MIOCENE CALC-ALKALINE PLUTONISM IN THE CHILEAN SOUTHERN ANDES

MIGUEL A. PARADA*, ESTANISLAO GODOY*, FRANCISCO HERVÉ* and RICARDO THIELE*

ABSTRACT The studied segment of the Chilean Southern Andes (41°00′-41°45′S) consists mainly of an extensive Miocene calc-alkaline plutonic belt which includes three granitoids units. The Cayutue unit consists of gabbro, quartz-gabbro, diorite and quartz-diorite with hornblende, clinopyroxene and hyperstene; the Reloncaví unit is composed by biotite + hornblende + hyperstene tonalites and the Chapo Lake unit includes biotite + muscovite leucogranitoids. The latter unit is restricted to small plutons that do not exceed 5% of the belt. Small bodies of hornblende-gabbro and andesite porphyry are recognized within the Cayutue granitoids. Whole rock Rb-Sr isochrons on Reloncaví granitoids indicate slightly older ages (26 ± 2 Ma; 16 ± 1 Ma) than K-Ar biotite ages (10.3-12.2 Ma), as well as low initial 87Sr/86Sr ratios (0.7031 and 0.7045). The emplacement of the Miocene plutonic belt was controlled by a NNE-trending fault system, active since the Oligocene. The plutons have a minimum emplacement depth of 6 km and the subsolidus uplift could have occurred at a rate of 0.4-0.6 km/My. The high Al2O3 contents and the FeO*MgO vs FeO* of the studied rocks point to a calc-alkaline character. The low K2O contents of some samples are, however, similar to those of tholeiitic suites. The Reloncaví unit and Peninsula Rollizos gabbros seem to result from a plagiorock + hornblende fractionation process of a Cayutue magma type derived from a one-stage partial fusion of an upper mantle source, whereas the lago-Chapo unit could have been generated in the continental crust.

RESUMO O segmento estudado dos Andes chilenos (41°00′-41°45′S) consiste principalmente em um extenso cinturão plutônico epizonal do Mioceno, que inclui três unidades granitoides. A Unidade Cayutue consiste em gabros, quartzo gabros, dioritos e quartzo dioritos com hornblenda, clinopiroxeno e hiperstênio; a Unidade Reloncaví é composta por biotita + hornblenda + hiperstênio tonalitos e a Unidade Lago Chapo inclui biotita + muscovita leucogranitoides. A última unidade é restrita a pequenos plutons que não excedem 5% do cinturão. Pequenos corpos de hornblenda gabro e andesito pôrfirito são reconhecidos nos granitoides de Cayutue. As jécorras de Rb-Sr da rocha total dos granitoides de Reloncaví indicam idades levantadas ao redor de 16 Ma (15.4 Ma) que as idades K-Ar de biotitas (10.3-12.2 Ma), bem como baixas razões iniciais 87Sr/86Sr (0.7031 e 0.7045). A colocação do cinturão plutônico mioceno foi controlado por um sistema de falhas de direção NNE, ativo desde o Oligoceno. Os plutons têm uma profundidade mínima de colocação de 6 km e a aporte subsolidus deve ter ocorrido a uma razão de 0,4-0,6 km/My. O alto teor de Al2O3 e a razão FeO*MgO versus FeO das rochas estudadas apontam para um caráter calcio-alkalino. Os baixos teores de K2O de algumas amostras são, entretanto, semelhante aos das suítes toleíticas. A Unidade Reloncaví e os gabros da Península Rollizos parecem resultar de um processo de fracionamento de plagiocláiso-hornblenda de um magma tipo Cayutue derivado de um estado de fusão parcial de uma fonte do Manto Superior, enquanto a Unidade Chapo pode ter sido gerada na crosta continental.

INTRODUCTION The granitoids of the studied area (41°00′-41°45′S) belong to a NNE-trending, 50 km wide plutonic belt, which crops out along most of the Andes between 39° and 42°S (Fig. 1). Directly south of 42°S the belt widens further and is known as the Patagonian batholith. They are exposed east of a Cenozoic graben (Central Valley), whose westward uplifted block is made up of micaschists and disrupted ophiolites of a Late Paleozoic subduction complex (Hervé et al. 1981), and volcanic rocks of the Upper Tertiary coastal volcanic belt (Vergara & Munizaga 1974). The Sotomó-Chaiguenes High Grade Metamorphic Complex (SChMC), a probable equivalent of the above mentioned micaschists and the Leña hornfelsic sandstones (Mioceno?) are the only known host rock of the batholith (Thiele et al. 1985). Stratovolcanoes of basaltic composition with minor amounts of andesite and dacite (Osorno, Calbuco, La Picada), and numerous smaller eruptive centers of basaltic composition were built mainly during the Quaternary on top of the granitoids.

Recent radiometric dating (Munizaga et al. 1984) has shown that apart from small Paleozoic to Jurassic plutons north of 40°S, the plutonic belt is Miocene in age. It extends into Argentina, where it is flanked eastward by a Late Cretaceous plutonic belt down to 45°S (González & Valvano 1979, González & Lizuain 1984). Research on the geology, geochemistry, and emplacement features of this young and short-lived plutonism is, however, lacking. Date presented in this paper, though restricted to a small area, are used to discuss a petrogenetic model of the plutonic belt.

PLUTONIC UNITS Three units may be distinguished in the plutonic rocks of the area, based on field relationships, texture and modal composition: Reloncaví, Cayutue and Chapo Lake. Small bodies of amphibole gabro (Peninsula Rollizos gabbro) and porphyritic andesites (Petrohué andesite porphyry) have also been recognized (Fig. 2). Contacts between the units were mostly interpolated by air photographs because good rock exposures are restricted to shorelines.

Reloncaví Unit Medium to fine grained biotite-hornblende ± pyroxene tonalites, and minor biotite-hornblende granodiorites are found in this unit (Fig. 3). They cover half of the area occupied by granitoids forming two parallel NE-trending stripes (Fig. 2). Much of the western one underlies volcanic rocks and debris of the Calbuco volcano, while the eastern one, crops out on both sides of the Reloncaví fjord. Massive sandstones (Lenga hornfelses), probable equivalents of the Miocene Ayacara Formation, and rocks of the SChMC are intruded by tonalites of this unit. Andalusite-sillimanite gneisses found in the complex are interpreted as contact metamorphism assemblages. Diorite stocks from the Cayutue unit were found within Reloncaví unit showing gradational boundaries. Sympeltic mafic dykes and monzogranitic microporphyritic dykes intrude the Reloncaví rocks.

The color index (CI) of the granitoids varies between 20 and 36. They contain zoned plagioclase, intestinal quartz, biotite, hornblende ± ortho and clino.pyroxene ± interstitial
K-feldspar. Hornblende is poikilitic, it frequently includes plagioclase and its margins are often replaced by biotite.

**Figure 1** - Geological setting: 1- coastal range metamorphics (Upper Palaeozoic) and SCHMC; b. granitoids (Upper Palaeozoic); 2- a. Mesozoic and Cenozoic sedimentary and volcanic rocks; b. Recent strato-volcanoes; 3- Quaternary glacial and alluvial sediments; 4- Miocene plutonic belt; 5- Cretaceous plutonic belt

**Cayutue unit** The rock types of this unit are medium to fine grained qz-gabbro, diorite and qz-diorites with hornblende ± pyroxene (Fig. 3) and CI about 29. Minor amounts of hornblende tonalites are also found. This unit covers the second half of the granitoid area, and was intruded in NE-trending stripes which alternate with those of the Reloncaví unit. Dykes are more common in this unit which is also intruded by the Petrohué andesite porphyry. Peninsula Rollizos gabbro seems to grade toward the more mafic components of the Cayutue unit.

Texture is panidiomorphic to subidiomorphic. Medium-grained rocks crop out mainly around the Todos los Santos lake, Cayutue inlet and Reloncaví fjord. Fine-grained types have been found at Chapo Lake and north of southern Reloncaví fjord. The modal mineralogy includes zoned plagioclase, hornblende and interstitial quartz. Clinopyroxene, orthopyroxene, and biotite are minor constituents, the latter replaces hornblende. Both isolated and hornblende-mantled ortho and clinopyroxene crystals occur in the fine-grained granitoids. Most of the rocks of this unit show mineral orientation.

**Figure 2** - Geological map of the studied area: 1- Quaternary sediments; 2- lava flows and pyroclastics of modern stratovolcanoes, smaller eruptive centers and slightly older volcanic rocks; 3- Peninsular Rollizos gabbro (Miocene); 4- Chapo Lake unit (leucogranitoids, Miocene); 5- Cayutue unit (gabbro, diorites and qz-diorite, Miocene); 6- Reloncaví unit (tonalites and granodiorites, Miocene); 7- Sotomé-Chaïquenes High Grade Metamorphic Complex (SCHM: schists and gneisses, ?Palaeozoic); 8- cones of smaller eruptive centers (Holocene)

**Chapo Lake unit** This leucogranitoid unit includes biotite tonalites, syenites, and granites (Fig. 3) with minor muscovite. It is represented by only two small independent plutons, intruding the Reloncaví unit. The Chapo Lake unit intrusion followed closely in time to the Reloncaví unit, a fact that is suggested by the lack of chemical interaction and thermal disequilibrium in the contacts.

Rocks are medium to fine-grained, locally porphyritic and often with a tectonic mineral orientation. K-feldspar often develops perthitic and poikilitic phenocrysts. Quartz is interstitial to granular and the plagioclase is optically unzoned with the exception of the bigger plagioclase crystals. Biotite is usually chloritized and muscovite, found confined to the feldspar grains, is a late magmatic mineral.
GEOCHRONOLOGY Six biotite K-Ar dates (Munizaga et al. 1984) and two Rb-Sr whole rock isochrons (Fig. 4; Munizaga et al. in prep.) are variable from granitoids of the Reloncaví unit. The K-Ar ages range from 12.8 to 10.3 Ma and the Rb-Sr isochron gave 16 ±1 Ma and 26 ±16 Ma, with initial 87Sr/86Sr ratios of 0.7045 and 0.7031, respectively.

The K-Ar samples are evenly distributed between the western and eastern stripes of the Reloncaví unit. The former is slightly older (12.8-12.2 Ma) than the latter (10.7-10.3 Ma). This small, yet significant age difference of the Reloncaví granitoids, points to a rather independent cooling and uplift history of each stripe.

Even though both Rb-Sr isochrons gave concordant ages, the older one is less reliable owing to a sample distribution restricted to the low Rb/87Sr values. The Miocene crystallization age of the Reloncaví unit is extended to the remaining units, which are here considered to be almost contemporaneous intrusions.

EMPLACEMENT AND UPLIFT The NE trend of the two main plutonic units is controlled by regional lineaments and faults of a similar orientation, oblique to the NNE-trending Liquiñe-Ofqui Fault Zone (LOFZ; Thiele et al. 1986). Dextral movements took place in the fault zone during Oligocene to Miocene times (Hervé 1976, Hervé et al. 1979) and may have originated a set of related en echelon NE tension faults. Emplacement of the Miocene plutonic strips may have been favoured by these faults.

A depth of emplacement close to 6-7 km (2 kb) may be estimated by means of PT curves for the assemblage andalusite-sillimanite-Kfeldspar-muscovite-quartz. This assemblage is present in a hornfelsic granitic gneisses in the SchMC. If a 500°C/km regional geothermal gradient before the intrusions is assumed, a temperature of 300-3500°C may be calculated at such depth. This temperature range is similar to the Ar retention temperature in biotite.

Based in the Rb-Sr vs K-Ar age differences and assuming that the plutons were not invaded by the erosion during the quaternary glaciations, the limits on the rate of uplift may be estimated. If uplift started soon after crystallization (16 Ma), the rate was close to 0.4 km/Ma; however if uplift began 12 Ma ago, after thermal equilibrium (300-3500), between the plutons and the host rocks was reached, the rate of uplift increases to 0.6 km/Ma. The intensive erosion, which took
place during uplift, is responsible for the small amount of older host rocks and the lack of related volcanics. The erosion debris were deposited either in the Central Valley or infilled the oceanic trench.

GEOCHEMISTRY A wide compositional range in which intermediate and basic types prevail results from the major element contents of the granitoids (Table 1, Fig. 5a). Their oxide variation diagrams show smooth distribution curves in which the Peninsula Rollizos gabbros do not fall in the trends as is expected by their probable cumulate nature. Al2O3 and FeO*/MgO vs FeO* ratios are similar to those of calc-alkaline series (Fig. 5b) although some of the low K2O values (Fig. 5c) may be compared to those of tholeitic series.

REE analyses by INAA were determined in four representative samples. Chondrite-normalized patterns are shown in figure 6. A hornblende gabbro (PET-20) and two-pyroxene diorite (PET-62) from Cayutue unit have low REE contents (seven to 20 times chondrite). They exhibit relatively flat patterns and a small negative Eu anomaly in PET-62 (Fig. 6a). The two Cayutue samples fall within the range of the Holocene basalts of the area. Compared with the average of the low-SiO2 andesites sampled at Ancud (420S; Lopez-Escobar et al. 1976) in the Miocene coastal volcanic belt (100 km to the west of the studied area), the Cayute samples have lower REE abundances, but similar (La/Lu)N ratio.

The variation in chondrite-normalized REE abundance of a hornblende + biotite tonalite (CAN-342) and biotite + muscovite monzonte (PET-96) from Reloncaví and Chapo Lake unit respectively are similar (Fig. 6b). PET-96 exhibits, however, higher REE contents. Both samples are LREE enriched and HREE depleted. The Chapo Lake monzonte shows a slight negative Eu anomaly. Picture from the Miocene coastal volcanic belt at Los Angeles (37°30'S) which have similar SiO2 content than CAN-342 tonalite shows significantly higher REE contents and slightly lower (La/Lu)N ratio (Lopez-Escobar et al. 1976). The Central Chile Late Tertiary granodiorites, however, have similar HREE abundances but slightly higher LREE contents and larger Eu anomaly (Fig. 6b) than the studied samples (Lopez-Escobar et al. 1979).

Table 1 – Major (wt. %) and trace element (ppm) abundances of representative samples from the granitoids units and Peninsula Rollizos gabbro. Major element compositions were determined by wet chemical analysis at the Department of Geology, University of Chile. Trace elements were determined by instrumental neutron-activation analysis at the Comisión Chilena de Energía Nuclear using techniques of Cortes (1984)

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PETROGENETIC DISCUSSION

A co-singularity of the two largest plutonic units (Reloncavi and Cayutue) is compatible with their field relationships, their spatial and temporal proximity and with their similar chemical-mineralogical characteristics. The available geochemical data favor a fractionation model in order to explain the compositional variation either within these units or between them. The Cayutue sample, for example, shows a slight REE enrichment and a significant Sc, Cr and Co depletion (Table 1) with respect to the SiO$_2$ content, which points to clinopyroxene fractionation. In fact, clinopyroxene, orthopyroxene, and hornblende have low (≤1) crystal/andesite-basaltic liquid REE partition coefficients but the Sc, Cr, and Co partition coefficients are, sufficiently high only in the first phase (Lindstrom & Weill 1978, Irving 1978) to produce such depletion.

Concerning the compositional variation between Cayutue and Reloncavi units, the modal mineralogy and the fractionated Eu anomaly- free REE pattern of the Reloncavi sample are consistent with presence of hornblende and plagioclase in the residual phase assemblage after fractionation of a Cayutue magma type. The large amount of crystallizing hornblende could balance the Eu depletion produced by plagioclase crystallization. It is worth noting that this model is also consistent with the cumulate nature of the Peninsula Rullizos hornblende gabbro.

Figure 5 - A. Oxide variation diagrams for the Miocene granitoids; closed circles: Chapo Lake unit; open circles: Reloncavi unit; crosses: Cayutue unit; closed triangles: Peninsula Rullizos gabbro; asterisk: andesite porphyry. B. FeO* vs FeO*/MgO; dashed line separates tholeiitic from calc-alkaline field (Miyashiro 1975). A typical calc-alkaline trend (Amagai) is included for comparison. Symbols as in figure 5a. C. K$_2$O vs SiO$_2$ classification diagram after Peccerillo & Taylor (1976). Dashed field includes lava flow compositions from Osorno and Calbuco volcanoes. Symbols as in figure 5a, except open triangle, which represents a dacitic dome sample from Puyehue volcano. D. Calc-calkali ratio vs silica diagram of the studied granitoids. Dashed lines represent trends of migmatic arcs with different maturity after Brown (1982). The field of modern calc-alkaline andesites given by Brown (op. cit.) is also included.

Figure 6 - Chondrite-normalized REE pattern of Miocene igneous rocks. A. Gabbro (PET-20) and diorite (PET-62) from the Cayutue unit; field: range of Holocene basalts of the area, broken line: Miocene low SiO$_2$ andesite average at Ancud. B. Tonalite (CAN-342) and monzonite (PET-96) from Reloncavi and Chapo Lake unit respectively, broken line: Miocene dacite at Los Angeles; dashed-dotted line: central Chile Miocene granodiorite average.

Whichever is the source of the Reloncavi and Cayutue units it must be able to generate great volumes of dioritic and tonalitic magma and should therefore be (in the unlikely case of total fusion) at least as basic as the Cayutue and Reloncavi granitoids.

The Reloncavi unit $^{87}$Sr/$^{86}$Sr initial ratios (0.7031 and 0.7045) are lower than those obtained in the Paleozoic subduction complex (0.706-0.712) at Pichilemu (34°30'S) (Hervé et al. 1984), which is therefore an unlikely source rock. Both the low initial ratio (0.7031) of the Reloncavi unit and the high CaO(Na$_2$O+K$_2$O) ratios in all the samples (Fig. 5d) are similar to those found in immature arc rocks (Brown 1982), where magmas are generated by one-stage fusion of subcrustal material. Even though in this case the nature of the subcontinental rocks is speculative, the lack of earlier magmatic events in the area, rule out a fusion of pre-existing underplated material. The low-fractionated REE pattern of the Cayutue unit granitoids is compatible with an origin by partial fusion of garnet-free mantle rocks. A common source for the granitoids and for the Holocene volcanic rocks (Osorno and Calbuco and other eruptive centers) is suggested by the similar REE patterns (Fig. 6a), SiO$_2$ and K$_2$O.
contents (Fig. 5c) and Mg/(Mg+Fe*) and Sr87/Sr86 initial ratios values (for ratios in volcanic, see Moreno, et al. 1985, Lahsen et al. 1985). The low Sr initial ratios (0.7043-0.7406) and the primitive REE patterns of the Holocene volcanics in the area have also been interpreted as evidence of an origin from the upper mantle (op. cit.).

The enriched REE pattern of the low-SiO2 andesites and dacite from the Upper Tertiary coastal volcanic belt compared to the Cayutue and Reloncaví REE pattern respectively (Fig. 6) may be explained by contamination of the source in incompatible elements, probably released during subduction of oceanic crust at shallow depth. Such contamination, therefore, did not significantly affect the eastern coeval plutonics and volcanics. Furthermore, crustal contamination in all the Upper Cenozoic igneous rocks of the area could not be significant due to fast magmatic ascent along deep faults (i.e., LOFZ) cutting a rather thin continental crust (Lomnitz 1962, Herron 1981). Fusion of the underlying mantle to originate the Miocene-Holocene magmatism could have been enhanced by decompression associated to these deep faults.

The source of the Chapo Lake felsic magma is also speculative. According to experimental results obtained by Wylie et al. (1976), granites could not have originated by high-pressure melting of either peridotite, basalt or subducted oceanic sediments. Therefore they restrict the origin of granites to crustal environments under PT conditions achieved during regional metamorphism. Under such conditions the small volumes of this unit could represent liquids from low melting degrees of basaltic materials, which is in agreement with Spulber and Rutherford's (1983) experiments on basalt melt at low pressure. The fractionated REE pattern of the sample PET-96 (Fig. 6b) supports this hypothesis in which the hornblende is a REE-consuming residual phase. Moreover, the presence of muscovite in some Chapo Lake granitoids suggests a source containing pelitic rocks. The participation in the origin of the Chapo Lake granitoid of both metabasaltic rocks in the amphibolite facies and metapelites favors the Palaeozoic subduction complex (which include both rock types) as a probable source.

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REFERENCES


