Cenozoic tholeiitic volcanism in the Colbún area, Linares Precordillera, central Chile (35°35'-36°S)

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ABSTRACT

Upper Eocene to Middle Miocene volcanic rocks are found in the Colbún area, Linares Precordillera, central Chile (35°35'-36°S). Based on stratigraphic characteristics, K-Ar and Ar-Ar dating, two different units are recognized: **1-** a Lower Unit (Upper Eocene to Upper Oligocene), in which silicic volcanic rocks predominate in the lower level and basic volcanic rocks in the upper, and **2-** an Upper Unit (Lower to Middle Miocene), consisting of aphanitic basalts and rhyolitic welded-tuffs. Geochemical characteristics of the Colbún volcanic rocks, such as their low K_2O contents, high MgO/FeO ratios, flat REE patterns, MORB normalized Nb to Sc close to unity, relatively low initial Sr isotopic ratios (0.703575-0.704028) and high initial Nd isotopic ratios (0.512919-0.513003) are all consistent with a tholeiitic affinity and a low degree of crustal involvement in the evolution of the parental magmas. Pb isotopic relationships and the enrichment of some incompatible elements such as K, Rb, Sr and Ba suggest recycling of subducting Nazca plate material. This was accompanied by crustal thinning and development of caldera type structures. The Colbún rocks are the isotopically most primitive rocks of the Chilean Andes. Geochemical relationships suggest that these rocks were emplaced in a back-arc, intracontinental, postorogenic extensional geotectonic environment. The Colbún magmas evolved mainly by closed crystal fractionation from primary magmas generated in the mantle. The chemical and isotopic similarities exhibited by rocks ranging in age from the Late Eocene to Middle Miocene suggest that the sources and processes, involved in the generation and evolution of these magmas, were more or less constant during this time span of 20 m. y.

Key words: Tholeiitic, Primitive magmas, Petrogenesis, Cenozoic, Precordillera, central Chile.

RESUMEN

Volcanismo toleítico Terciario en el área de Colbún, Precordillera de Linares, Chile central (35°35'-36°S. En la Precordillera de Linares, Chile central (35°5'-36°S), afloran rocas volcánicas, cuyas edades varían del Eoceno Superior al Mioceno Medio. Sobre la base de criterios estratigráficos y dataciones K-Ar y Ar-Ar, se han diferenciado dos unidades: **1-** una Unidad Inferior (Eoceno Superior a Oligoceno Superior), con predominio de rocas volcánicas silíceas en la base y básicas en el nivel superior y **2-** una Unidad superior (Mioceno Inferior a Medio), con

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basaltos afíricos y tobas soldadas riolíticas. Las características geoquímicas de las rocas volcánicas de Colbún, tales como bajos contenidos en K_2O, razones MgO/FeO altas, patrones de REE planos, abundancia normalizada con respecto al MORB cercana a la unidad para los elementos Nb a Sc, razones isotópicas iniciales de Sr relativamente bajas (0.703575-0.704028) y relativamente altas de Nd (0.512919-0.513003), son consistentes con una afinidad toleítica y con un grado de contaminación cortical bajo en la evolución de los magmas parentales. Las relaciones isotópicas de Pb y el enriquecimiento en algunos elementos incompatibles, tales como K, Rb, Sr y Ba, sugieren un reciclamiento de material subductado de la placa de Nazca, el cual estuvo acompañado por un adelgazamiento cortical y el desarrollo de estructuras tipo calderas. Isotópicamente, las rocas de Colbún son las más primitivas de los Andes chilenos. Relaciones geoquímicas sugieren que estas rocas se emplazaron en un ambiente geotectónico de trasarco, intracontinental, postorogénico y extensional. Los magmas de Colbún evolucionaron, principalmente, por cristalización fraccional a partir de magmas primarios generados en el manto. Las semejanzas químicas e isotópicas presentadas por estas rocas emplazadas entre el Eoceno Superior y el Mioceno Medio sugieren que las fuentes y procesos, involucrados en su génesis y evolución, se mantuvieron relativamente constantes durante este lapso de tiempo de 20 millones de años.

Palabras claves: Toleítico, Magmas primitivos, Petrogénesis, Cenozoico, Precordillera, Chile central.

INTRODUCTION

The western side of the Andean Cordillera (Precordillera) is composed mainly of Cenozoic volcanic and continental volcanoclastic rocks forming a continuous belt of stratified rocks, dykes and subvolcanic bodies between latitudes 33 and 37°S (Vergara and Drake, 1978, 1979; Karzulovic *et al.*, 1979.; Thiele, 1980; Vergara, 1985; Troncoso and Muñoz, 1988; Gana and Wall, 1996; López-Escobar and Vergara, 1997). This belt has been labeled with different names based on the latitude: in the northern sector (33-34°S) it is called the Abanico Formation (Thiele, 1980; Gana and Wall, 1996), southward (34.5°S), it is known as Coya-Machalí Formation (Klohn,1960; Charrier *et al.*, 1990) and in the Linares Precordillera (35°35'-36°S), where the area of the present study is, it is named the Colbún Formation (Karzulovic *et al.*, 1979).

The Linares Precordillera region is characterized by a dense vegetation cover that hinders any geological field work. As a result of the construction of the Colbún and Machicura hydroelectric power plants, the Colbún area is an exception. Together with the power plants, a dam, roads, trails, tunnels and quarries were built, exposing quality outcrops, allowing to establish the stratigraphy and main structural characteristics of the Colbún area. On the basis of previous works, mainly related to the Santiago Precordillera (northern sector; Vergara and Drake, 1979; Villarroel, 1990; Vergara *et al.*, 1993; Gana and Wall, 1996; Vatin-Perignon *et al.*, 1996), the authors postulate that the Cenozoic volcanic and subvolcanic rocks found in the Colbún area are part of the Precordillera belt, running between 33 and 37°S.

This paper deals with the geological setting, petrography, radiometric ages and the geochemical characteristics of the Upper Eocene-Middle Miocene volcanic rocks of the Colbún Formation. This formation is located in the Linares Precordillera, limited to the north by the Maule river (35°40'S), and the Putagán river in the south (35°50'S) (Fig. 1). The main objective of this paper is to contribute to a better understanding of the geochronology and geochemistry of the Cenozoic magmatism of this segment of the central Chile Andean Cordillera, an example of isotopically primitive volcanism of tholeiitic affinity, associated with crustal extension and ignimbritic pyroclastic flows.

REGIONAL GEOLOGY AND STRATIGRAPHY

Karzulovic *et al.* (1979) defined the volcanic and volcaniclastic rocks of the Colbún area (35°40'-35°50'S) as the Colbún Formation. This formation is exposed in the Andean Precordillera of Linares, forming a NNE belt, 11 km wide and 70 km long. Preliminary K-Ar and Ar-Ar age determinations

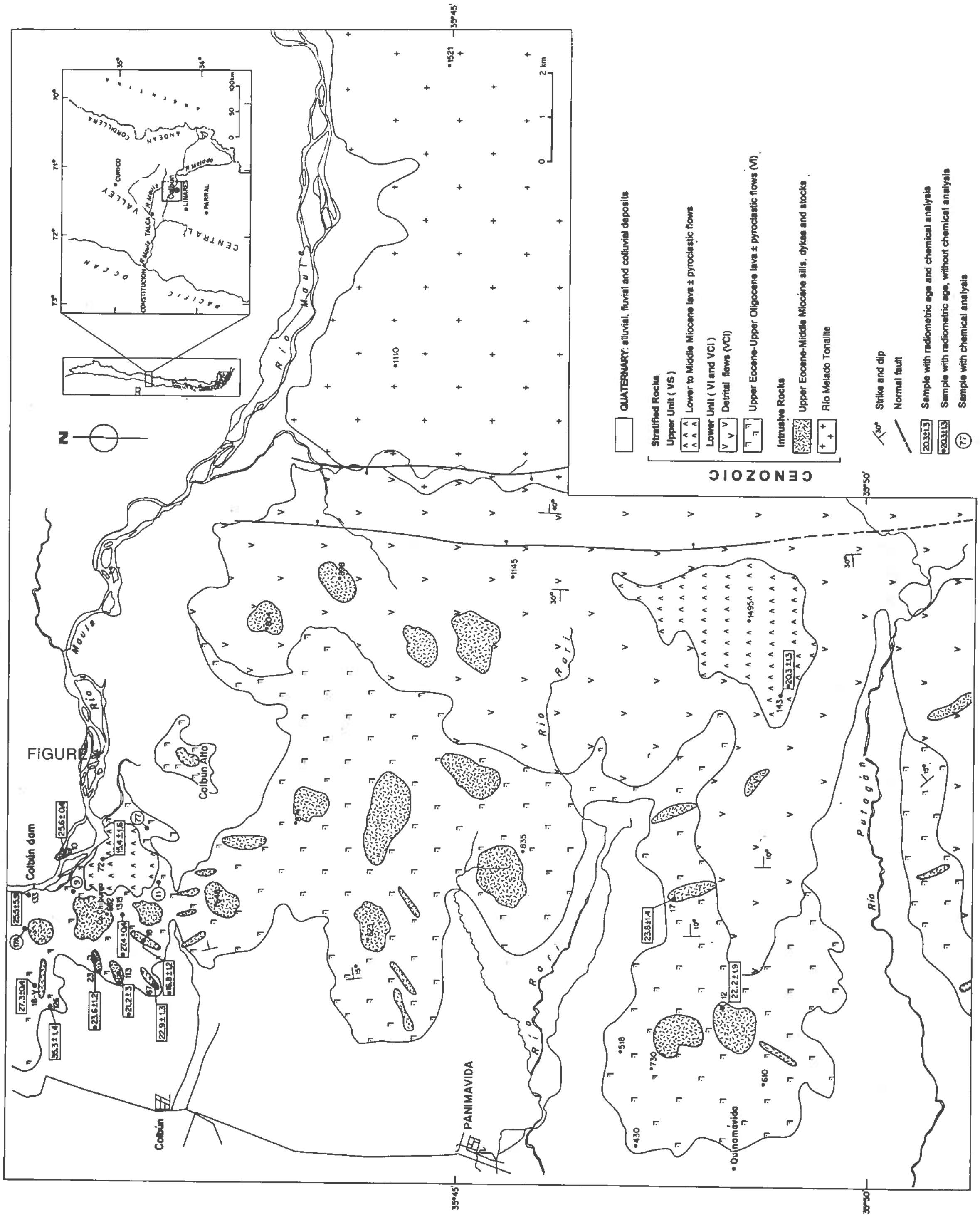

FIG. 1. Geological sketch map of the Colbún area. The locations of the samples analyzed for geochronology and geochemistry (Tables 1, 2 and 3) are shown. Also included are the samples of

yielded an Upper Oligocene-Miocene age (Karzulovic *et al.*, 1979; Vergara *et al.*, 1996). Six new K-Ar age determinations, reported in this paper, confirm this age range for the Colbún Formation.

Since these rocks are continental in nature and lack fossils of chronostratigraphic value, different authors have assigned different ages to the Colbún volcanic and volcanoclastic rocks. In fact, these rocks were first considered as the eastern extension of the Lower to Middle Cretaceous units found in the Coastal Cordillera (González and Vergara, 1962), later they were considered as the western extension of the Pliocene-Pleistocene units (Cola de Zorro Formation; Vergara and Muñoz, 1982) outcropping in the Andean Cordillera (Duhalde and Rehnfeldt, 1982). The Geologic Map of Chile, edited by the Servicio Nacional de Geología y Minería (SERNAGEOMIN, 1982) presents the Colbún rocks forming a thin belt of Cenozoic volcanic rocks in fault contact with Upper Cretaceous and lower Cenozoic rocks. Vergara (1985) described the Colbún Formation as an approximately 1,500 m thick sequence consisting of volcanic rocks at the base and volcanoclastic rocks at the roof. The strata from this formation are homoclinal, dipping gently eastward on its western margin. When in contact with the Río Melado Tonalite (23 Ma; Drake *et al.*, 1982), the strata dip westward. The strata form a gentle 11 km wide synclinal. The strike of its axis is N5-10°E, changing to north-south close to the contact with the Río Melado Tonalite. In the contact zone, the volcanoclastic rocks exhibit effects of contact metamorphism and hydrothermal alteration. In this same zone, the Río Melado Tonalite is cut by two north-south normal faults (Fig. 1). These faults generate a graben that produces a topographic depression.

Rocks of the Colbún Formation can be grouped into two main units, separated by an erosional unconformity (Fig. 2). The older Lower Unit, (VI and VCI) contains lava flows with K-Ar and Ar-Ar ages varying from 35.3 to 27.4 Ma (Upper Eocene to Upper Oligocene; Table 1 and Figs. 1 and 2). The younger Upper Unit, (VS) contains lava flows with K/Ar ages varying from 20.3 to 15.4 Ma (Lower to Middle Miocene; Table 1). Sills, dykes, volcanic necks and stocks, with K-Ar ages in the 35-15 Ma range, are also found.

The Lower Unit (VI and VCI) is characterized by two contrasting lithofacies (Fig. 2, part B). The lower lithofacies (VI) is essentially volcanic and is cut by Miocene dykes and stocks (Fig. 2). The upper lithofacies (VCI) is mainly volcanoclastic and consists of detrital flow deposits. The lower lithofacies (VI) is further subdivided into two levels of volcanic rocks: a lower one which is silicic and an upper which is basic.

The silicic level of the lower lithofacies (VI) is about 200 m thick and consists of thinly laminated and stratified cinder-tuffs, rhyolitic breccias and breccia-tuffs, dacitic to rhyolitic welded-tuffs, glassy silicic flows, pumice flow tuff and rhyolitic fall cinder-tuff (Fig. 2). This package of silicic rocks is very homogeneous in composition, with the exception of intercalations of thin lenses of basic to intermediate lava flows and volcanoclastic sediments.

Associated with these silicic rocks are intrusive and extrusive domes, with strong flow banding, and poorly sorted breccias, such as the Colbún breccia (Karzulovic *et al.*, 1979). The latter breccia varies in thickness from 20 to 80 m. It is heterolithologic and composed of angular lithic clasts, whose size varies from 3 cm to 1 m in diameter. The matrix is a cinder tuff, with abundant fragments of collapsed pumice. In the lower level of the Colbún breccia there exists a 20 to 30 cm layer of pumiceous tuff, exhibiting a foliation parallel to the strata. Overlying this breccia, exclusively in the Colbún dam area, is an 80 m thick deposit of cineritic volcanoclastic material. The latter deposit is composed of 20 to 30 cm thick layers, each showing inverse grain-size gradations.

In the same stratigraphic horizon as the silicic level of the Lower Unit (VI), at the locality of Quinamávida, located immediately south of Panimávida (Fig. 1), Troncoso and Muñoz (1988) and Troncoso (1992) found and described a Lower Eocene taphoflora. Actually, the base of this silicic level is not known, as it is covered by Quatemary sediments of the Maule river and Central Valley.

The silicic level, of the Lower Unit (VI), is overlain by an approximately 200 m thick level consisting of 2 to 3 m thick basaltic to basaltic andesite (andesites are less abundant) lava flows and pyroclastic fall tuff.

The Upper lithofacies of the Lower Unit (VCI) is about 500 m thick, and consists of 0.5 m thick layers of volcaniclastic deposits, mainly detrital flows. These layers exhibit normal and inverse gradations and traction structures (Fig. 2). Since this unit lacks volcanic intercalations, it is not further discussed in this paper.

TABLE 1. K-Ar AND ^{40}Ar-^{39}Ar RADIOMETRIC AGES OF THE COLBUN VOLCANIC AND SUBVOLCANIC ROCKS.

Sample	Rock type	Dated material	K_2O (%)	Rad. Ar (nl/g)	Atm. Ar (%)	Age (Ma ± 2σ)
Upper Unit						
72	Basalt	Whole-rock	0.303	0.182	82	15.4 ± 1.6 [1]
143	Rhyolitic tuff	Plagioclase	0.408	0.324	62	20.3 ± 1.3 [1]
Lower Unit						
113	Andesite-dacite dyke	Plagioclase	0.137	0.599	66	21.2 ± 3.0 [1]
67	Basaltic andesite dyke	Whole-rock	0.39	0.349	59	22.2 ± 1.3 [1]
133	Andesite-dacite flow	Plagioclase	0.11	0.11	81	25.5 ± 5.9 [1]
126	Rhyolite	Whole-rock	0.862	1.195	18	35.3 ±1.4 [1]
18	Andesite dyke	Whole-rock	0.16	0.16	77	16.8 ± 1.2 [2]
12	Basaltic andesite stock	Whole-rock	0.25	0.33	74.4	22.2 ± 1.9 [2]
17	Basalt sill strata	Whole-rock	0.35	0.22	43	23.8 ± 1.4 [2]
10	Andesite sill	Whole-rock	0.33	0.34	55.2	25.6 ± 0.4 [2]
1315	Andesite flow	Whole-rock	0.53	0.26	58	27.4 ± 0.4 [2]
18 V	Dacitic tuff	Plagioclase				27.4 ± 0.3 [3]

[1] K-Ar ages measured in the laboratories of the Servicio Nacional de Geología y Minería (this paper).
[2] K-Ar ages from Karzulovic *et al.* (1979).
[3] ^{40}Ar-^{39}Ar age from Vergara *et al.* (1996).

The Miocene Upper Unit (VS) has a more restricted areal distribution. In the study area, it is represented by two discreet, 50 to 100 m thick, outcrops, located in the extreme northwestern and central south part of figure 1. Stocks, sills and contemporary dykes are also observed in this unit, which overlies, with an erosional unconformity, the Lower Unit (Fig. 2). Flows of the Upper Unit have approximately the same slope of the Lower Unit.

Rocks of the northwestern outcrop consist of aphanitic basaltic flows which unconformably overlie basalts and basaltic andesites of the Lower Unit (VI). The rocks of the central-south outcrop are part of an ignimbritic pyroclastic flow which overlies detrital flows of the Lower Unit. The Miocene sills and dykes are probably feeders of the Miocene volcanism of the area (Figs. 1 and 2).

PETROGRAPHY AND MINERALOGY

The primary paragenesis of the silicic rocks of Lower Unit (VI) consists of phenocrysts of plagioclase (intermediate to sodic), clinopyroxene and orthopyroxene, magnetite and amphibole. Veinlets of zeolite are found as secondary phases, including wairakite, indicative of geothermal fields.

Basalts and basaltic andesites from the Lower Unit (VI) vary in texture from the more common aphanitic to porphyritic. Clinopyroxene ± orthopyroxene, plagioclase and titanomagnetite are the main mineral phases, usually occurring as microphenocrysts. The groundmass varies from intergranular to hyalophytic and contains microlites of plagioclase, grains of clinopyroxene and orthopyroxene and magnetite. Neither macroscopic nor microscopic differences are observed between the basalts and basaltic andesites, which can only be distinguished on the basis of their chemistry. The andesites are generally more porphyrytic and richer in orthopyroxene microphenocrysts. The groundmass of the andesites has a hyalophytic flow texture and contains microlites of plagioclase. All samples commonly contain veinlets and microamigdules filled with zeolite, chlorite and, rarely calcite.

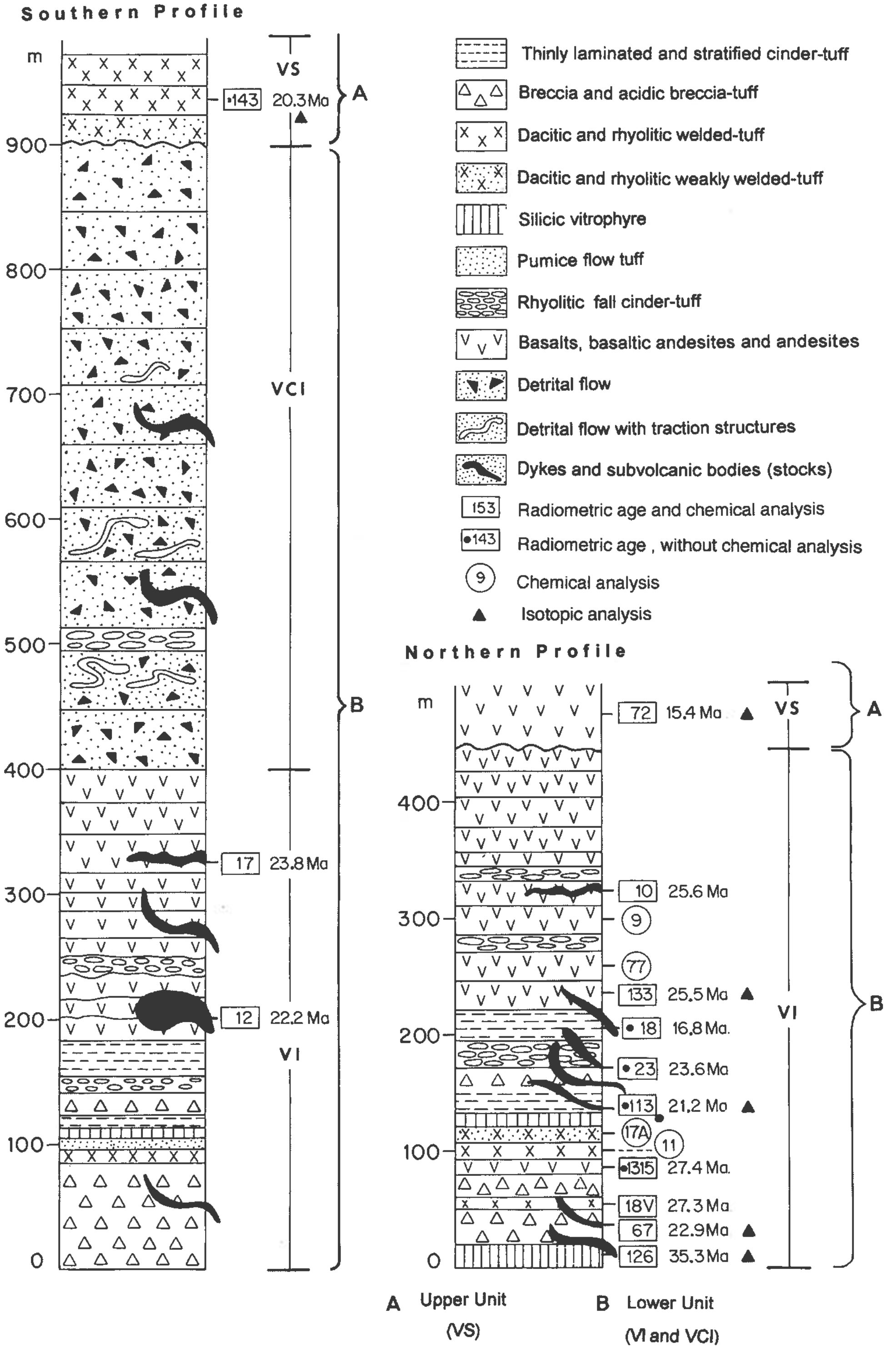

FIG. 2. Stratigraphic columns of the Colbún area. The stratigraphic location of the samples analyzed for geochronology and geochemistry are also shown.

Recently, Vergara *et al.* (1997b) reported the mineral chemistry of these Cenozoic basaltic lavas. Their igneous paragenesis is dominated by clinopyroxene ± orthopyroxene, plagioclase and opaque (mainly titanomagnetite). Pyroxene phenocrysts evolved from $Wo_{45}En_{46}Fs_{9}$(Mg#=Mg/[Mg+Fe^{2+}]=0.85) in the less differentiated basaltic rocks to $Wo_{37}En_{48}Fs_{15}$ (Mg# = 0.79) in the most differentiated ones. For the same lavas, the clinopyroxene microlites are richer in the Fs component ($Wo_{35}En_{46}Fs_{19}$) and have lower magnesium numbers (Mg#= 0.71). In the most differentiated basaltic rocks it is possible to observe orthopyroxene ($Wo_{5}En_{55}Fs_{40}$-$Wo_{3}En_{45}Fs_{52}$) in equilibrium with augitic clinopyroxene ($Wo_{39}En_{35}Fs_{26}$). In the Leterrier *et al.* (1982) diagrams, all clinopyroxene phenocrysts fall on the boundary between the tholeiitic and calc-alkaline fields.

Plagioclase phenocrysts are strongly zoned, varying from An_{80-90} in the cores to An_{67} in the rims. Plagioclase microlites and microphenocrysts are always less anorthitic (An_{50-60}) than the phenocrysts. As the An content decreases, the Or content increases. In fact, in the most differentiated basaltic rocks, where the plagioclase composition falls in the An_{42}-An_{34} range, the Or content is about 1%. However, in the most basic lavas, the Or content is extremely low (<0.5%). Because of secondary overprints, some plagioclase crystals are partially or totally albitized. These secondary transformations also generated stilbite type zeolites, heulandite and laumontite (in the lowest levels), wairakite (in those areas probably related to paleogeothermal fields associated with caldera rims), and mafic phylosilicates. The latter display a high interstratified cation content, having Ca>0.1 a p.f.u (atoms per formula unit), which is indicative of a high smectite content (Vergara *et al.*, 1997b).

The extrusive rocks of the Miocene Upper Unit (VS) are aphanitic basalts and ignimbritic pyroclastic flows of rhyolitic composition. The basalts contain microphenocrysts of plagioclase ($An_{92}Ab_{7}Or_{1}$ and clinopyroxene ($En_{45-47}Fs_{13-19}Wo_{34-38}$), in a hyalophitic to intergranular groundmass. The groundmass contains plagioclase microlites ($An_{55}Ab_{43}Or_{2}$), grains of clinopyroxene, magnetite and interstitial basaltic glass.

The ignimbritic pyroclastic flows are found at Cerro Descabezado, north of Putagán river (Fig. 1). It is a 100 m thick package of ignimbrites, consisting of different units of sequential cooling. Sample 143, collected at Cerro Descabezado, is a rhyolitic welded tuff, light pink in color, with a strong eutaxitic texture, formed by crystals and crystal fragments of sodic plagioclase, lesser amounts of quartz and abundant fragments of collapsed pumice. The matrix has a vitroclastic flow texture, with shards and small grains of crushed pumice, small fragments of plagioclase, quartz, magnetite, and interstitial volcanic ash. Veinlets of secondary zeolites are common in these rocks.

RADIOMETRIC AGES

Table 1 lists those samples, discussed in this paper, that have radiometric ages. The geographic and stratigraphic locations of these samples are illustrated in figures 1 and 2. Six new K-Ar age determinations, carried out at the Servicio Nacional de Geología y Minería (SERNAGEOMIN), yield Upper Eocene to Miocene ages for the volcanic rocks of the Colbún area (see Appendix).

GEOCHEMISTRY

Twelve representative samples were selected to examine the geochemical features of the volcanic rocks of the Colbún area (Table 2). All these samples have a loss of ignition (LOI) less than 3.5%. Most of the samples were collected in the northern part of the study area (Fig. 1), where the Colbún hydroelectric power plant is located.

Table 2 shows the major and trace element abundances of the analyzed samples together with their radiometric ages. The distribution and separation of the samples in the table is based on the SiO_2 content and is valid for the Upper and Lower units.

Most samples with age determination also have corresponding geochemical analyses (Table 1). Samples 10, 17 and 12 are duplicates of Karzulovic *et al.* (1979) sample numbers 1.1, 3.2 and 1.5, (Table 1, p. J-134), which also have K-Ar ages.

On the basis of the SiO_2 *versus* Na_2O+K_2O relationship (Fig. 3), the volcanic rocks from both units are sub-alkaline, showing a continuity in their compositional variation. The most basic samples belong to the VI lithofacies of the Lower Unit (Upper Eocene-Upper Oligocene). In the Upper Unit (Miocene), the most basic terms are basaltic andesites. On the AFM diagram (Fig. 4), all these Cenozoic volcanic rocks exhibit a tholeiitic affinity, however, primitive rocks enriched in MgO are not observed. Samples number 17 and 77 (Table 2) are Al_2O_3 rich (> 20%) and can be classified as high-alumina basalts. This is because they are comparatively rich in plagioclase phenocrysts, however, they are comparatively poor in MgO and enriched in total FeO (Fig. 4).

In the basalt to andesite transition, Al_2O_3, MgO, TiO_2, FeO and CaO decrease (Fig. 5), and K_2O and Na_2O tend to increase as SiO_2 increases. Na_2O tend to decrease in the silicic members. The light scatter in the behaviour of Na_2O and K_2O could reflect the mobility during processes of low grade metamorphism (presence of zeolite facies). P_2O_5 increases from basalt to andesite, but decreases in the andesite-rhyolite transition. Ba, Rb, Zr, Nb and Y also exhibit a positive correlation with SiO_2, but for V, Cr and Ni the correlation with SiO_2 is negative (Table 2).

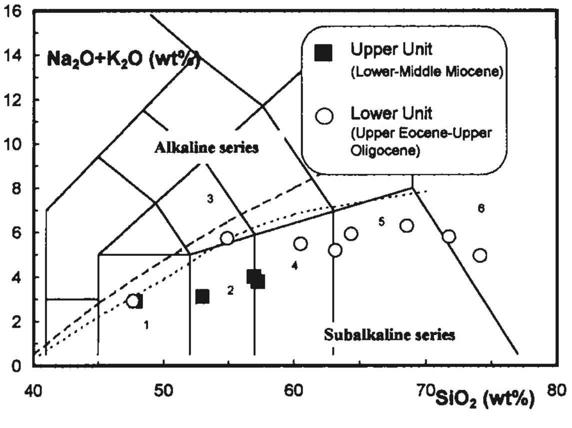

FIG. 3. SiO_2 *versus* (Na_2O+K_2O) classification scheme for volcanic rocks according to Le Maitre *et al.* (1989) and applied to the Upper Eocene to Middle Miocene volcanic rocks of the Colbún area. The fields included in this diagram are: **1**- basalt; **2**- basaltic andesite; **3**- basaltic trachyandesite; **4**- andesite; **5**- dacite; **6**- rhyolite. The boundaries between the alkaline and subalkaline fields are from Kuno (1966; dotted line) and Irvine and Baragar (1971; dashed line).

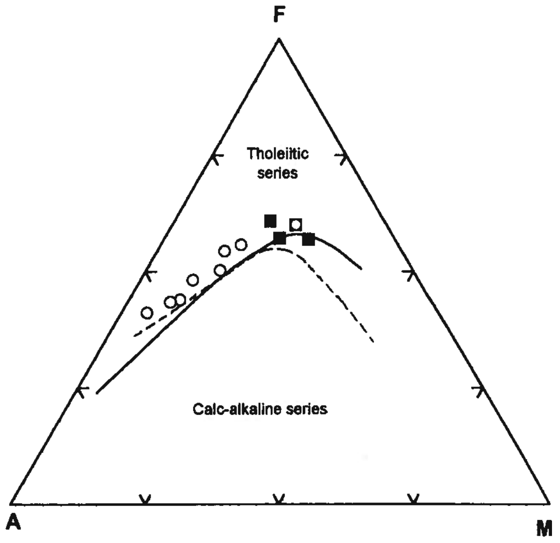

FIG. 4. AFM diagram (A= $Na_2O + K_2O$; F = FeO; M = MgO) of the Upper Eocene to Middle Miocene volcanic rocks of the Colbún area. Symbols as in figure 3. The boundaries between the tholeiitic and calc-alkaline fields are from Kuno (1968; solid line) and Irvine and Baragar (1971; dashed line).

Trace element abundances normalized to N-MORB are shown in figure 6. Basalts, basaltic andesites and andesites are enriched in K, Rb, Sr and Ba relative to N-MORB. The scatter shown by these elements is probably related to their mobility during alteration to zeolite facies. The concentration of elements from Nb to Sc are similar to those of N-MORB. All rocks are depleted in Cr with respect to N-MORB. The normalized trace elements patterns of the dacites and rhyolites have slopes analogous to the basalts and basaltic andesites, but are enriched in incompatible trace elements and depleted in Cr. TiO_2 becomes significantly depleted with the degree of differentiation. The overall N-MORB normalized trace elements patterns of the rocks in this study are intermediate between those of island arc tholeiites and calc-alkaline lavas of active continental margins.

TABLE 2. CHEMICAL ANALYSES OF THE CENOZOIC VOLCANIC AND SUBVOLCANIC ROCKS FROM THE COLBUN AREA, LINARES PRECORDILLERA, CENTRAL CHILE (35°35'-36°S).

	Lower Unit								**Upper Unit**			
SAMPLE	**77**	**9**	**10**	**133**	**11**	**18-V**	**126**	**17-A**	**17**	**72**	**12**	**67**
Rock type	β	β–α	α	δ–α	δ	ρ	ρ	ρ	β	β	β–α	α
Age (K-Ar)			25.6	25.5		27.4	35.3		23.8	15.4	22.2	22.9
SiO_2	46.13	52.61	58.55	62.15	62.41	66.50	70.20	71.83	46.44	51.94	54.90	56.41
TiO_2	1.00	1.11	1.06	0.82	0.81	0.56	0.40	0.46	1.02	1.05	1.09	1.09
Al_2O_3	21.12	16.69	15.45	15.93	15.67	13.44	13.81	11.49	21.17	16.14	14.75	15.23
Fe_2O_3	4.02	6.68	5.29	2.24	4.10	4.03	1.79	2.76	4.08	2.77	5.16	2.13
FeO	6.00	3.80	3.44	4.88	2.48	1.72	2.52	1.52	5.88	8.00	5.88	7.84
MnO	0.15	0.16	0.21	0.15	0.11	0.12	0.14	0.08	0.15	0.19	0.17	0.20
MgO	3.86	2.82	2.02	1.96	1.35	1.25	0.50	0.79	3.85	5.14	3.27	3.77
CaO	11.60	6.40	5.31	5.05	4.15	3.14	2.72	3.05	11.51	9.65	7.18	7.97
Na_2O	2.61	4.90	4.79	3.93	4.34	4.91	4.18	3.85	2.60	2.72	3.13	3.21
K_2O	0.20	0.59	0.51	1.17	1.40	1.18	1.49	0.94	0.20	0.32	0.72	0.51
P_2O_5	0.10	0.13	0.16	0.16	0.17	0.13	0.09	0.10	0.09	0.13	0.14	0.15
LOI%	3.32	3.68	2.87	1.35	3.02	2.60	1.78	2.65	3.22	1.73	3.13	1.39
Sum	**100.11**	**99.57**	**99.66**	**99.79**	**100.01**	**99.58**	**99.62**	**99.52**	**100.21**	**99.78**	**99.52**	**99.90**
Ba	55	186	144	261	258	283	375	260	55	86	160	140
Rb		12	14	22	34		35	5	5	12	15	
Nb	3	3	6	7	9	2	5	7	3	5	3	4
Sr	315	265	254	210	296	166	161	153	310	245	266	252
Zr	33	68	118	124	117	164	162	140	34	53	76	84
Y	18	25	33	38	25	45	42	39	18	25	22	26
Cr	48	5	7	4	17	15	2	11	51	80	6	25
V	287	262	106	125	99	18	6	16	280	284	350	330
Ni	15	8	8	8	11	17	4	14	16	10	9	8
Co	32	25	21	14	16	10	4	7	28	26	28	28
Sc	32	36	33	23	18	20	13	16	30	37	40	36
Cu	66	50	16	18	16	24	7	29	67	68	78	66
Zn	84	107	105	91	75	102	81	82	80	90	98	88
Hf		2	2	4	3	4	4	4	1	2	2	
La	3	6	6	10	11	11	13	9	3	5	5	6
Ce	7	14	15	24	25	27	30	21	7	13	13	14
Nd	6	10	11	16	14	19	20	15	6	9	9	10
Sm	1.85	3.00	3.16	4.32	3.28	5.46	5.12	4.24	1.90	2.48	2.33	3.14
Eu	0.74	1.15	1.33	1.27	1.32	1.53	1.27	1.15	0.73	0.88	1.05	1.05
Gd	2.45	3.39	4.14	5.54	3.29	6.61	6.06	4.95	2.49	2.92	2.80	3.80
Dy	2.90	4.07	5.20	6.06	3.62	7.94	6.49	6.11	3.00	3.48	3.48	4.51
Ho	0.60	0.88	1.12	1.33	0.78	1.71	1.43	1.36	0.62	0.76	0.78	0.98
Er	1.76	2.56	3.31	3.87	2.21	4.98	4.05	3.95	1.81	2.16	2.45	2.84
Yb	1.78	2.57	3.27	3.94	2.25	4.87	4.10	4.04	1.83	2.15	2.40	2.81
Lu	0.26	0.40	0.48	0.61	0.33	0.74	0.64	0.63	0.27	0.33	0.37	0.44

Chemical analyses were performed at the Departmento de Geología, Universidad de Chile, by J.M. Martínez, using an ICP-AES (inductively coupled plasma atomic emission spectrometry). Rb, Nb and Hf were analyzed in XRAL Laboratories (Toronto, Canada) by X-ray fluorescence (Rb y Nb) and instrumental neutron activation analysis (Hf). Major elements are expressed as oxides in wt% and trace elements in ppm. Rock types, according to figure 3, are: β = basalt; β-α = basaltic andesite; α = andesite; δ-α = silicic andesite; δ = dacite; ρ = rhyolite. Radiometric ages are in table 1. Considering their ages, the samples have been grouped into two units as described in the text, and within each unit, they are ordered according to their SiO_2 content. Location of samples in figures 1 and 2. **Sample 77-** Lower Unit (VI) clinopyroxene basaltic flow. **Sample 9-** Lower Unit (VI) clinopyroxene basaltic andesite flow. **Sample 10-** andesite sill, intruding the Lower Unit (VI). **Sample 133-** Lower Unit (VI) andesitic flow. **Sample 11-** Lower Unit (VI) andesitic flow. **Sample 18-V-** Lower Unit (VI) dacitic welded-tuff. **Sample 126-** Lower Unit (VI) vitrophyric rhyolite. **Sample 17-A-** Lower Unit (VI) rhyolitic welded-tuff. **Sample 17-** Lower Unit (VI) basaltic sill. **Sample 72-** Upper Unit basaltic flow (northern sector). **Sample 12-** basaltic andesite stock, intruding the Lower Unit. **Sample 67-** basaltic andesite dyke, intruding the Lower Unit.

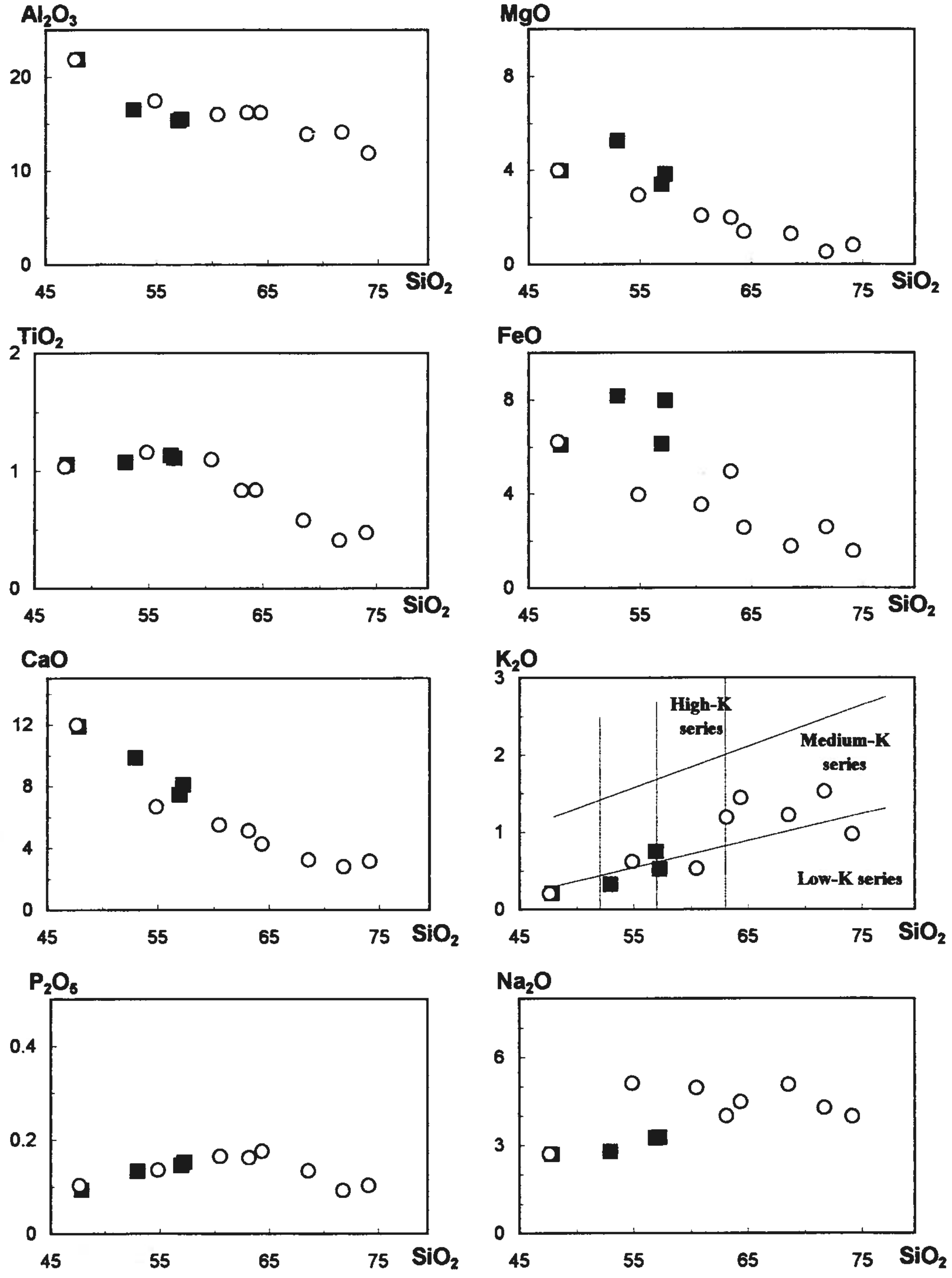

FIG. 5. Harker diagrams (major elements expressed as oxides in weight percent; data are considered on volatile free basis) of the Upper Eocene to Middle Miocene volcanic rocks of the Colbún area. Symbols as in figure 3.

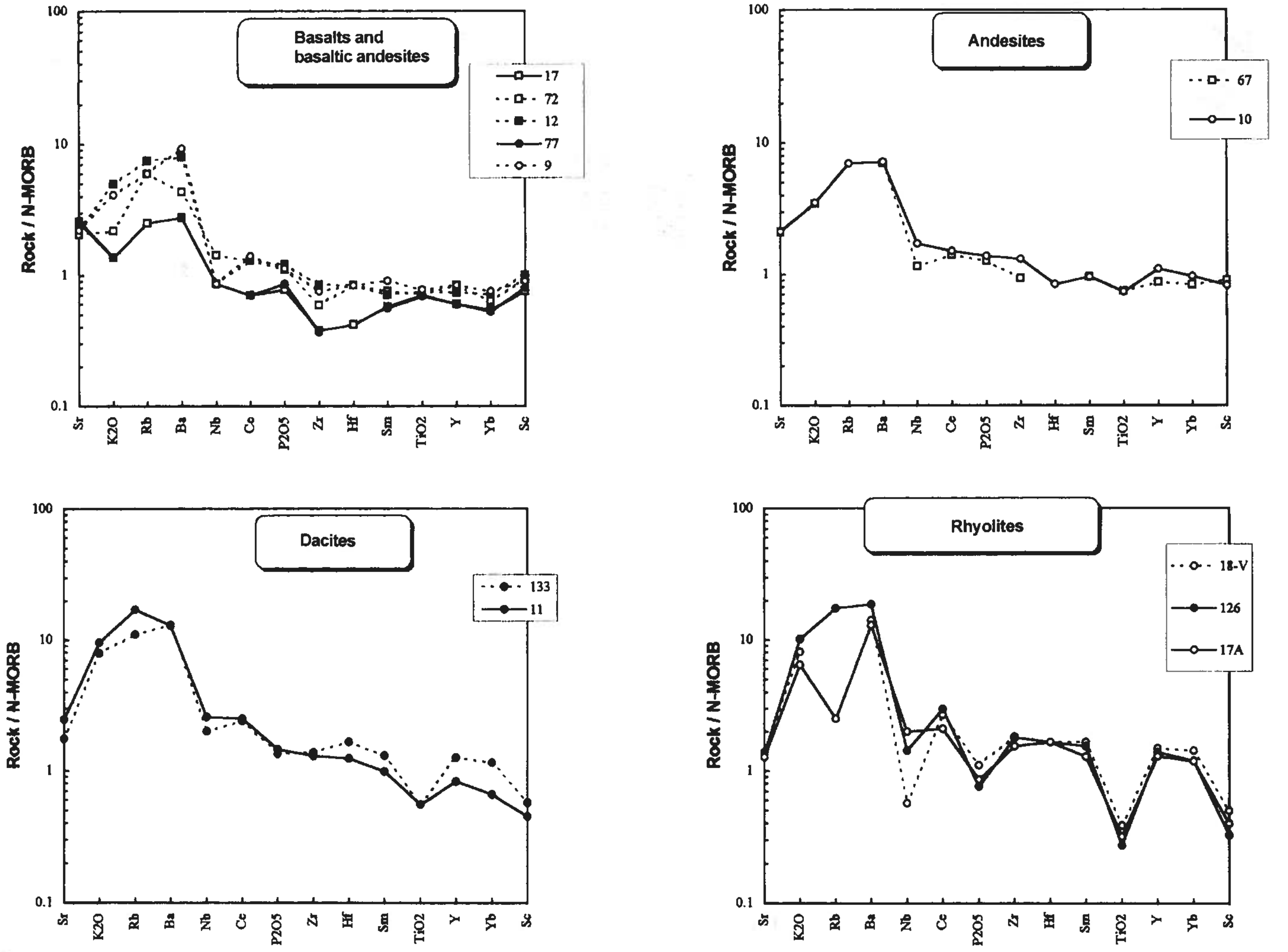

FIG. 6. N-MORB normalized spidergrams of the Upper Eocene to Middle Miocene volcanic rocks of the Colbún area. Normalization factors are from Pearce (1982). Lower Unit (Upper Eocene-Upper Oligocene) rocks are labeled with circles and Upper Unit (Lower to Middle Miocene) rocks are labeled with squares.

The chondrite normalized REE patterns of the Colbún basalts and basaltic andesites are similar, having $(La/Yb)_N$ between 1 and 1.5 (Fig. 7), and REE abundances varying between 8 and 15 times chondrites. The REE patterns of the andesites, dacites and rhyolites are also relatively flat, and their abundances are 20 to 40 times chondrites. The REE patterns of the rhyolites show a significant Eu negative anomaly.

Some incompatible trace element ratios exhibited by the most basic members (basalts to andesites) are significant. For example,the La/Nb ratio varies from 0.6 to 2, the Nb/Y ratio is less than 0.4, Ba/Nb ranges from 10 to 60 and Ba/La between 12 and 29. These ratios are different from those observed in Andean type lavas, where Ba/La>20 and La/Nb>1.6 (Stern and Skewes, 1995), and island arc tholeiites, which are enriched in LILE compared to LREE and HFSE (Peate *et al.*, 1997).

The initial $^{87}Sr/^{86}Sr$ of the Colbún area volcanic rocks are low (0.703465-0.703885). The lowest values are found in basalts, basaltic andesites and andesites and higher ratios in rhyolites (Table 3). The initial $^{143}Nd/^{144}Nd$ are relatively high (0.512896-0.512976), and homogeneous, lacking any correlation with the degree of differentiation of the lavas. Similar initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios have been reported for Oligocene and Miocene

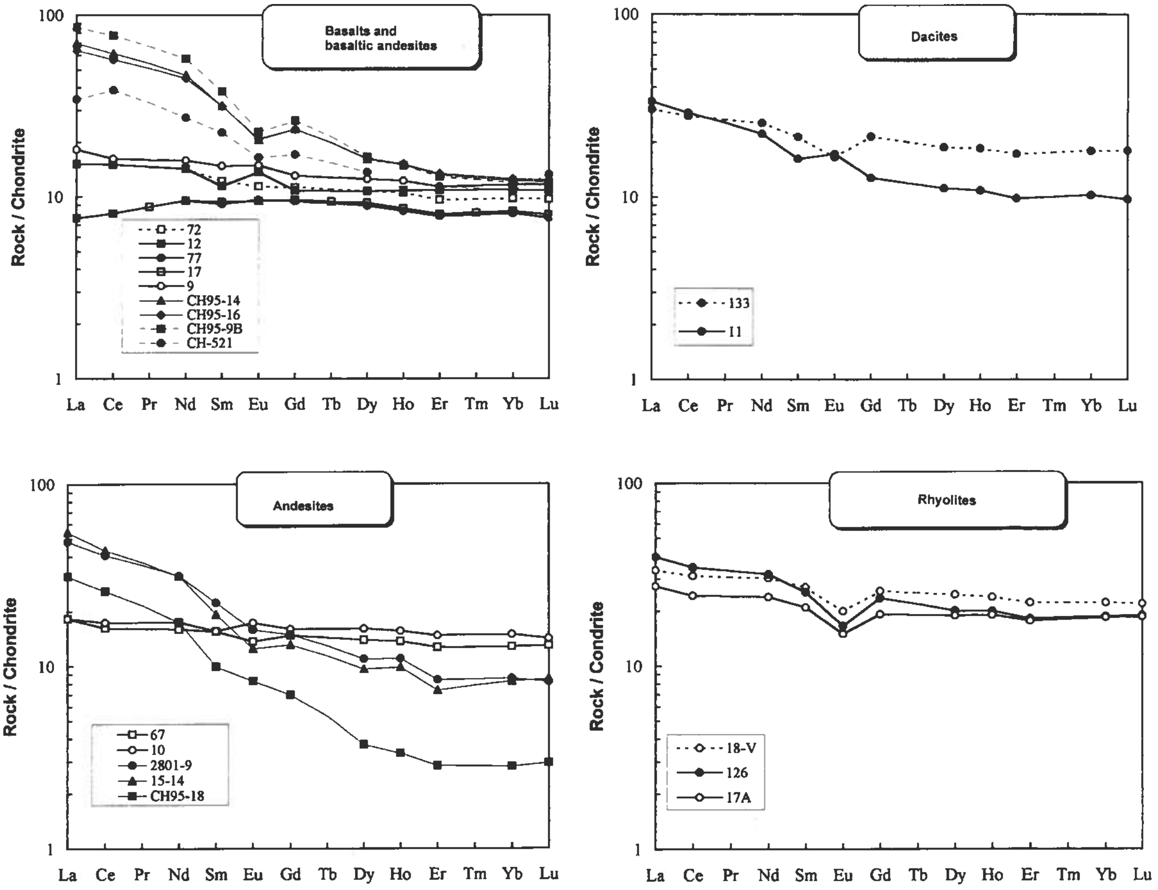

FIG. 7. Chondrite normalized REE patterns of the Upper Eocene to Middle Miocene volcanic rocks of the Colbún area. Normalization factors are from Nakamura (1974). Lower Unit (Upper Eocene-Upper Oligocene) rocks are labeled with circles and Upper Unit (Lower to Middle Miocene) rocks are labeled with squares. Samples CH95-14, CH95-16, CH95-9B, 2801-9, 15-14 and CH95-18 are from Vatin-Perignon *et al.* (1996), and correspond to samples from the Farellones Formation in the Aconcagua river area (~33°S). Sample CH-521 is a basalt collected at Cerro Abanico, Andean Cordillera in the Santiago area (from Villarroel, 1990).

dacites and rhyolites from the Parral intermontane trough, located in the Central Depression about 40 km southwest of Linares (Fig. 1; Vergara *et al.*, 1996). The Pb isotopic ratios are also quite homogeneous, (Table 3). The highest $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios are found in the Miocene rhyolitic ignimbrite (sample 143). This sample also exhibits the highest $^{87}Sr/^{86}Sr$ initial ratio (0.703757). The lowest Pb and Sr isotopic ratios are represented by sample 72, which is a Miocene basalt (15.4 Ma, Table 3). No relationship has been observed between the isotopic ratios and the K-Ar age of the lavas.

TABLE 3. ISOTOPIC Sr, Nd AND Pb RELATIONS FROM SELECTED VOLCANIC AND SUBVOLCANIC ROCKS FROM THE COLBUN AREA.

Sample	Type	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Upper Unit						
67	α	0.703743	0.512986	18.473	15.579	38.306
72	β	0.703620	0.512974	18.459	15.594	38.299
113	α	0.703991	0.512919	18.512	15.589	38.385
143	ρ	0.704028	0.512958	18.520	15.609	38.447
Lower Unit						
126	ρ	0.703960	0.512947	18.507	15.598	38.410
133	δ–α	0.703575	0.513003	18.499	15.596	38.387

Rock type as in figure 3. Typical error for the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios is ± 0.000015. The isotopic values are corrected for fractionation by using the following values: $^{86}Sr/^{88}Sr = 0.1194$, $^{146}Nd/^{144}Nd = 0.7219$ and the Todt *et al.* (1996) values for the standard NBS-981 Pb isotopic compositions. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios were normalized to 0.71025 for NBS 987 and 0.511860 for the La Jolla standard, respectively. Samples were prepared at the Florida International University (FIU, U.S.A.) and analyzed by TIMS (thermal ionization mass spectrometry) at the Carnegie Institution, Washington (U.S.A.).

DISCUSION AND CONCLUSIONS

The Colbún volcanic rocks can be grouped into two units: a Lower Unit of Upper Eocene-Lower Oligocene age and an Upper Unit of Lower to Middle Miocene age. In general, the ages of the analyzed volcanic and subvolcanic rocks vary almost continuously from Upper Oligocene (27 Ma) to Middle Miocene (15 Ma). The only exception being a vitrophyric rhyolite collected at the base of the Lower Unit, whose age is 35.3 Ma (Upper Eocene). The age of the latter sample is consistent with the age of a taphoflora found in the same stratigraphic level by Troncoso and Muñoz (1988) and Troncoso (1992). Since rocks of similar age have not been found east of Colbún, and the base of this silicic level is not known, as it is covered by Quaternary sediments of the Maule river and Central Valley, the authors postulate: **1-** that some of the rocks of the Lower Unit could be older than Upper Eocene, and **2-** this stratigraphic level could be representative of an Eocene paleovolcanic arc developed where the actual Central Depression is located. However, in the Parral area (Fig. 1), which is located in the Central Depression, 40 km southwest of Linares, an Eocene extensional trough, filled with volcanic material similar to Colbún, has been documented 500 m below the Quaternary cover (Vergara *et al.*, 1997a, c). This trough, which is internally subdivided into blocks, has a graben geometry, and would have generated continental intermontane subtroughs since the Eocene. The graben structure is controlled by deep N30-40°E normal faults. The geochronological, chemical and isotopic similarities between the Parral and Colbún volcanic rocks suggest that both sequences belong to the same volcanic events. Since the Colbún rocks are actually exposed at the surface, they probably experienced uplifting after their emplacement. In contrast, K-Ar ages and fission track thermochronology on apatites show that the Parral rocks were not subjected to tectonic movement after their emplacement (Vergara *et al.*, 1997c).

Ar-Ar and K-Ar ages similar to those of the Colbún rocks have been reported in volcanic and subvolcanic rocks, sills and dykes of the Abanico Formation, located in the Santiago area Precordillera (33-34°S; Gana and Wall, 1996). This suggests that the Colbún and Abanico Formations can be correlated in time. On the basis of structural, petrographic (large volumes of magma extruded) and paleogeothermal criteria, Thiele *et al.* (1991) and Vergara *et al.* (1993) have interpreted the volcanism associated with the Abanico Formation as being generated in a caldera-type volcano-tectonic depression. Likewise, the authors postulate that the Colbún breccia is a co-ignimbrite lag breccia deposit, as defined by Druitt and Sparks (1982) and Walker (1985) and formed during a caldera collapse and that the Upper Eocene-Upper Oligocene volcanic cycle was related to a caldera volcano-tectonic environment. The lithology of the Colbún breccia, combined with the presence of wairakite, indicates a high paleogeothermal gradient, which is also consistent with the existence of caldera structures.

Studying the isotopic variations exhibited by Cretaceous to Miocene volcanic rocks in central Chile, Nyström *et al.* (1993) noticed that with decreasing age, the Sr and Nd isotopic ratios evolved toward a MORB signature. On this basis, they proposed that the Abanico Formation volcanism was related to a rapid ascent of magmas caused by a crustal thinning event. Similar geotectonic and magmatic conditions appear to have existed during the Upper Eocene to Middle Miocene, in the Colbún area. Considering that most volcanic episodes have a duration of less than 5 m.y., a time span of 20 m. y. (35-15 Ma) for the Colbún area volcanic rocks, suggests the possible existence of several magmatic cycles. A similar chronology has been suggested for the Eocene-Miocene volcanism of the Central Depression, between 33 and 42.5°S (López-Escobar and Vergara, 1997). This emphasizes the similarity between the Precordillera and Central Depression volcanisms.

The Upper Unit is geochemically similar to the Lower Unit, despite their difference in age. The lavas studied have low MgO (< 6%), Cr (<100 ppm) and Ni (<50 ppm) contents, indicating that they are not representative of primary magmas generated by partial melting of a mantle source. These low values suggest an early fractionation of olivine and clinopyroxene. However, since the SiO_2 poorest basalts (<48% in SiO_2) are enriched in Al_2O_3 (high alumina basalts) and CaO and depleted in K_2O, MgO, Cr and Ni (Figs. 5 and 6) in relation to the other basalts, it seems that calcic plagioclase (An_{80-90}) crystallized before the mafic silicates. The continuous trend displayed by the major elements in basalts to rhyolites, independent of the age of the samples, suggests that the source and processes involved in the generation of these rocks were similar during this time span of 20 Ma. The strong TiO_2, P_2O_5 and Nb negative anomalies exhibited by the rhyolites can be explained by ilmenite±titanomagnetite+apatite fractionation during the andesite-rhyolite transition. These anomalies are typical of silicic rocks generated in magmatic arc environments (Pearce, 1982).

The trend of major elements (Fig. 5) is consistent with an evolution by a crystal fractionation process dominated by plagioclase-pyroxene-magnetite (titanomagnetite in the basalts and basaltic andesites), from primary magmas of similar geochemical features. This model is supported by the parallel behaviour exhibited by the multielement and REE pattems of the basaltic and silicic rocks (Fig. 6 and 7). The REE pattems of the high alumina basalts show positive Eu anomalies, whereas these anomalies are negative in the rhyolites. Independent of their age, the REE patterns of the Colbún area lavas are relatively flat and similar to the REE patterns exhibited by basaltic rocks from the Nazca plate. The geochemical features of the Colbún magmatism are rather tholeiitic in nature, in contrast to the calc-alkaline magmatism of the Miocene age Farellones Formation (33-34°S; Vergara *et al.*, 1988; Thiele *et al.*, 1991; Vatin-Perignon *et al.*, 1996), which overlies the Abanico Formation (Upper Eocene-Oligocene; Gana and Wall, 1996). The latter also has a tholeiitic affinity (Villarroel, 1990). Furthermore, the tectonic discrimination diagram of Cabanis and Lecolle (1989; Fig. 8) suggests that, while the Colbún magmatism was associated with an intracontinental post-orogenic environment, with a strong extensional back-arc trough component, the magmatism associated with the Farellones Formation is essentially calc-alkaline of orogenic affinities.

In the $(^{87}Sr/^{86}Sr)_0$ *versus* $(^{143}Nd/^{144}Nd)_0$ diagram (Fig. 9), the Colbún volcanic and subvolcanic rocks plot along the mantle array between the Pacific N-MORB basalts and the SVZ of the Andes. The latter are associated with a subduction environment and

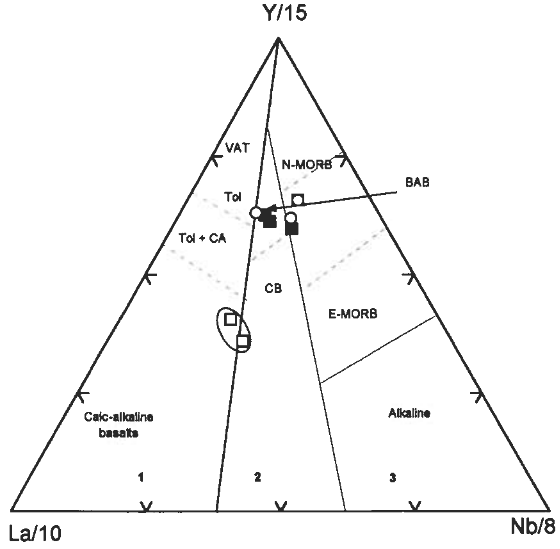

FIG. 8. Tectonic discrimination diagram of Cabanis and Lecolle (1989) applied to basalts and basaltic andesites of the Colbún area. For comparison, Miocene basalts (CH95-14 y CH95-16) from the Farellones Formation in the Aconcagua river area are shown as squares within the circled area (data are from Vatin-Perignon *et al.*, 1996).

some show effects of crustal contamination. The $(^{87}Sr/^{86}Sr)_0$ ratios (0.703465-0.703885) and $(^{143}Nd/^{144}Nd)_0$ values (0.512919-0.513003) suggest that the magmas from which the Colbún rocks originated lack a significant crustal component. These data support the hypothesis of Nyström *et al.* (1993), who postulated that the isotopic charateristics of Cretaceous to Miocene magmatism evolves toward a MORB signature with decreasing time. However, the fact that the $(^{87}Sr/^{86}Sr)_0$ ratios of the Colbún rocks are higher and the $(^{143}Nd/^{144}Nd)_0$ ratios are lower than values exhibited by N-MORB, suggests that either the parental magmas underwent some degree of crustal contamination or the mantle source was enriched in radiogenic isotopes by interaction with fluids derived from the subducted slab. The latter possibility could explain the proximity between the Colbún rocks and HIMU rocks on the $(^{87}Sr/^{86}Sr)_0$ *versus* $(^{143}Nd/^{144}Nd)_0$ diagram (Fig. 9). The enrichment of K, Rb, Sr and Ba in these Cenozoic rocks can also be explained by a source contamination involving recyled crustal sediments. The Colbún rocks are enriched in radiogenic Pb isotopes with respect to the Pacific N-MORB (Fig. 10), and occupy an intermediate position between the latter basalts and marine sediments, close to the position of the SVZ of the Andes. According to Hickey *et al.* (1986), this situation could be explained by contamination of the mantle source with a component, derived from the subducted slab, that is relatively enriched in ^{207}Pb, ^{208}Pb and Ba/Nb, typical characteristics of pelagic sediments.

An increase in the crustal thickness with decreasing time is reflected in the La/Yb ratios (Ellam, 1992). On this basis, Kay *et al.* (1994) and Stern and Skewes (1995) postulated an Andean crustal thickening from the Oligocene to the present, between latitudes 27 and 34°S. The La/Yb ratios of the Colbún rocks (<5), irrespective of their age, are lower than those found in rocks from the SVZ (La/Yb=5 to 10), emplaced in a relatively thin (<40 km) continental crust (Stern and Skewes, 1995). This suggests that, in the Colbún area, the thickness of the crust remained approximately constant from the Upper Eocene to the Middle Miocene.

Therefore, major element abundances as well as the Sr- Nd isotopic relationships, the relatively flat REE patterns and the MORB normalized Nb to Sc close to unity, are all consistent with a tholeiitic affinity for the Cenozoic lavas of Colbún area. Crustal contamination seems to be insignificant in their evolution. Nevertheless, the Pb isotopic relationships and the enrichment of some LILE, such as K, Rb, Sr and Ba, indicate a source

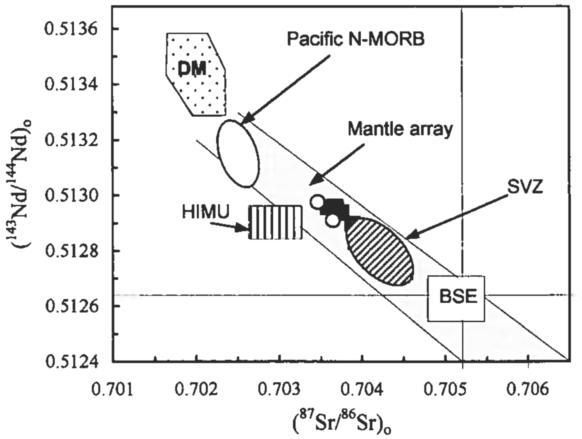

FIG. 9. $(^{87}Sr/^{86}Sr)_0$ *versus* $(^{143}Nd/^{144}Nd)_0$ diagram of the Colbún volcanic and subvolcanic rocks. The DM (isotopic composition of the depleted mantled reservoir), HIMU (isotopic composition of the high mantle uranium reservoir), BSE (isotopic composition of the bulk silicic earth reservoir) and the mantle array are from Rollinson (1993) and references therein. The Pacific N-MORB field is from Peate *et al.* (1997) and the SVZ of the Andes field is from Hickey *et al.* (1986). Symbols as in figure 3.

contamination with subduction derived fluids during an extensional tectonic regime, which also caused a crustal thinning and the development of caldera type structures.

In summary, both Colbún units, the Lower and Upper, are composed of volcanic rocks of tholeiitic affinities. The most basic members are isotopically similar to HIMU and constitute the isotopically most primitive volcanic rocks ever reported in the Andes. Geotectonic discrimination diagrams based on geochemical relationships, suggest that the Colbún related magmas were emplaced within an intracontinental, post-orogenic, extentional back arc-type trough environment. The Colbún magmas evolved mainly by closed crystal fractionation, with insignificant crustal involvement. The chemical and isotopic similarities, exhibited by the rocks ranging in age from Upper Eocene to Middle Miocene, suggest that the sources and processes involved in the generation and evolution of these magmas were more or less constant during this time span of 20 m. y. It is beyond the scope of this paper to determine the number of magmatic episodes which occurred during this period of time.

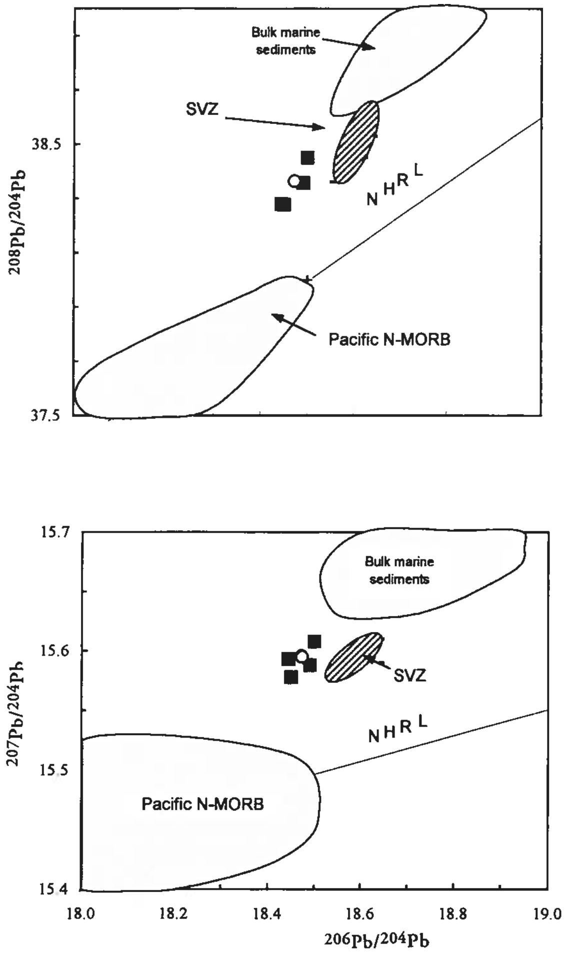

FIG. 10. Pb isotopic relationships of the Colbún area volcanic and subvolcanic rocks. The Pacific N-MORB and marine sediments fields are from Peate *et al.* (1997). NHRL (northern hemisphere reference line) is from Hart (1984). Symbols as in figure 3.

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APPENDIX

K-Ar AGES OF ROCKS FROM THE COLBUN AREA

The analyzed samples were selected after a detailed microscopic study. The samples were clean, without amygdules, or secondary minerals. The new geochronological data (Table 1), interpreted as emplacement and/or crystalization ages, correspond to the following samples:**a-** sample 126, K-Ar age of 35.3±1.4 Ma (Upper Eocene, according to the time scale of Berggren *et al.*, 1995, and adopted in this paper), is a vitrophyric rhyolite collected at a dome which crops out at the base of the Lower Unit. It is the oldest rock reported in this paper and the only one of Eocene age; **b-** sample 133, K-Ar age of 25.5±5.9 Ma (Upper Oligocene), is an andesite collected from a flow located in the northernmost outcrop of the study area. Although this sample does not exhibit microscopic evidence of alteration, it has a relatively large analytical error, and thus, this age must be considered with caution; **c-** sample 143, K-Ar age of 20.3±1.3.(Lower Miocene), is a rhyolitic welded-tuff collected from an ignimbritic flow at Cerro Descabezado (Fig. 1). This flow unconformably overlies the detrital flows of the Lower Unit (VCI); **d-** sample 72, K-Ar age of 15.4±1.6 Ma (Middle Miocene), is a basalt collected from a flow outcropping in the northern part of the Colbún area (Fig. 1), on the southern bank of the Maule river. This flow overlies lava flows and pyroclastic rocks of the Lower Unit (VI), and is representative of the youngest volcanic activity in the area. This is a whole-rock K-Ar age with 82% atmospheric Ar; it is probably a reset age; **e-** samples 67, K-Ar age of 22.9±1.3 (Lower Miocene), is an andesite collected from a radial dyke at the Cerro Chiburgo volcanic neck (Fig . 1); **f-** sample 113, K-Ar age of 21.2±3.0 (Lower Miocene), is a silicic andesite also collected from a radial dyke at the Cerro Chiburgo volcanic neck (Fig. 1).

Vergara *et al.* (1996) reported an Ar-Ar age of 27.3±0.34 Ma (Upper Oligocene) for a dacitic welded-tuff (sample 18V) collected from an ignimbritic flow belonging to the basal level of the Lower Unit (VI). Karzulovic *et al.* (1979) reported the first K-Ar age determinations for samples collected in the Colbún-Machicura dam area. Only five ages, corresponding to volcanic rocks of the Colbún formation (Fig. 1), are considered in this paper **a-** sample 1315, K-Ar age of 27.4±0.4 Ma (Upper Oliogocene), was collected from an andesitic flow in a reconnaissance gallery at the central hydroelectric power plant engine house. The age of this sample is consistent with the ages of lava and pyroclastic flows from this sector; **b-** sample 10, K-Ar age of 25.6±0.4 Ma (Upper Oligocene), is an andesite collected from a sill; **c-** sample 17, K-Ar age of 23.8±1.4 Ma (Oligocene-Miocene boundary), is a basalt collected from a sill; **d-** sample 12, K-Ar age of 22.2±1.9 Ma (Lower Miocene), is a basaltic andesite collected from a stock located east of Quinamávida, and **e-** sample 18, K-Ar age of 16.8±1.2 Ma (Lower Miocene), is an andesite collected from a radial dyke at Cerro Chiburgo.

The oldest ages, 35.3 Ma (Eocene) and 27.4 Ma (Upper Oligocene), correspond to a rhyolitic dome and an ignimbritic flow found at the base of the Lower Unit, respectively. Both appear to be related to a caldera structure, at present eroded and cut by the Maule river.