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Rb–Sr Ages and Initial $^{87}Sr/^{86}Sr$ Ratios of Late Paleozoic Granitic Rocks from Northern Chile

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Abstract: Rb–Sr whole-rock isochron ages were determined on three suites of so-called Paleozoic granitic rocks from northern coastal Chile. The granitic rocks from the Valparaiso and Ci Funcho areas are dated as 296.3±5.4 Ma and 262.2±4.6 Ma, respectively, which are in accord with geologically estimated age. The rocks from the Chañaral area is dated as 212.8±8.6 Ma, which is correlated close to the Triassic-Jurassic boundary age. A K–Ar age of 196±6 Ma was obtained on biotite in granite from Esmeralda between Ci Funcho and Chañaral. These age results demonstrate that no Precambrian plutonism occurred in the studied area, and that so-called Paleozoic granitic rocks in the Ci Funcho-Chañaral area are divided into Permian and early Mesozoic in age.

Initial $^{87}Sr/^{86}Sr$ ratios of the ilmenite-series granitic rocks from the coastal region are 0.70641 (Valparaiso), 0.70635 (Ci Funcho) and 0.70455 (Chañaral). These relatively low ratios deny substantial crustal contribution to the granitoids. The initial ratios of magnetite-series granitoids from porphyry- and manto-type mineralized areas (Chiquicamata, El Salvador and Tocopilla) are as low as 0.70344 to 0.70464.

Introduction

Granitic rocks of late Paleozoic age in northern Chile occur between latitudes 24° and 28°30′S (HALPERN, 1978) (Fig. 1). Ages of emplacement for coastal granitic rocks, however, are not well known except for sporadic K–Ar and few Rb–Sr ages ranging from 180 to 270 Ma. Accordingly, a discussion arises as to the existence of Precambrian granites along the coast. In fact, basement rocks in the coastal region of southern Peru show Rb–Sr whole-rock ages of about 1,900 Ma for gneisses and late Precambrian or early Paleozoic ages for granitic rocks (COBBING *et al.*, 1977; SHACKLETON *et al.*, 1979).

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In an attempt to know the emplacement ages of so-called Paleozoic granitic rocks exposed along the coast of northern Chile, and to find evidence for Precambrian metamorphism and plutonism in this region, we carried out Rb–Sr whole-rock dating of granitic rocks from Valparaiso, Ci Funcho and Chañaral areas. The coastal Paleozoic granitic rocks are generally of felsic ilmenite-series, and are quite different from mafic magnetite-series ones of later intrusive activities of the Andean orogeny (ISHIHARA and ULRIKSEN, 1980). These two series of granitoids are discussed with reference to their initial $^{87}Sr/^{86}Sr$ ratios.

Geology and Analyzed Samples

Paleozoic granitic rocks of the coastal ranges constitute the basement for the famed andesitic activities of Jurassic onward. In the Valparaiso-San Antonio area (30°–33°30′S), northwest of Santiago, they intrude or in part graduate into geneisses and amphibolites of Quintay Formation (CORVALAN and DAVILA, 1964). The granitoids are often foliated, thus they may be classified as a katazonal granitoids, and a Precambrian age may be assumed. The coastal granitoids of the Ci Funcho and Chañaral areas, on the other hand, intrude into non-metamorphic Paleozoic sedimentary rocks. The granitoids are fine-grained and massive containing subsolidus muscovite in the well fractionated phases. They may be an epizonal granitoid.

The analyzed samples from the Valparaiso (79SA 6A~D[1]) area were taken from good outcrop at the Los Piqueros bridge site 3 km south of Concon or 7 km north of Viña del Mar. On the outcrop, the granites show some variation on the grain size and composition including magnetic susceptibility. The analyzed samples are representative facies in 10 m apart. The sample C is most strongly foliated and most magnetic. This is separated from massive granite of the sample B by schlieren layer. The sample D is an aplitic dikelet, 10 cm wide.

Under the microscope, the samples A–C are coarse-grained biotite granite. Plagioclase is euhedral and unzoned, and K-feldspars are perthite or microcline. These crystals exhibit stress effect as bent of twinning or outline. Quartz filling interstices of the feldspars shows also sutured outline. Biotite, Y ≒ Z = greenish brown, is fine grained and appears to be the latest crystallized mineral. Sphene is not uncommon and may be secondary in origin because its grains often make veinlet cutting through salic minerals. The sample D is the most fractionated rock in the outcrop. Muscovite is contained in the groundmass. Garnet, up to 1 mm in diameter, is a minor constituent.

In the Ci Funcho area, all the samples were taken along the bay coast of Pta. Molina (25°40′S). They are essentially biotite granite and in some cases contain colorless amphiboles (79CF13). The grain size varies from medium to fine. Plagioclase is euhedral and is often zoned; K-feldspars are mostly orthoclase but partly microcline or perthite. Biotie is euhedral to subhedral, and its Y ≒ Z color is bright brown. Plagioclase is moderately sericitized. Some calcite occurs in the calcic core of plagioclase.

In the Chañaral area, the sample 79CH2 (26°21.7′S, 70°29.7′W) was taken at about 15 km east of Chañaral, 79CH4 and 5 just west of Chañaral, and 79CH7~9 from 6 km southwest of Chañaral. The main rock type here is massive biotite granite (nos. 2 and 5). Plagioclase is generally unzoned one; K-feldspars are usually perthitic. The biotite color (Y ≒ Z) is brownish. In the leucocratic phase (79CH7), muscovite is seen associated with green biotite. The samples 79CH8 and 9 are dikelet, 22 cm and more than 1 m wide, respectively. They are fine, equigranular rocks containing needle-shaped muscovite and some green biotite. The sample 79CH4 is a well digested xenolithic block of 15 m in diameter. It is quartz-free biotite-plagioclase rock, in which greenish and pale brown biotites grow over the plagioclase crystals. Sericite is also present as fine radiating fibrous crystals. This may be completely recrystallized rock.

Biotite granite used for K–Ar dating (79SE14) was taken from 5 km east of Esmeralda, which is located about 30 km south of Ci Funcho and 50 km north of Chañaral. This is an S-type ilmenite series granite containing quartz xenolith (3 × 5 cm.).

In addition, some Mesozoic-Cenozoic magnetite-series granitoids from mineralized areas were analyzed for Sr isotopic study. These are two samples from the Chiquicamata area, one from Tocopilla coast, and one from the El Salvador mine. Descriptions of these rocks are given in ISHIHARA *et al.* (1984).

[1] Locality map of dated samples is given in ISHIHARA *et al.* (1984).

Analytical methods

Rb and Sr concentrations of whole-rock

samples were determined by X-ray fluorescence except for three samples that have high Rb/Sr ratios and were analyzed by isotope dilution. $^{87}Sr/^{86}Sr$ ratios were measured on a VG Isomass 54E mass spectrometer. All $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr$ ratio $= 0.1194$. Replicate analyses of the E and A standard gave an average $^{87}Sr/^{86}Sr$ ratio of 0.70808 ± 0.00002 (1σ). Isochron ages were calculated by the least-square method of YORK (1966), taking account of $\pm 5\%$ and 2% error in $^{87}Rb/^{86}Sr$ ratio for X-ray fluorescence and isotope dilution respectively, and $\pm 0.015\%$ error in $^{87}Sr/^{86}Sr$ ratio. Errors in Rb–Sr age and intercept were given on 2σ level.

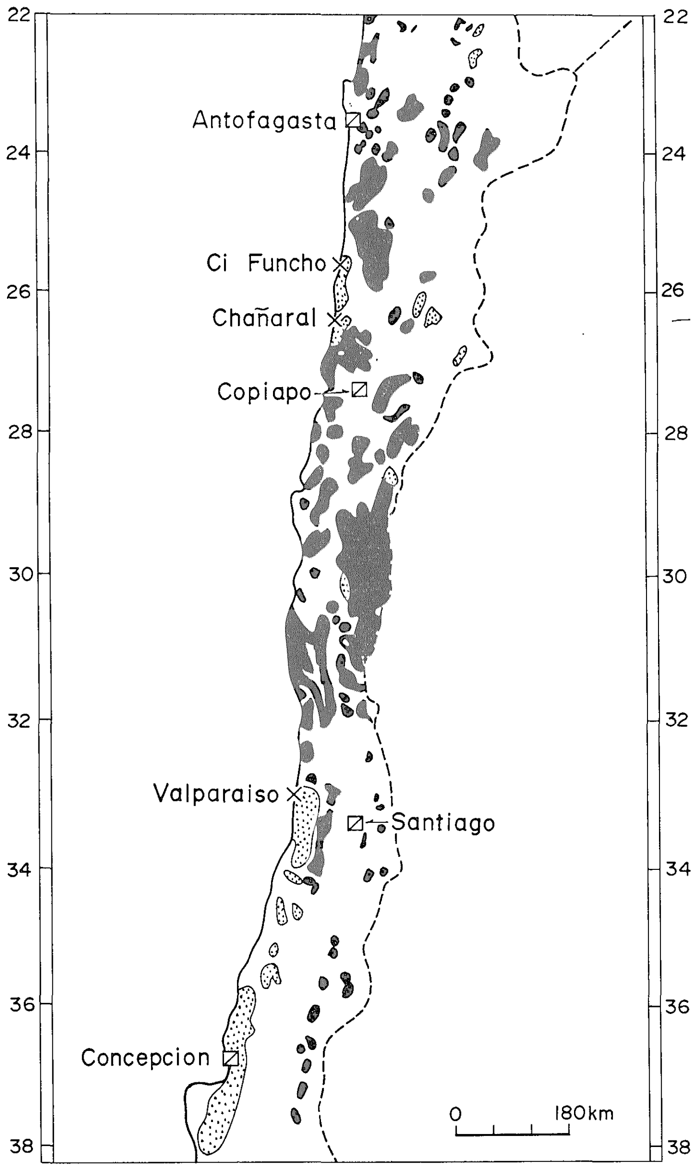

Fig. 1 Exposure of granitic rocks in northern Chile.
Solid area: Mesozoic-Cenozoic; dotted area: late Paleozoic.

Table 1 Rb–Sr analytical data for granitic rocks from northern Chile.

Sample No.	Rock type	Rb (ppm)	Sr_N** (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Valparaiso area					
79 SA 6 A	biotite granite	111	120	2.68	0.71798
6 B	biotite granite	103	119	2.51	0.71681
6 C	biotite granite	141	126	3.24	0.71997
6 D	muscovite-biotite granite (dike)	202.2*	14.42*	40.61	0.87761
Ci Funcho area					
79 CE 12	biotite granite	134.0*	46.25*	8.389	0.73759
13	hornblende-biotite granite	109	324	0.974	0.70996
14	biotite granite	140	181	2.24	0.71485
Chañaral area					
79 CH 2	biotite granite	225 224	77.6 75.0	8.40 8.65	0.73722
4	sericite-biotite diorite (xenolith)	69.9	50.6	4.00	0.72150
5	biotite granite	60.4	167	1.05	0.70775
7	muscovite-biotite granite	62.8	98.6	1.84	0.71014
8	biotite-muscovite granite (dikelet)	89.0	28.0	9.20	0.73043
9	biotite-muscovite aplite (dike)	191.7*	9.387*	59.14	0.88517

* Isotope dilution. ** Normal Sr

K–Ar age determination was carried out on biotite of granite from Esmeralda. Argon was extracted and purified in a pyrex, high vacuum system, and isotopic ratios of argon were measured on a Micromass 6 mass spectrometer. Potassium content was determined by atomic absorption analysis. Error in K–Ar age was given on 1σ level.

Decay constants used in age calculation are $= {}^{87}Rb\lambda = 1.42 \times 10^{-11}/y$, ${}^{40}K\lambda_{\beta} = 4.962 \times 10^{-10}/y$, ${}^{40}K\lambda_{e} = 0.581 \times 10^{-10}/y$, ${}^{40}K/K = 0.01167$ atom %. All quoted ages from other papers were recalculated using these constants.

Results and discussion

Rb–Sr analytical data for granitic rocks from the Valparaiso, Ci Funcho and Chañaral areas are given in Table 1, and K–Ar age for granite from the Esmeralda area (79SE14) is given in Table 2.

Valparaiso area

The Rb–Sr data for granites from the Valparaiso area are plotted in an isochron diagram (Fig. 2). Four samples yielded an isochron age of 296.3 ± 5.4 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70641 ± 0.00037. Sample 6D has an extremely high Rb/Sr ratio, and the isochron is much influenced by this point. Nevertheless, the age is correlated to Late Carboniferous and concordant to geologically estimated age. According to the compilation of age data by DRAKE *et al.* (1982), gneissic granitic rocks in the Valparaiso area yielded U–Pb zircon ages of 383–305 Ma. Also reported are K–Ar mineral ages of 270–295 Ma on granitic rocks of this area. These K–Ar ages, together with the present Rb–Sr whole-rock age, confirm the plutonism at about 300 Ma, although

Table 2 K–Ar age for granite from Esmeralda

Sample No.	Rock	Mineral	K_2O (%)	Rad ^{40}Ar (10^{-6}mlSTP/g)	Atm.^{40}Ar (%)	Age (Ma)
79 SE 14	biotite granite	biotite	7.96	53.2	7.7	196±6

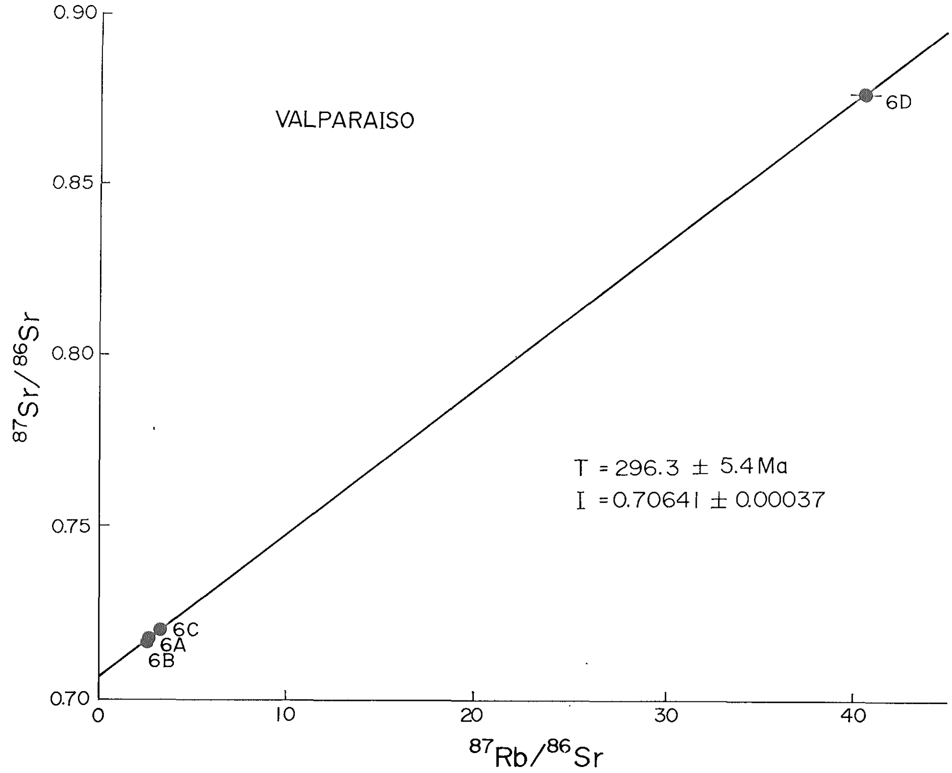

Fig. 2 Rb–Sr isochron plot for granites from the Valparaiso area.

there might have been an earlier plutonism in the area at around 400 Ma as represented by the zircon ages.

Ci Funcho area

Three-point isochron for granites from the Ci Funcho area gives an age of 262.2 ± 4.6 Ma with an initial ratio of 0.70635 ± 0.00018 (Fig. 3). The age is correlated to Early Permian and in accord with the geological estimation. McBride *et al.* (1976) reported a K–Ar biotite age of 272 ± 8 Ma for granodiorite (Sample No. Z-713) from Pta. Molina of the Ci Funcho area, locality of which (25°39′S, 70°38′W) is very close to 79CF12 and 13. Although the K–Ar age is slightly older than the Rb–Sr whole-rock age, both are still within the limit of concordance, and this suggests a simple thermal history for the granites.

The initial $^{87}Sr/^{86}Sr$ ratio of 0.70635 for the granites is much higher than that of 0.7033 reported for the above-mentioned granodiorite Z–713 (McNutt *et al.*, 1975). The Rb/Sr ratio (0.5) of the granodiorite is between those for 13 and 14, and no information is available to recognize the former as genetically different rock. Thus the cause of the discrepancy is not known.

Chañaral area

Four samples of granite from the Chañaral area define an isochron of 212.8 ± 8.6 Ma with an initial ratio of 0.70455 ± 0.00038 (Fig. 4). Two points (79CH2 and 4) are plotted above the isochron and excluded from the Calculation. Sample 2 is about 20 km east of samples 7, 8 and 9, and is very coarse-grained granite. Sample 4 is diorite xenolith included in the granite. These lines of evidence may be the cause for the deviation from the isochron.

Halpern (1978) reported Rb–Sr model age of 226 Ma for two adamellites from Chañaral area, assuming an initial $^{87}Sr/^{86}Sr$ ratio of 0.7045. Our result is slightly younger

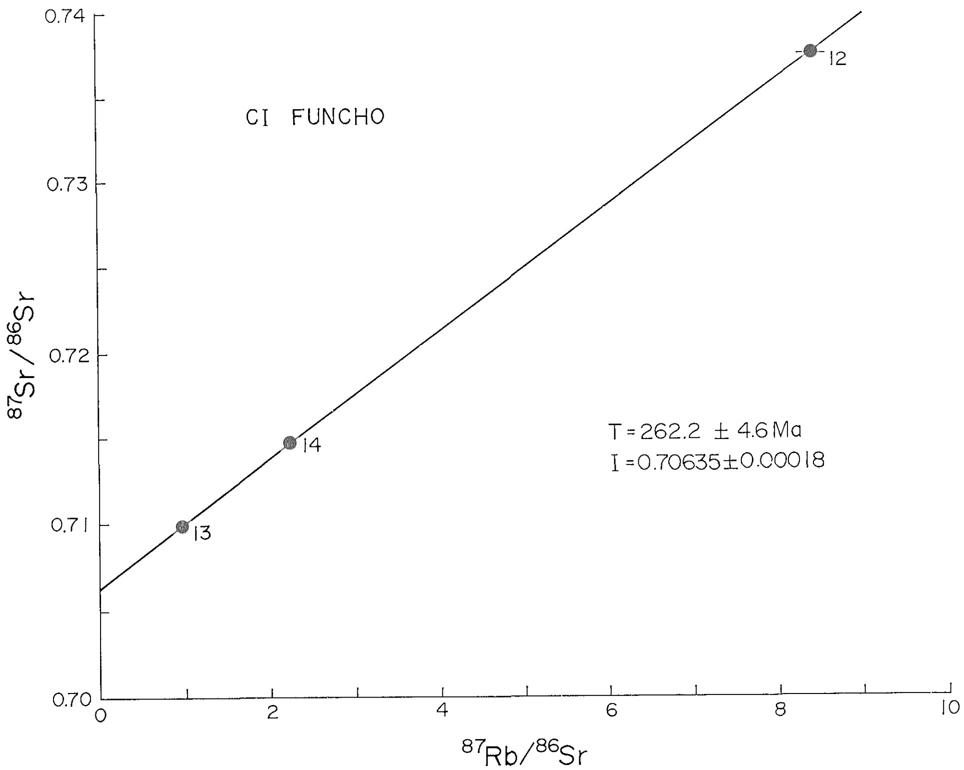

Fig. 3 Rb–Sr isochron plot for granites from the Ci Funcho area.

than this model age, but age difference is considered insignificant because of the uncertainty in the model age. Ferrar *et al.* (1970) reported a K–Ar biotite age of 192 ± 3 Ma for granodiorite (SH–163) for the Chañaral area, locality of which (26°25′S, 70°40′W) is close to that of 7, 8 and 9. They also reported 186–195 Ma ages on biotite from granitic rocks in the coastal region south of Chañaral.

In addition, Berg and Breitkreuz (1983) recently reported Rb–Sr biotite and U–Pb zircon ages on granitic rocks from the area south of Chañaral. The age of the so-called late Paleozoic granite is 199 Ma, whereas Mesozoic granitic rocks range from 190 to 124 Ma, gradually decreasing eastward. The former age, which was obtained on the El Barquito pluton near Chañaral, is similar to the K–Ar ages of Ferrar *et al.* (1970). All these mineral ages on so-called late Paleozoic granitic rocks are about 20 Ma younger than the Rb–Sr whole-rock age, and probably indicate the time of cooling for granites.

The age of 213 Ma for granites from the Chañaral area is correlated to earliest Jurassic or latest Triassic, but not to Paleozoic as estimated by geological evidence. As shown in Table 2, biotite of granite from Esmeralda gives a K–Ar age of 196 ± 6 Ma, which is similar to biotite ages for granites from the Chañaral area. Thus, so-called late Paleozoic granitic masses distributed along the coastal Ci Funcho-Chañaral area, whose extent is 25 km E–W and 125 km N–S, are divided at least into Permian (Pta. Molina) and late Triassic (Esmeralda and Chañaral). K–Ar ages of early Mesozoic have been reported at several localities in so-called Paleozoic batholiths of Chile. The chronological history may be more complicated than ever thought, and needs to be examined further by Rb–Sr

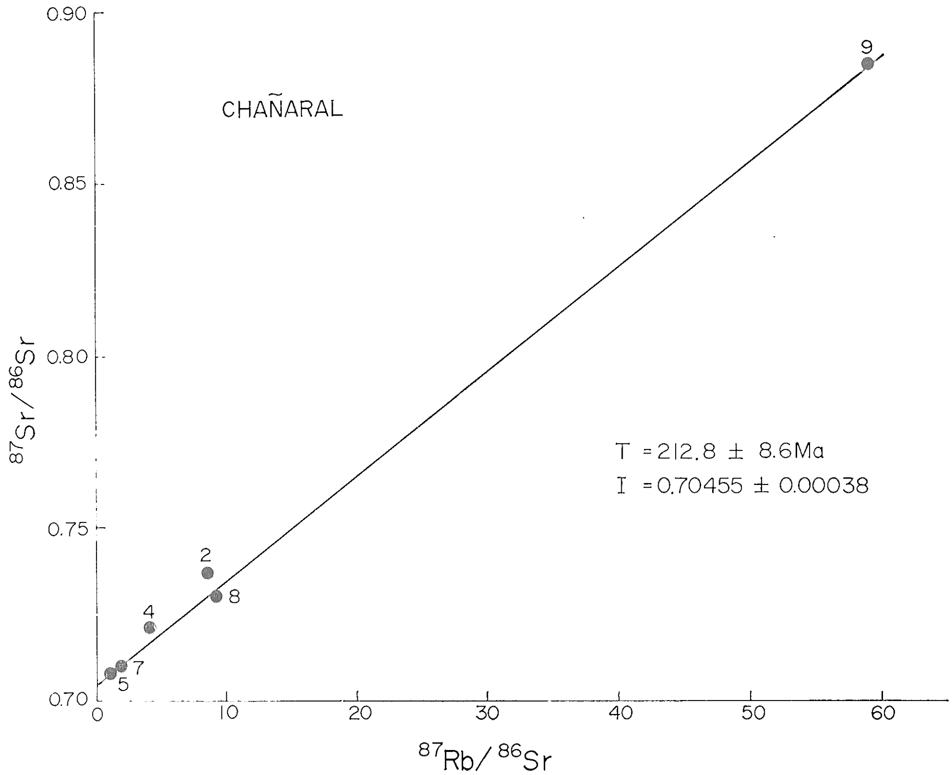

Fig. 4 Rb–Sr isochron plot for granitic rocks from the Chañaral area.

whole-rock and $^{40}Ar/^{39}Ar$ methods.

Initial $^{87}Sr/^{86}Sr$ ratio

The initial $^{87}Sr/^{86}Sr$ ratio for granites from the Chañaral area is 0.70455, and lower than those for the Valparaiso (0.70641) and Ci Funcho (0.70635) areas. BERG and BRETKREUZ (1983) also reported initial ratios of 0.7043∼0.7048 on granitic rocks from the coastal region near Chañaral. These relatively low initial ratios deny substantial crustal contribution to the granitoids. HALPERN (1978) reported initial ratios for various types of rocks from the El Salvador mining area. The lowest ratios, 0.7033 ± 0.0004, were obtained for the Paleogene porphyry, 0.7043∼0.7045 for quartz diorite of Cretaceous and Permian ages, and a higher ratio of 0.7072 for Permian granitic rocks. Apparently there is no rocks in the El Salvador area showing ages similar to that of the Chañaral area. The large variance but generally decreasing tendency in the initial $^{87}Sr/^{86}Sr$ ratio with age, as shown in the El Salvador area, is also found in the coastal granitoids studied. The finding of 212.8 Ma ilmenite-series granite with a low initial ratio of 0.70455 in the Chañaral area, however, makes the time gap between the late Paleozoic ilmenite-series and Jurassic magnetite-series granitic activities much shorter than ever thought. Initial $^{87}Sr/^{86}Sr$ ratios of Jurassic magnetite-series granitoids in the Chañaral area are also similar, varing from 0.7043 to 0.7059 (McNUTT *et al.*, 1975). Reconnaissance study was made on similar magnetite-series granitoids from Tocopilla-Antofagasta coast where Paleozoic basement occurs in limited extent. The initial $^{87}Sr/^{86}Sr$ ratio for quartz diorite is 0.70344 (Table 3), hence the Jurassic magmatism in this area appears to be originated in more undifferentiated materi-

Table 3 Initial $^{87}Sr/^{86}Sr$ ratios for mineralized magnetite-series granitoids of Mesozoic-Cenozoic age in northern Chile.

Sample No.	Rock type	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$	Assumed age (Ma)
79 CHU 3	sphene-bearing biotite-hornblende granodiorite (Fortuna)	84	702	0.347	0.70481	0.70464	35
79 CHU 7	hornblende-biotite pyroxene tonalite (Andina)	181	546	0.960	0.70491	0.70436	40
79 PT-L	biotite tonalite (L porphyry)	53	745	0.206	0.70451	0.70438	45
79 TC 8	hornblende-biotite pyroxene quartz diorite	12	332	0.105	0.70371	0.70344	180

Sample Locality 79 CHU 3: west of Chuquicamata open pit, 68°56.1′W, 22°16.2′S
79 CHU 7: *do.*, 68°58.5′W, 22°21.3′S
79 PT-L : Inca Adit of El Salvador mine, Dr. 8532N, 3956W
79 TC 8 : Tocopilla-Antofagasta coast, 70°20.4′W, 23°08.4′S

al than that of the Chañaral area.

McNutt *et al.* (1975) find eastward increase in initial $^{87}Sr/^{86}Sr$ ratio from 0.7022 to 0.7077 for mid-Cretaceous to Quaternary plutonic and volcanic rocks of the Central Andes. However, low initial $^{87}Sr/^{86}Sr$ ratios have been reported on small intrusives related to porphyry copper deposits along the western flank of the Andes, such as El Salvador (0.704; Gustafson and Hunt, 1975) and Disputada (0.7037~0.7044; Halpern, 1979). Our reconnaissance study also indicates relatively low values as 0.70464 and 0.70436 for the Fortuna granodiorite and the Andina tonalite at Chiquicamata, respectively, and 0.70438 for "L porphyry" at El Salvador (Table 3). Hence there are pulsations of magmatism with low initial ratio in the Mesozoic-Cenozoic magnetite-series granitic terrane, where major ore deposits occur associated with granitoids with relatively low initial $^{87}Sr/^{86}Sr$ ratios.

Conclusions

A Precambrian-looking, foliated granite of so-called late Paleozoic age in coastal Chile at 32°57′S (Valparaiso) was found to be late Carboniferous. Instead, massive granites occurring at 26°23′S (Chañaral) were identified to have an age close to the Triassic-Jurassic boundary. Relatively low initial $^{87}Sr/^{86}Sr$ ratios (0.70455~0.70641) of ilmenite-series granitoids suggest only small contribution from high Rb and matured continental crust. The initial ratios of magnetite-series granitoids of Jurassic onward are not much different from those of late Paleozoic ilmenite-series granites, although contrasting difference has been known on opaque mineralogy and major and minor element geochemistry between the two series of granitoids.

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北部チリーの後期古生代花崗岩類の Rb–Sr 年代と $^{87}Sr/^{86}Sr$ 初生値

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要　旨

北部チリー海岸地域 Valparaiso, Ci Funcho, Chañaral 地区のいわゆる古生代花崗岩類の Rb–Sr 全岩アイソクロン年代は，それぞれ 296.3±5.4 Ma, 262.2±4.6 Ma, 212.8±8.6 Ma, $^{87}Sr/^{86}Sr$ 初生値は 0.70641, 0.70635, 0.70455 である．また Esmeralda 産花崗岩の黒雲母による K–Ar 年代は 196±6 Ma である．Valparaiso 及び Ci Funcho 地区の年代は古生代後期を示し，地質学的に推定される年代とあうが，Chañaral 地区の年代は三畳紀—ジュラ紀境界の年代に近い．これらの年代測定結果から，この地域には先カンブリア時代の深成活動はなさそうであること，また Ci Funcho–Chañaral 地区では，いわゆる古生代花崗岩類にはペルム紀のものと中生代前期のものが存在することがわかった．

いわゆる古生代花崗岩類の $^{87}Sr/^{86}Sr$ 初生値は 0.70455–0.70641 であり，花崗岩形成に際して地殻物質の寄与は大きくなかったことを示す．一方鉱化作用を伴う中—新生代花崗岩類の初生値は 0.70344–0.70464 である．

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