indicating that a shallow level of granitic pluton is now exposed. yet, the granite is associated with no mineralization. The ilmenite-series granitoids are known to be poorly mineralized by sulfide minerals in general granitic terrains (Ishihara, 1977, 1980). The general lack of sulfide mineralization in the Paleozoic granitic terrains in Chile, therefore, may partly be attributed to the reducing character of the related granitoids.

Cassiterite and wolframite are characteristic minerals in ore deposits of the ilmenite-series granitic terrains, but scheelite occurs more commonly with the magnetite-series granitoids (Ishihara, 1977). No tin deposits but a few tungsten prospects have been reported from Chile (Ruiz et al., 1965). The tungsten deposits are connected generally with breccia pipe mineralization in the porphyry copper belt, which is composed of the magnetite-series rocks. Scheelite and tourmaline are common constituents in these deposits. Thus the tungsten mineralization in Chile is different from major wolframite mineralization in the ilmenite-series terrains of the world.

In the Mesozoic-Cenozoic magnetite-series terrains of the Coast Range, manto-type copper and magnetite deposits occur in the Jurassic (e.g., Buena Esperanza, Cu) and Cretaceous (eg., Cerro Iman, Fe; El Salado, Cu) magmatic belts. Spatially connected granitoids to these deposits have magnetic susceptibility around $600–700 \times 10^{-6}$ emu/g. On the other hand, weakly magnetic Jurassic granitoids, which have been found in Taltal-Chañnaral area, have no association with important mineralization. In the Andean Cordillera, unaltered

Tertiary granitoids with the values 800–1,200 × 10^{-6} emu/g were observed near porphyry copper deposits at Chuquicamata, El Salvador and Andina. There are certain correlations between the magnetic susceptibility to granitoids and the type of mineralization within the magnetite-series granitic terrains, which can probably serve as a useful guide for mineral exploration.

Concluding Remards

It was found that Paleozoic granitoids of Chile are composed of the ilmenite-series and weakly magnetic magnetite-series. These reduced-type of granitic magmatism generally indicates the incorporation of C-bearing crustal materials in source magma (ISHIHARA, 1977), which is also seen in the reported initial $^{87}Sr/^{86}Sr$ ratios of the Andean orogenic belt (Fig. 8). On the other hand, the Mesozoic-Cenozoic granitoids consist of the magnetite-series rocks that have a low range of the initial ratios (0.7035–0.7060). This series of magmas may have been brought up from subducted oceanic plate and/or subcontinental lithosphere (HALPERN, 1980) without significant interaction with crustal materials. These different modes of magma ascent must require different tectonic setting, so that there must have been a drastic change in regional setting of the Andean orogeny between the two periods of granitic magmatism. Predominance of the magnetite-series granitoids in the whole orogeny belt agrees with the general pattern observed in the Circum-Pacific region (TAKAHASHI et al., 1980).

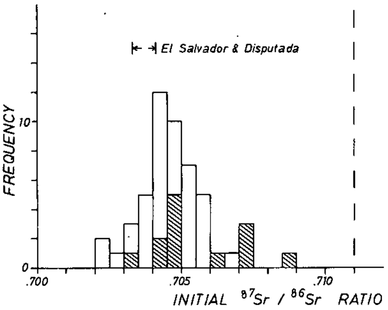

Fig. 8 Histogram of initial $^{87}Sr/^{86}Sr$ ratios reported from the studied area. Among data of McNUTT et al. (1975) and HALPERN (1978, 1979), igneous rocks older than mid-Tertiary are plotted. Shaded is the Paleozoic and open is the Mesozoic-Cenozoic. Broken line is the ratio expected by partial melting of the Paleozoic metasedimentary rocks (HALPERN, 1978, 1979).

Lack of "ture" magnetite-series granitoids in the Paleozoic magmatism as well as their deeply eroded level would explain the paucity of sulfide mineralization of this age. Within the magnetite-series terrains of the Jurassic onward, the variation in magnetite content in host granitoids appears to have bearing on the style of mineralization, that is, porphyry vs. manto type, although further studies are necessary to arrive at conclusion.

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チリーにおける磁鉄鉱系とチタン鉄鉱系花崗岩類

石原舜三・C. E. ウルリクセン

要旨：チリー中北部の花崗岩類の野外調査を実施し，携帯用帯磁率計によりそれらの磁化率を測定し，鏡下観察をおこなった．チリーの花崗岩類は2時期からなる古生代花崗岩類と，ジュラ紀以降の中生代—新生代花崗岩類からなり，重要なポーフィリー型，マント型銅鉱床は後者に関係している．古生代花崗岩類はチタン鉄鉱系か若干の磁鉄鉱を含む磁鉄鉱系とからなる一方，中生代—新生代花崗岩類はほとんどすべて磁鉄鉱系から構成される．両者は異なる構造場に産出するから，チリーでも中生代の初めに著しい広域構造場の転換があったものと予想される．

チタン鉄鉱系花崗岩類の生成には地殻物質の関与が考えられるが，今回の調査結果を既存のSr初生値と比較すると，チタン鉄鉱系の同比は磁鉄鉱系よりも高く，チタン鉄鉱系の生成には地殻物質が関係している．中生代—新生代磁鉄鉱系花崗岩類の横断面性質変化はSr初生値では不明瞭であるが，磁鉄鉱含有量に増加する結果が得られた．この結果はシェラネバタその他のアメリカ大陸西海岸の花崗岩類で共通の性質であるが，チリーでは全般的に磁鉄鉱量が多く，より酸化的である．

マント型銅鉱床や鉄鉱床は海岸沿いに分布し，ポーフィリー型銅鉱床はアンデス山地よりに産出する．後者の方が磁化率が高く，磁鉄鉱含有量が多い．磁化率は鉱床探査に使用しうる可能性がある．この事実は，また，磁鉄鉱系花崗岩活動と関連鉱化作用にも海岸側と内陸側とで，酸化還元状態に差があったことを示唆しているかも知れない．