The relation of the mid-Tertiary coastal magmatic belt in south-central Chile to the late Oligocene increase in plate convergence rate

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ABSTRACT

The mid-Tertiary Coastal Magmatic Belt in south-central Chile, which crops out both in the Central Valley and, south of 41°S, in the Coastal Cordillera as far west as the Pacific coast, formed when the locus of Andean magmatic activity expanded, both to the west and to the east relative to its previous and current location in the Main Cordillera. This expansion of the magmatic arc occurred in conjunction with a regionally widespread episode of late Oligocene to Miocene extension which thinned the crust below the proto-Central Valley in south-central Chile and generated sedimentary basins west of, within, and east of the Main Cordillera. The extrusive rocks of the mid-Tertiary Coastal Magmatic Belt are interbedded with the late Oligocene to Miocene continental and marine sediments deposited in these basins, and forty-seven of the fifty new and previously published age determinations for these rocks are within the time period 29 Ma (late Oligocene) to 18.8 Ma (early Miocene). The initiation of extension, basin formation and the westward migration of magmatic activity coincides closely to the beginning, in the late Oligocene, of the current period of both high convergence rate (>10 cm/yr) and less oblique convergence, which together resulted in an approximately three-fold increase in trench-normal convergence rate between the Nazca and South American plates. Extension continued, along with a transient steepening of subduction angle as indicated by the westward migration of the volcanic front during the formation of the mid-Tertiary Coastal Magmatic Belt, during an approximately 10 million year period after the trench-normal convergence rate tripled across the Nazca and South American plate boundary. The mid-Tertiary Coastal Magmatic Belt includes igneous rocks chemically similar to modern Andean arc magmas, as well as rocks with ocean island basalt chemical affinities characterised by lower Ba/La (<19), La/Nb (<1.6) and initial $^{87}Sr/^{86}Sr$ ratios (<0.7035), and higher $\varepsilon_{Nd(T)}$ values (>+5). The latter formed by melting of mantle uncontaminated by components derived from the dehydration of subducted oceanic lithosphere. This suggests the formation of the mid-Tertiary Coastal Magmatic Belt may have involved upwelling of asthenospheric mantle, possibly through a slab-window, due to the transient episode of invigorated asthenospheric wedge circulation caused by the three-fold increase in late Oligocene trench-normal convergence rates between the Nazca and South Amercan plates. The change in subduction geometry and the transient period of invigorated asthenospheric circulation caused by this increase in convergence rate may have combined to produced moderate extension across the southern South American continental margin by inducing an episode of slab rollback of the subducting Nazca plate.

Key words: Andean magmatism, Geochronology, Tectonics, Geochemistry, Isotopes, Tertiary, Chile.

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RESUMEN

La relación del Cinturón Magmático del Terciario-medio del centro-sur de Chile con el incremento de la razón de convergencia de placas en el Oligoceno superior. El Cinturon Magmático del Terciario-medio de la Costa en el centro-sur de Chile, que aflora en el Valle Central y, al sur de los 41°S, en la Cordillera de la Costa y a lo largo de la costa del Océano Pacifico, se formó cuando el foco de la actividad magmática se expandió tanto al oeste como al este de su posición previa y actual en la Cordillera Principal. Esta expansión del arco magmático ocurrió durante el Oligoceno superior-Mioceno en conjunción con un episodio regional de expansión cortical, que adelgazó la corteza bajo el Valle Central embrionario en el centro-sur de Chile y generó cuencas sedimentarias en, al oeste y al este de la Cordillera Principal. Las rocas extrusivas de este cinturón están asociadas con rocas sedimentarias, continentales y marinas, del Oligoceno superior-Mioceno, depositadas en estas cuencas. De un total de cincuenta determinaciones de edades para estas rocas, nuevas y previamente publicadas, cuarenta y siete se ubican entre 29 Ma (Oligoceno superior) y 18,8 Ma (Mioceno inferior). El inicio de la extensión, de la formación de las cuencas y la migración hacia el oeste de la actividad magmática coincide con el comienzo, en el Oligoceno superior, del actual periodo caracterizado por una alta razón de convergencia (>10 cm/año) y de convergencia menos oblicua, lo cual, en conjunto, generó un aumento de tres veces en la velocidad de convergencia de las placas de Nazca y Sudamericana. La extensión continuó por aproximadamente 10 millones de años después que la razón de convergencia, entre las placas de Nazca y Sudamericana, se triplicó y la migración hacia el oeste del frente volcánico, durante ese lapso, sugiere un aumento transitorio del ángulo de subducción. El Cinturón Magmático del Terciario-medio de la Costa incluye rocas ígneas con composiciones químicas similares a las rocas del arco volcánico moderno y, también, rocas con afinidades oceánicas, caracterizadas por bajas razones Ba/La (<19) y La/Nb (<1,6), bajas razones $^{87}Sr/^{86}Sr$ (<0.7035) y altos valores de $\varepsilon_{Nd(T)}$ (>+5). Estas últimas se formaron por fusión parcial de manto astenosférico no contaminado con componentes provenientes desde la deshidratación de litosfera oceánica subductada. Esto sugiere que la formación del Cinturón Magmático del Terciario-medio de la Costa puede haber involucrado alzamiento de manto astenosférico, posiblemente a través de una ventana en la placa subductada, debido a un periodo transitorio de circulación vigorosa en la astenosfera, causado por el incremento en tres veces de la razón de convergencia entre las placas de Nazca y Sudaméricana, ocurrido durante el Oligoceno superior. El cambio en la geometría de subducción y el periodo transitorio de circulación astenosférica vigorosa, generados por el incremento en las razones de convergencia, se pueden haber combinado para producir una extensión moderada en el margen continental del sector sur de Sudamérica, al inducir un episodio de 'rollback' de la Placa de Nazca subductada.

Palabras claves: Magmatismo andino, Geocronología, Tectónica, Geoquímica, Isótopos, Terciario, Chile.

INTRODUCTION

Mid-Tertiary igneous rocks between 36 and 43.5°S in south-central Chile have been divided into two belts (Vergara and Munizaga, 1974; López-Escobar and Vergara, 1997; Muñoz *et al.*, 1997; Stern *et al.*, 2000). One belt outcrops in the Main Andean Cordillera, which is the location of the currently active Andean volcanic arc. The other belt, which is the focus of this paper, outcrops to the west of the Main Cordillera, both within the Central Valley (longitudinal depression) as well as in the Coastal Cordillera, as far west as the Pacific coast (Fig. 1). Contemporaneous mid-Tertiary magmatic activity at these latitudes also occurred to the east of the Main Andean Cordillera, extending almost to the Atlantic Coast at latitude 42°S (Ramos *et al.*, 1982; Rapela and Kay, 1988, Kay *et al.*, 1993, in press).

What the authors refer to here, as the mid-Tertiary Coastal Magmatic Belt, has been previously called the Coastal Cordillera Volcanic Belt (Vergara and Munizaga, 1974), the Eocene-Miocene Longitudinal Depression Volcanic Belt (López-Escobar *et al.*, 1976; López-Escobar and Vergara, 1997; Vergara *et al.*, 1999), and/or the Central Valley Upper Oligocene-Miocene Volcanic Belt (Stern and Vergara, 1992). It has been suggested that the early stages of this magmatic activity may have begun in the late Eocene (Vergara and Munizaga, 1974; López-Escobar and Vergara, 1997; Vergara *et al.*, 1999). However, the greatest volume of mid-Tertiary Coastal Magmatic Belt rocks, which occur within the Central Valley, were formed in the late Oligocene through early Miocene (Fig. 2; Muñoz *et al.*, 1997; Stern *et al.*, 2000).

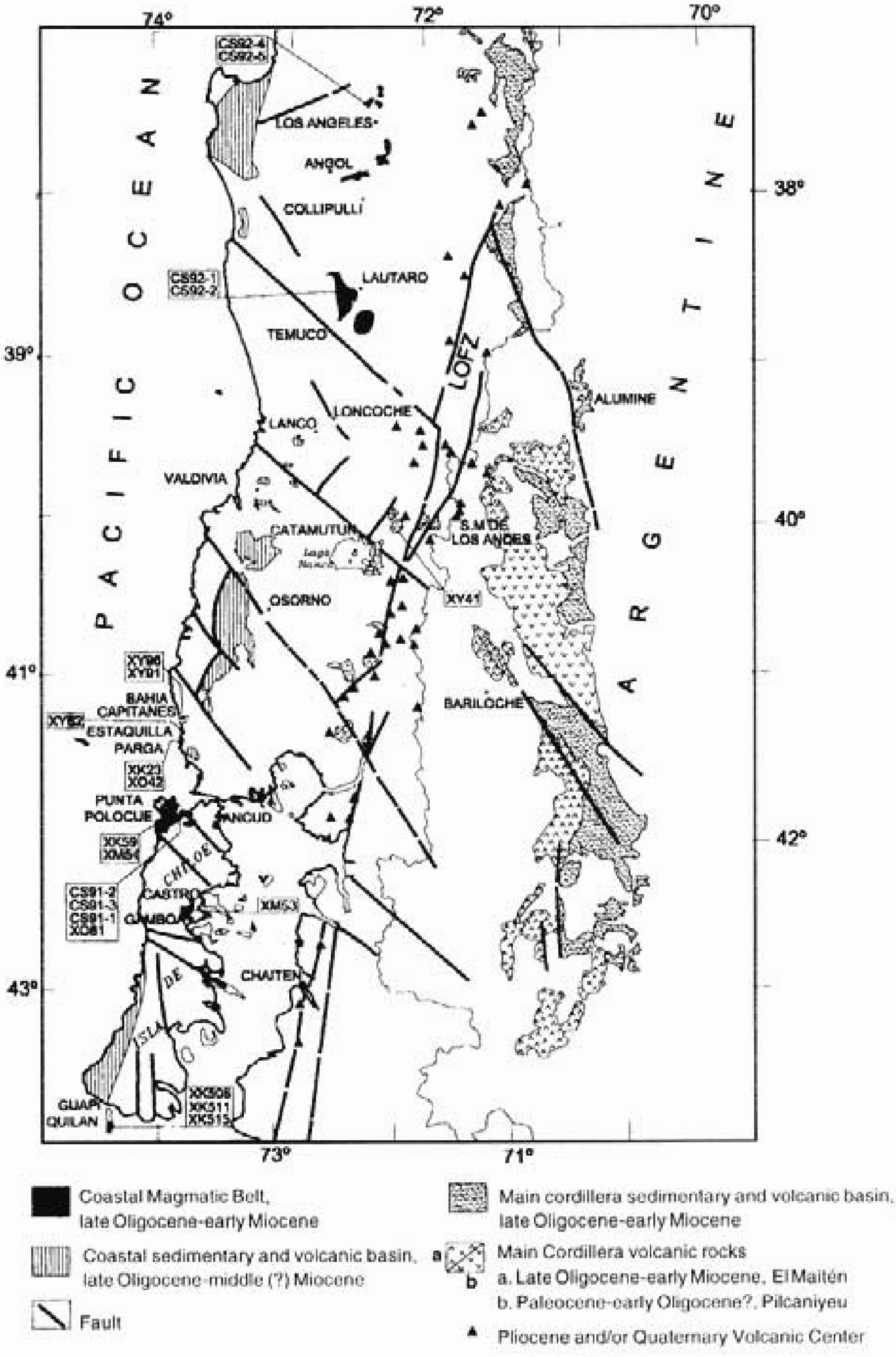


FIG. 1. Location map of outcrops of the mid-Tertiary Coastal Magmatic Belt of south-central Chile between 37°S and 43.5°S. The map also shows the contemporaneous mid-Tertiary sedimentary basins west of the Main Andean Cordillera, and outcrops of mid-Tertiary igneous and sedimentary rocks both in and east of the Main Cordillera (SERNAGEOMIN, 1982, 1998[1]; Campos *et al.*, 1998; Rapela *et al.*, 1988; Spalletti and Dalla-Salda, 1996; Delpino and Deza, 1995; Nullo *et al.*, 1993; Jordan *et al.*, in press) as well as regional north-south and northwest-southeast fault systems (Muñoz, 1997), including the Liquiñe-Ofqui Fault Zone (LOFZ).

[1] 1998. Estudio Geológico-Económico de la X[a] Región Norte (Inédito), *Servicio Nacional de Geología y Minería*, Informe Registrado IR-15-98, 6 Vols.

The mid-Tertiary Coastal Magmatic Belt is comprised of volcanic and volcaniclastic rocks interbedded with late Oligocene and early Miocene continental and marine sedimentary rocks (Cisternas and Frutos, 1994; Kelm *et al.*, 1994), and associated volcanic necks and hypabyssal intrusives. Igneous rocks of this belt are exposed along the eastern margin of the Central Valley at Colbún-Machicura (35.7°S; López-Escobar and Vergara, 1997; Vergara *et al.*, 1999) and near Parral (36.4°S; Vergara *et al.*, 1997a and 1997b), within the Central Valley in the vicinity of Los Angeles, Angol and Temuco (Fig. 1; Vergara and Munizaga, 1974; Vergara, 1982; Rubio, 1993; Cisternas and Frutos, 1994), along the coast at Bahia Capitanes, Estaquillas, and Caleta Parga (Alfaro *et al.*, 1994; Troncoso *et al.*, 1994), on the island of Chiloé in the vicinity of Ancud (Valenzuela, 1982; Stern and Vergara, 1992) and Castro (Valdivia and Valenzuela, 1988), and on Guapi Quilán Island (43.5°S) just off the southern coast of Chiloé. A notable lack of mid-Tertiary igneous rocks occurs between Temuco and Bahía Capitanes (Fig. 1), coincident with an uplifted tectonic block of Paleozoic-Triassic metamorphic rocks (Chotin, 1975; Muñoz, 1997). South of Chiloé, mid-Tertiary volcanic rocks occur in the vicinity of Isla Magdalena, Aisén (45°S; Hervé *et al.*, 1995). However, the origin of these rocks has been attributed to the development of pull-apart basins associated with strike-slip motions along the Liquiñe-Ofqui Fault Zone (LOFZ; Fig. 1) during the period of oblique plate convergence prior to the late Oligocene, and they are not considered here to be part of the mid-Tertiary Coastal Magmatic Belt.

In this paper, the authors present new chronologic, petrochemical, and isotopic analysis for samples from the mid-Tertiary Coastal Magmatic Belt between 37 and 43.5°S, as well as a single sample of similar age from within the Main Andean Cordillera (Table 1; Fig. 1). This study of the mid-Tertiary Coastal Magmatic Belt, like previous studies, is regional in nature in the sense that individual mid-Tertiary magmatic centers have not been mapped and/or sampled in detail. However, the new data add to that previously available for the mid-Tertiary Coastal Magmatic Belt, particularly in the area south of 41°S where this belt outcrops along the Pacific coast, and provide an improved basis for understanding the origin of this belt in the context of tectonic evolution of the southern Andes during the late Oligocene and Miocene, when the trench-normal convergence rate between the Nazca and South American plates increased significantly.

TECTONIC SETTING

Volcanic rocks of the mid-Tertiary Coastal Magmatic Belt were emplaced both upon Paleozoic-Triassic metamorphic basement and interbedded with late Oligocene to Miocene continental and Miocene marine sedimentary sequences, indicating that this magmatic activity occurred in association with subsidence and the initiation of the development of the present day Central Valley. The late Oligocene to early Miocene magmatic activity in the mid-Tertiary Coastal Magmatic Belt (Fig. 2) ended prior to the rapid subsidence associated with Miocene marine sedimentation. Marine sedimentation in the area of the present day Central Valley ceased either by the early (Martínez and Pino, 1979) or middle (S. Elgueta and J. Urqueta, 1998)[2] Miocene, and Miocene marine strata were subsequently deformed and uplifted by a phase of compression in the middle or late Miocene.

The formation of the mid-Tertiary Coastal Magmatic Belt, the deposition of the associated late Oligocene and Miocene sedimentary rocks, and the initiation of the development of the present day Central Valley in south-central Chile occurred during a regionally widespread episode of extension (Nyström *et al.*, 1993; Thiele *et al.*, 1991; Spalletti and Dalla Salda, 1996; Vergara *et al.*, 1999; Godoy *et al.*, 1999; Jordan *et al.*, in press). Evidence for an extensional origin of the Central Valley is well preserved south of 40°S, where this sedimentary basin between the Coastal and Main Cordillera corresponds spatially to an area of significant positive gravity anomaly, suggesting that extension thinned

[2] 1998. Sedimentología y estratigrafía de las Cuencas terciarias en la Región de Los Lagos (39°-42° S), Chile. *In* SERNAGEOMIN, 1998. Estudio Geológico-Económico de la X* Región Norte (Inédito), *Servicio Nacional de Geología y Minería*, Informe Registrado IR-15-98, 6 Vols.

TABLE 1. LOCATION AND PETROLOGY OF THE SAMPLES STUDIED.

Locality Latitude	Sample	Texture	Phenocrysts	Groundmass microcrysts	Secondary minerals	Lithology
Los Angeles 37°30'S	CS92-4	Porphyritic	Pl-Cpx	Glass, Pl-Cpx	Ca-Cy	Andesite
	CS92-6	Porphyritic	Pl-Cpx-Opx Pl-Cpx	Glass,	Cy	Andesite
Temuco 39°00'S	CS92-1	Porphyritic	Pl-Cpx	Trachytic, Pl-Cpx	Cy	Andesite
	CS92-2	Porphyritic	Pl-Cpx-Opx	Intergranular, Pl-Cpx-Ol-Opx	Idd	Andesite
Parga 41°30'S	XK23	Aphanitic		Intersertal, Pl-Ol-Cpx	Idd-Ru-Ca-Si-Ch-Hm	Basalt
	XO42	Porphyritic	Pl-Ol-Cpx	Intersertal, Pl-Ol-Cpx-glass	Idd-Ch-Ca-Cy-Li	Basalt
Bahía Capitanes 41°08'S	XY91	Aphanitic	Minor Pl-Cpx	Intergranular, Pl-Cpx-Ol-Opx-Mt	Ze-Si	Basaltic andesite
	XY96	Porphyritic	Pl-Cpx-Ol	Intersertal, Pl-Cpx-Ol-Mt-glass	Bw	Dacite
Estaquillas 41°20'S	XY62	Fluidal	Minor Pl-Cpx	Glass, Pl	Ca-Cy	Rhyolite dome
Punta Polocué, Chiloé, 42°00'S	XM54 (CS91-5)	Aphanitic		Trachytic, Pl-Ol-Cpx-glass	Ca-Idd	Basaltic andesite
	XK59	Aphanitic		Trachytic, Pl-Ol-Cpx-glass	Ca-Id	Basaltic andesite
Ancud, Chiloé 42°00'S	X081	Porphyritic	Pl-Cpx-Opx	Trachytic, Pl-Cpx-Ol		Basaltic andesite
	CS91-2	Aphanitic	Minor Pl-Cpx-Ol	Intersertal, Pl-Cpx-Ol-Mt	Idd	Basaltic andesite
	CS91-3	Aphanitic	Minor Pl-Cpx	Intersertal-Trachytic, Pl-Cpx-Mt		Basaltic andesite
	XK62 (CS91-1)	Glassy, flow banded, lithic rich	Pl	Glass		Rhyodacitic pyroclastic flow
Gamboa, Castro 42°30'S	XM53 (CS90-0)	Coarse Porphyritic	Pl-minor Bt-Qtz	Felsic	Cy	Dacitic sill
Guapi Quilán, 43°30'S	XK506	Porphyritic	Pl-Cpx-Opx-minor Ol	Intersertal-Hyalopilitic, Pl-Cpx-Mt	Idd-H	Andesite
	XK511	Porphyritic	Pl-Opx	Trachytic, Pl-Cpx-Mt		Andesite
	XK515	Porphyritic	Pl-Opx	Intersertal, Pl-Mt	Hm	Andesite
Lago Ranco, Main Cordillera 40°15'S	XY41	Porphyritic	Pl		Ch-Ep-Ca-Cy	Basaltic andesite

Cpx= clinopyroxene; **Opx**= orthopryroxene; **Ol**= olivine; **Mt**= magnetite; **Pl**= plagioclase; **Idd**= Iddingsite; **Bw**= bowlingite; **Ca**= calcite-carbonates; **Cy**= clays; **Ze**= zeolite; **Ep**= epidote; **Ch**= chlorite; **Ru**= rutile; **Si**= silica; **Hm**= hematite; **Li**= limonite; **Bt**= biotite; **Qtz**= quartz, **Ab**=albite.

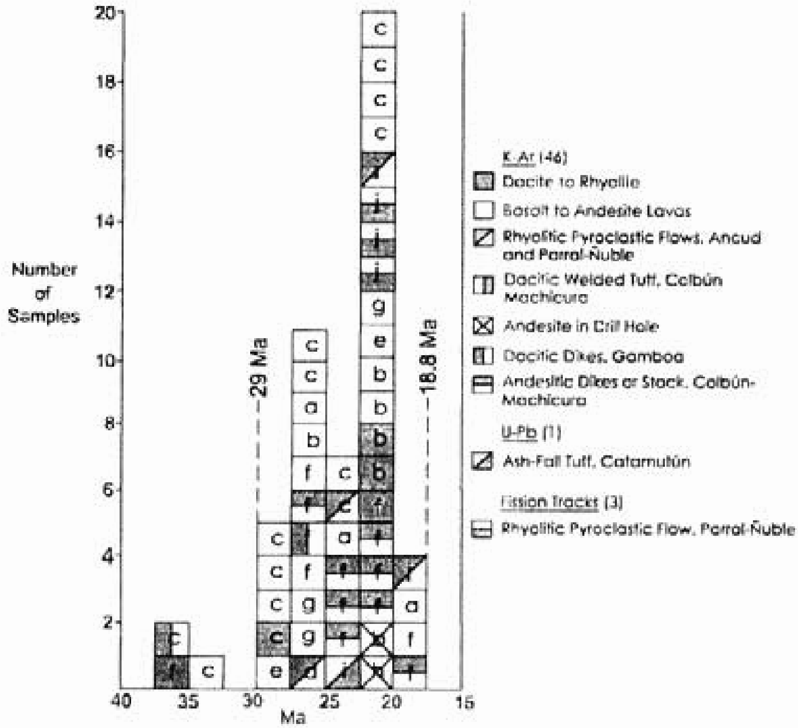


FIG. 2. Histogram of the fifty new and previously published ages for samples from the mid-Tertiary Coastal Magmatic Belt of south-central Chile between 36°S and 43.5°S; from **a-** Cisternas and Frutos (1994); **b-** López-Escobar and Vergara (1997) and Vergara and Munizaga (1974); **c-** this paper (Table 2); **d-** Stern and Vergara (1992); **e-** Rubio (1993); **f-** Vergara *et al.* (1999); **g-** Troncoso (1999); **h-** McDonough *et al.* (in press) and Karzulovic *et al.* (1979); **i-** Elgueta and Urqueta (1998)[2]; and **j-** Vergara *et al.* (1997b). Forty-seven of the fifty ages are in the range late Oligocene (29 Ma) to early Miocene (18.8 Ma), and all the samples from within the area of the Central Valley are in this same range, indicating that the formation of the mid-Tertiary Coastal Magmatic Belt occurred during a single well defined episode of approximately 10 million years. This episode began in the late Oligocene, at essentially the same time (27 ± 2 Ma; Somoza, 1998) as the three-fold increase in trench-normal convergence rate between the Nazca and South American plates.

the underlying crust (J. Muñoz, M. Araneda and M. McDonough)[3]. Seismic reflection profiles substantiate a crustal thickness of only 33 km beneath the western portion of the Central Valley at the latitude of Osorno (McDonough *et al.*, 1997). Also, south of 40°S, the western edge of the present day Central Valley is limited by an approximately north-south system of low angle normal faults (Fig. 1) which correspond to the contact between the Paleozoic-Triassic metamorphic basement of the Coastal Cordillera and the late Oligocene through Miocene continental and marine sedimentary sequences in the valley (Kelm *et al.*, 1994; Muñoz, 1997; McDonough *et al.*, 1997). These faults were active during the late Oligocene and Miocene, generating a proto-Central Valley and controlling both the emplacement of igneous rocks and the location of sedimentary basins. Similar faults also occur bounding contemporaneous sedimentary basins on the eastern flank of the Andes (Fig. 1; Spalletti and Dalla Salda, 1996; Jordan *et al.*, in press).

The north-south normal faults along the western margin of the Central Valley are intersected and displaced by a regional northwest trending strike-slip fault system (Fig. 1; Muñoz, 1997). The northwest trending strike-slip faults represent reactivated older structures, possibly previously active during the Paleozoic and Mesozoic (Rapela *et al.*, 1988; Muñoz, 1997). They are associated with positive magnetic anomalies generated by mafic and ultramafic bodies which have been tectonically emplaced into the

[3] 1998. Geofísica Regional. *In* SERNAGEOMIN, 1998. Estudio Geológico-Económico de la X Región Norte (Inédito). *Servicio Nacional de Geología y Minería*, Informe Registrado IR-15-98, 6 Vols.

Paleozoic-Triassic metasedimentary and metavolcanic basement (Godoy and Kato, 1990; Ugalde *et al.*, 1997).

The regionally widespread episode of late Oligocene to Miocene extension that initiated the development of the Central Valley in south-central Chile was temporally related to a major plate reorganization in the southeast Pacific (Cande and Leslie, 1986; Tebbens and Cande, 1997). This plate reorganization resulted in both less oblique convergence and a greater than two-fold increase in convergence rate between the Nazca (Farallon) and South American plates (Pardo-Casas and Molnar, 1987; Somoza, 1998), and consequently a three-fold increase in the rate of trench-normal convergence, as well as possibly changes in the geometry of subduction (Frutos and Cisternas, 1994).

CHRONOLOGY AND PETROCHEMISTRY

Thirty-seven previously published radiometric dates for samples from the mid-Tertiary Coastal Magmatic Belt between 36 and 42.5°S have yielded ages ranging from 40.4 to 18.8 Ma (Vergara and Munizaga, 1974; García *et al.*, 1988; Stern and Vergara, 1992; Rubio, 1993; Cisternas and Frutos, 1994; Troncoso, 1999; McDonough *et al.*, in press). Here the authors present 14 new K-Ar ages (Table 2), major and trace-element compositions (Table 3), and Sr, Nd and Pb isotopic data (Table 4) for samples from the Mid-Tertiary Coastal Magmatic Belt south of 37°S (Table 1; Fig. 1). The new data are described separately for the area between Los Angeles and Temuco (37-39°S), at Bahía Capitanes, Estaquillas and Caleta Parga (41-41.5°S), on the island of Chiloé (42 42.5°S), and from Guapi Quilán Island (43.5°S) off the south coast of Chiloé. The authors also present an age date and chemical data for a single mid-Tertiary sample from within the Main Andean Cordillera at Lago Ranco (40.25°S).

METHODS

Major and selected trace elements, including Cr, Ni, Co, V, Y, Nb, Zr, Sc and Pb were determined by atomic absorption and ICP-AE at the analytical laboratory of SERNAGEOMIN, Santiago, as were the new K-Ar ages. Cs, Rb, Sr, Ba, Hf, Ta, Th, U and REE concentrations were obtained, with a precision <5%, by ICP-MS analysis at either the Plasma Analytical Laboratory of University of Kansas, Lawrence, or Act Labs, Denver. Isotope dilution concentrations for Rb, Sr, Sm, Nd and Pb, and Sr, Nd and Pb isotopic analysis (Table 4) were completed at the University of Colorado, Boulder, using isotope dilution mass-spectrometry techniques described by Farmer *et al.* (1991).

TABLE 2. K-Ar AGE DETERMINATIONS OF REPRESENTATIVE SAMPLES.

Sample	Locality	Dated material	%K	Ar rad (nl/g)	%Ar Atm	Age (Ma ± 2σ)	Lithology
CS92-6	Los Angeles	WR	1.369	1.350	20	25.2 ± 0.9	Andesite
CS92-1	Temuco	WR	0.875	0.975	83	28.4 ± 2.8	Andesite
CS92-2	Temuco	WR	1.072	1.180	35	28.1 ± 1.1	Andesite
XY91	Bahía Capitanes (Coast)	WR	1.173	1.513	50	32.9 ± 1.6	Basaltic andesite
XY96	Bahía Capitanes (Coast)	WR	2.008	2.160	24	27.5 ± 1.0	Dacite
XM54	Punta Polocue, Chiloé (Coast)	WR	0.704	0.669	92	24.3 ± 5.9	Basaltic andesite
XO81	Ancud, Chiloé	WR	0.614	0.496	39	20.7 ± 1.0	Basaltic andesite
CS91-2	Ancud, Chiloé	WR	0.586	0.458	41	20.0 ± 0.9	Basaltic andesite
CS91-3	Ancud, Chiloé	WR	0.905	0.781	37	22.1 ± 1.0	Basaltic andesite
XK62	Ancud, Chiloe	Glass	2.476	2.245	29	23.2 ± 0.8	Rhyolitic pyroclastic flow
XM53	Gamboa, Castro, Chiloe	WR	1.978	2.893	6	37.2 ± 1.2	Dacite
XK506	Guapi Quilán	WR	1.176	1.010	49	22.0 ± 0.9	Andesite
XK511	Guapi Quián	WR	1.052	1.081	30	26.2 ± 0.9	Andesite
XK515	Guapi Quilán	WR	1.200	1.352	29	29.0 ± 1.1	Andesite
XY41	Lago Ranco, Main Cordillera	Plagioclase	0.143	0.116	83	20.7 ± 2.4	Basaltic andesite

TABLE 3. MAJOR AND TRACE-ELEMENT CONTENTS OF REPRESENTATIVE SAMPLES.

	Los Angeles-Temuco				Parga-Bahía Capitanes-Estaquillas				
Sample	CS92-4	CS92-6	CS92-1	CS92-2	XK23	XO42	XY91	XY96	XY62
Latitude	37°30'S	37°30'S	39°S	39°S	41°30'S	41°30'S	41°08'S	41°08'S	41°20'S
Locality	Los Angeles	Los Angeles	North Temuco	North Temuco	Parga	Parga	Capitanes	Estaquillas	Punta
Rock Type	Andesite	Andesite	Andesite	Andesite	Basalt	Basalt	Basaltic andesite	Dacite	Rhyolite Dome
SiO_2	61.26	62.25	60.45	60.65	48.4	48.53	53.98	66.78	71.05
TiO_2	0.53	0.58	0.92	0.63	1.98	2.18	1.98	0.6	0.04
Al_2O_3	13.7	14.18	17.79	17.68	16.38	15.51	15.91	15.35	13.17
Fe_2O_3	1.48	1.76	1.93	2.92	1.35	6.76	1.59	0.28	0.66
FeO	3.35	3.41	3.8	2.15	7.51	3.02	6.26	3.51	0.24
MnO	0.13	0.11	0.14	0.1	0.15	0.06	0.06	0.15	0.04
MgO	4.69	4.1	2.07	3.15	6.45	7.03	3.34	0.67	0.07
CaO	5.41	5.01	6.18	6.44	8.51	8.1	6.9	3.13	0.65
Na_2O	2.29	3.02	4.24	3.59	3.73	3.79	3.54	4.3	3.5
K_2O	2.46	2.59	1.13	1.34	0.55	0.94	1.85	3.05	2.5
P_2O_5	0.12	0.15	0.23	0.13	0.32	0.31	0.28	0.18	0.05
LOI	4.48	2.66	0.86	1.04	4.15	3.75	4.11	1.83	7.91
Total	**99.9**	**99.81**	**99.74**	**99.82**	**99.88**	**99.98**	**99.78**	**99.83**	**99.85**
Cr	27	34	282	39	224	202	41	10	10
Ni	122	<2	<2	<2	119	113	<2	<2	6
Co	22		21	20	38	36	21	8	0.6
V	172		107	120	170	156	151	19	9
Pb	7.19	3.62	6.94	5.36	2.58	3.62	5.17	3.39	22.8
Cs	3	1	3.5	0.6	0.65	0.97			
Rb	58	45	39	37	16	22	63	130	175
Sr	205	348	302	480	373	353	277	144	16
Ba	366	409	323	278	170	152	415	553	125
Sc	17.7	22.4	14.4	16.2	26	25	27	14	5
Zr	136	135	144	104	240	243	251	321	99
Y	24	23	28	18	32	30	44	43	37
Nb	<5	<5	<5	<5	10.2	9	9.4	10.4	10.9
Ta	0.3	0.21	0.33	0.27	0.86	0.94	0.64	0.73	1.33
Hf	4.4	3.5	4	3.4	4.9	5.3	6.2	8	2.57
Th	4.9	3.6	2.6	3.7	1.8	2.5	5.9	10.1	5.3
U	1.2	0.8	0.8	0.9	0.6		1.6	2.9	4

	Punta Polocué, Chiloé		Ancud, Chiloé				Castro, Chiloé	Guapi Quilán Island			Main Cordillera
Sample	XM54	XK59	XO81	CS91-2	Cs91-3	CS91-1	XM53	XK506	XK511	Xk515	XY41
Latitude	42°S	42°S	42°S	42°S	42°S	42°S	42°30'S	43°25'S	43°25'S	43°25'S	40°14'S
Locality	Punta Polocué Chiloé	Ancud, Polocué Chiloé	Ancud, Chiloé	Ancud, Chiloé	Ancud, Chiloé	Gamboa, Chiloé	Guapi Castro	Guapi Quilán	Guapi Quilán	Lago Quilán	Ranco
Rock Type	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Rhyodacite Pyroc.flow	Dacite	Andesite	Andesite	Andesite	Basaltic andesite
SiO_2	52.29	54.53	52.72	53.7	54.7	69.59	67.56	58.71	59.08	58.42	54.18
TiO_2	1.24	1.29	1.33	1.18	2.72	0.36	0.55	0.93	0.94	1.38	0.84
Al_2O_3	16.96	16.83	16.83	17.67	14.85	13.18	15.54	16.11	15.71	17.31	18.09
Fe_2O_3	1.7	2.47	3.28	2.07	3.16	1.16	1.33	2.09	1.66	2.41	6.37
FeO	5.67	4.72	3.03	4.43	6.65	1.71	2.08	3.57	3.89	4.27	4.59
MnO	0.13	0.06	0.06	0.1	0.23	0.08	0.15	0.1	0.1	0.1	0.13
MgO	5.33	5.26	4.77	5.98	3.79	0.47	0.97	5.04	5.43	1.89	3.21
CaO	9.21	8.68	10.18	9.31	6.69	1.37	3.08	6.41	6.23	5.42	5.46
Na_2O	3.44	3.44	3.49	3.53	4.3	4.35	3.71	3.85	3.78	4.5	2.62
K_2O	0.96	0.8	0.65	0.58	1.04	3.78	2.71	1.58	1.34	1.61	0.37
P_2O_5	0.26	0.23	0.14	0.2	0.44	0.06	0.13	0.19	0.17	0.26	0.12
LOI	2.66	1.14	1.41	1.01	0.96	3.53	1.92	0.79	1.09	1.34	3.84
Total	**99.84**	**99.45**	**99.9**	**99.77**	**99.52**	**99.68**	**99.72**	**99.37**	**99.42**	**97.57**	**99.82**
Cr	183	131	156	8	11	14	105	184	178	0.116	40
Ni	24	24	<4	49	<2	<2	18	66	50	383	7
Co	27	26	27	34	28	11	9	18	21	15	25
V	159	134	169	301	110	9	37	108	85	57	182
Pb	3.82	4.15	3.31	3.46	5.58	17.1	10	6	<5	8	5.1
Cs		5.7	0.66	0.3	2.1	8.82	4.3	3.6	2.9	5.3	1.34
Rb	24	21	15	9.7	34	144	86	51	38	58	13
Sr	293	349	314	362	274	78	171	311	312	276	82
Ba	206	192	135	209	286	499	368	395	392	451	94
Sc	23	25	27	25	32	11	7	17	16	18	11
Zr	176	149	131	152	182	415	178	155	135	239	408
Y	25	24	27	21	37	54	16	18	18	31	65
Nb	7	<5	<5	7	<5	14	6.4	14	8	13	2.8
Ta	0.44	0.58	0.44	0.47	0.47		0.68	1	0.8	0.8	0.21
Hf	4.1	3.9	3.2	3.5	5.4	10.6	4.7	3.6	3.2	5.4	2.6
Th	2.6	2.6	2.4	2.6	4.1	11.7	6.7	4.5	3.7	5.4	1.7
U	0.8	0.7	2.9			3.7	2.2	1.3	1.3	1.4	0.2

(table 3 continued)

	Los Angeles-Temuco				Parga-Bahia Capitanes-Estaquillas					Punta Polocué, Chiloé		Ancud, Chiloé				Castro, Chiloé	Guapi Quilán Island			Main Cordillera
Sample	CS92-4	CS92-6	CS92-1	CS92-2	XK23	XO42	XY91	XY96	XY62	XM54	XK59	XO81	CS91-2	CS91-3	CS91-1	XM53	XK506	XK511	XK515	XY41
Latitude	37°30'S	37°30'S	39°S	39°S	41°30'S	41°30'S	41°08'S	41°08'S	41°20'S	42°S	42°S	42°S	42°S	42°S	42°S	42°30'S	43°25'S	43°25'S	43°25'S	40°14'S
Locality	Los Angeles	Los Angeles	North Temuco	North Temuco	Parga	Parga	Capitanes	Capitanes	Estaquillas	Punta Polocué Chiloé	Punta Polocué Chiloé	Ancud, Chiloé	Ancud, Chiloé	Ancud, Chiloé	Ancud, Chiloé	Gamboa, Castro	Guapi Quilán	Guapi Quilán	Guapi Quilán	Lago Ranco
Rock Type	Andesite	Andesite	Andesite	Andesite	Basalt	Basalt	Basaltic andesite	Dacite	Rhyolite Dome	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Rhyodacite Pyroc.flow	Dacite	Andesite	Andesite	Andesite	Basaltic andesite
La	12.2	13.2	12.1	11.6	14.5	17.2	19.6	27.4	7.1	13.9	14.2	10.8	10.9	17.6	33	18.9	19.3	18.2	22.7	8
Ce	28.3	31.2	30.2	28.4	35.1	39.9	48	62.1	19.2	34.8	33.1	24.3	25.7	43.6	77.2	42.4	37.3	35.5	45.7	17.7
Nd	14.9	18.6	18.2	15.1	28.4	24.1	28.4	30.8	9.9	20.1	20.8	15.4	15.1	27.8	55.4	18	16	15.2	22.6	10.9
Sm	3.9	4.19	4.08	2.68	5.09	5.75	6.95	7.38	3.8	4.68	4.62	3.62	3.47	6.67	8.92	3.7	3.4	3.4	5.1	2.97
Eu	0.88	1.14	1.28	0.66	1.77	1.82	1.8	1.3	0.19	1.44	1.38	1.25	1.22	2.21	1.61	0.91	1.1	1.1	1.49	0.97
Gd					6.18	6.39	7.7	7.74	4.79	4.98	4.89	4.84				3.16	3.3	3.4	5.3	3.57
Tb	0.71	0.7	0.81	0.46	1.09	1.09	1.41	1.41	1.06	0.88	0.82	0.72	0.62	1.28	1.66	0.62	0.5	0.6	0.8	0.65
Dy					6.17	6.2	7.87	7.86	6.19	4.89	4.79	5.16				3.61	3.3	3.2	5.4	3.78
Ho					1.26	1.28	1.63	1.51	1.26	0.99	0.98	1.09				0.72	0.7	0.6	1.5	0.85
Er					3.46	3.58	4.53	4.57	3.49	2.74	2.76	3.11				2.11	2	1.9	3.3	2.37
Yb	2.85	2.46	3	1.58	3.1	3.3	4.39	4.47	3.5	2.63	2.4	2.3	2.1	3.84	6.4	2.14	1.9	1.7	2.9	2.41
Lu	0.42	0.37	0.44	0.25	0.43	0.47	0.66	0.67	0.47	0.4	0.36	0.32	0.3	0.56	0.76	0.26	0.28	0.24	0.43	0.36
La/Yb	4.2	5.4	4	7.3	4.7	5.2	4.5	6.1	1.94	5.3	5.9	4.7	5.2	4.6	5.2	8.8	10.2	10.7	7.8	3.2
Ba/La	30	31	27	24	11.7	8.8	21.2	20.2	17.6	14.8	13.5	12.5	19.2	16.1	15.1	19.5	20.5	21.5	19.9	11.7
La/Nb	>2.4	>2.6	>2.4	>2.3	1.4	1.9	2.1	2.6	0.7	2	>2.8	>2.1	1.5	>3.5	2.3	2.9	1.4	2.3	1.7	2.9

TABLE 4. Sr, Nd AND Pb ISOTOPIC COMPOSITIONS OF REPRESENTATIVE SAMPLES.

SAMPLE	Age Ma	SiO_2 wt%	Rb ppm	Sr ppm	$^{87}Sr/^{86}Sr$ Measured	$^{87}Sr/^{86}Sr$ Initial	Sm ppm	Nd ppm	$^{143}Nd/^{144}Nd$ Measured	$^{143}Nd/^{144}Nd$ Initial	$\varepsilon_{Nd(T)}$	Pb ppm	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Los Angeles (37°30'S)															
CS92-4	(22.8)[1]	61.3	57.8	205	0.70400	0.70371	3.62	11.9	0.512869	0.512842	4.54	7.19	18.409	15.553	38.119
CS92-6	25.2	62.3	43.5	346	0.70452	0.70439	4.20	17.6	0.512774	0.512750	2.82	3.62	18.584	15.614	38.343
Temuco (39°S)															
CS92-1	28.4	60.5	38.5	302	0.70451	0.70437	2.96	11.9	0.512828	0.512803	3.87	6.94	18.562	15.585	38.287
CS92-2	28.1	60.7	34.8	451	0.70437	0.70428	2.27	10.4	0.512714	0.512691	1.71	5.36	18.571	15.583	38.353
BahiaCapitanes and Caleta Parga (41- 41°30'S)															
XK23	(30.2)[2]	48.4	14.2	353	0.70345	0.70337	3.75	14.1	0.512931	0.512899	5.86	2.58	18.486	15.571	38.146
XO42	(30.2)[2]	48.5	15.6	352	0.70364	0.70356	4.23	16.9	0.512868	0.512838	4.66	3.62	18.557	15.576	38.344
XY91	32.9	54.0	52.5	227	0.70569	0.70538	6.90	28.4	0.512723	0.512691	1.87	5.17	18.597	15.621	38.353
XY96	27.5	66.8	113	144	0.70715	0.70626	6.98	30.8	0.512624	0.512559	0.06	3.39	19.381	15.756	39.154
XY62	(30.2)[2]	71.1	172.6	15.4	0.72783	0.71402	4.46	9.44	0.512696	0.512645	0.89	22.8	18.718	15.631	38.681
PuntaPolocué, Chiloé (42°S)															
CS91-5	(24.3)[3]	52.3	21.2	313	0.70532	0.70525	4.62	20.1	0.512765	0.512743	2.66	3.82	18.513	15.608	38.126
XK59	(24.3)[3]	54.5	20.6	317	0.70437	0.70431	3.39	13.9	0.512748	0.512725	2.30	4.15	18.605	15.602	38.401
Ancud, Chiloé(42°S)															
XO81	20.7	52.7	12.7	296	0.70354	0.70350	1.45	4.78	0.512887	0.512862	4.89	3.31	18.541	15.575	38.275
CS91-2	20.0	53.7	8.0	297	0.70354	0.70351	1.74	5.76	0.512871	0.512847	4.58	3.46	18.547	15.584	38.292
CS91-3	22.1	54.7	28.4	237	0.70430	0.70419	2.23	7.67	0.512849	0.512824	4.17	5.58	18.654	15.596	38.409
CS91-1	(24.4)[4]	69.6	138.0	64.3	0.70735	0.70517	8.20	35.2	0.512768	0.512746	2.71	17.1	18.657	15.599	38.433
Gamboa, Chiloé(42°30'S)															
CS90-0	(37.2)[5]	67.6	85.3	176	0.70516	0.70442	3.57	16.99	0.512801	0.512770	3.51	2.44	19.357	15.709	38.958
XM53	37.2	67.6	84.5	159.1	0.70515	0.70447	3.95	17.5	0.512792	0.512759	3.29	10.0	18.651	15.597	38.518
Guapi Quilán (43°25'S)															
XK506	22	58.7	52.8	296	0.70435	0.70419	3.35	15.8	0.512812	0.512794	3.59	7.90	18.626	15.631	38.639
XK511	26.2	59.1	45.8	309	0.70536	0.70520	3.41	15.9	0.512852	0.512830	4.40	12.0	18.558	15.612	38.496
XK515	29	58.4	56.2	275	0.70494	0.70470	5.23	23.0	0.512740	0.512714	2.21	9.20	18.646	15.617	38.628
Main Cordillera (40° S)															
XY41	20.7	54.2	41.9	190.7	0.70456	0.70435	3.40	11.8	0.512818	0.512784	3.36	5.10	18.553	15.579	38.386

[1] CS92-4: 22.8 Ma age of sample taken as the average of the two new and published dates from the Los Angeles area (25.2 Ma for sample CS92-6 and 20.4 Ma for sample 1, Vergara and Munizaga, 1974).
[2] XK23, XY42 and XY62: 30.2 Ma age of samples taken as the average of the two new dates from the Bahia Capitanes area (32.9 Ma for sample XY91 and 27.5 Ma for sample XY96).
[3] CS91-5 and XK59: 24.3 Ma age of samples taken as the same as that determined for sample XM54 from the same volcanic neck at Punta Polocué.
[4] CS91-1: 24.4 Ma age of samples taken as the average of the two new and published dates for this pyroclastic flow (23.2 Ma for sample XM62 and 25.2 Ma for the sample dated by Stern and Vergara, 1992).
[5] CS90-0: 37.2 Ma age of sample taken as that determined for sample XM53 from the same sill at Gamboa, Chiloé.

LOS ANGELES TO TEMUCO (37-39°S)

Mid-Tertiary rocks from within the Central Valley in the area of Los Angeles, Angol, Collipulli, Lautaro and Temuco (Fig. 1) have previously been described by López-Escobar *et al.* (1976), Vergara (1982), Rubio (1993); Cisternas and Frutos (1994); López-Escobar and Vergara (1997), and Troncoso (1999). They include plagioclase + pyroxene ± olivine ± hornblende ± quartz ± K-feldspar andesites, dacites and rhyodacites, with minor or extensive alteration of olivine to iddingsite, calcite, chlorite and hematite, and of plagioclase to sericite and/or clay. As noted by López-Escobar and Vergara (1997), no basalts have been reported from this section of the mid-Tertiary Coastal Magmatic Belt. López-Escobar *et al.* (1976) presented major and trace element analysis for six samples, and López-Escobar and Vergara (1997) presented major and trace element and isotopic analysis for three samples from this area. Nine previously published K-Ar age determinations for samples from this portion of the Mid-Tertiary Coastal Magmatic Belt range from 18.8 to 28.8 Ma (Vergara and Munizaga, 1974; Rubio, 1993; Cisternas and Frutos, 1994; Troncoso, 1999).

Three new K-Ar age determinations for samples from this area range from 25.2± 0.9 to 28.4± 2.8 Ma (Table 2), within, but towards the high end, of the range of the previously published ages. These, and one other sample analyzed for major and trace elements alone, are andesites (Fig. 3) with sub-alkaline affinities and low TiO_2 (<1 wt %). They exhibit moderate light-rare-earth (LREE) enrichment relative to heavy-rare-earths (HREE; La/Yb = 4 to 7.3; Fig. 4), and large-ion-lithophile element (LIL) enrichment relative to LREE (Ba/La = 24 to 31; Fig. 5) compared to ocean island basalts (Ba/La<19; Hickey *et al.*, 1986; Stern *et al.*, 1990). Both these ratios are within the ranges (La/Yb = 4 to 9; Ba/La = 23 to 38) previously reported by López-Escobar *et al.* (1976) and López-Escobar and Vergara (1997). They also have high-field-strength-element (HFSE) depletion relative to REE (La/Nb > 2.3; Fig. 5) compared to ocean island basalts (La/Nb<1.6; Hickey *et al.*, 1986; Stern *et al.*, 1990). These ranges for La/Yb, Ba/La and La/Nb are all similar to

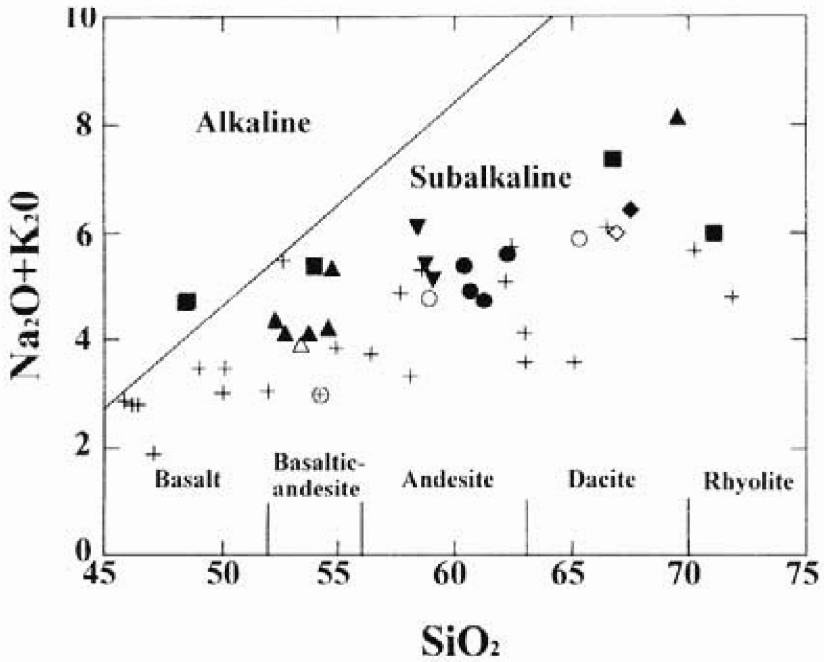


FIG. 3. Silica (SiO_2) *versus* total alkalies ($Na_2O + K_2O$) for samples from the mid-Tertiary Coastal Magmatic Belt of south-central Chile between 36°S and 43.5°S. Solid symbols represent data from this paper (Table 3) and open symbols data from López-Escobar and Vergara (1997), with different symbols for samples from different areas (**circles**= Los Angeles and Temuco; **squares**= Capitanes, Estaquillas and Parga; **upright triangles**= Ancud and Polocué, Chiloé; **diamonds**= Gamboa, Chiloé; **inverted triangles**= Guapi Quilán Island). Crosses are for samples from the mid-Tertiary Coastal Magmatic Belt to the north at Colbún-Machicura (35.7°S; Vergara *et al.*, 1999), and the circled plus represents a sample from the Main Cordillera (Table 3).

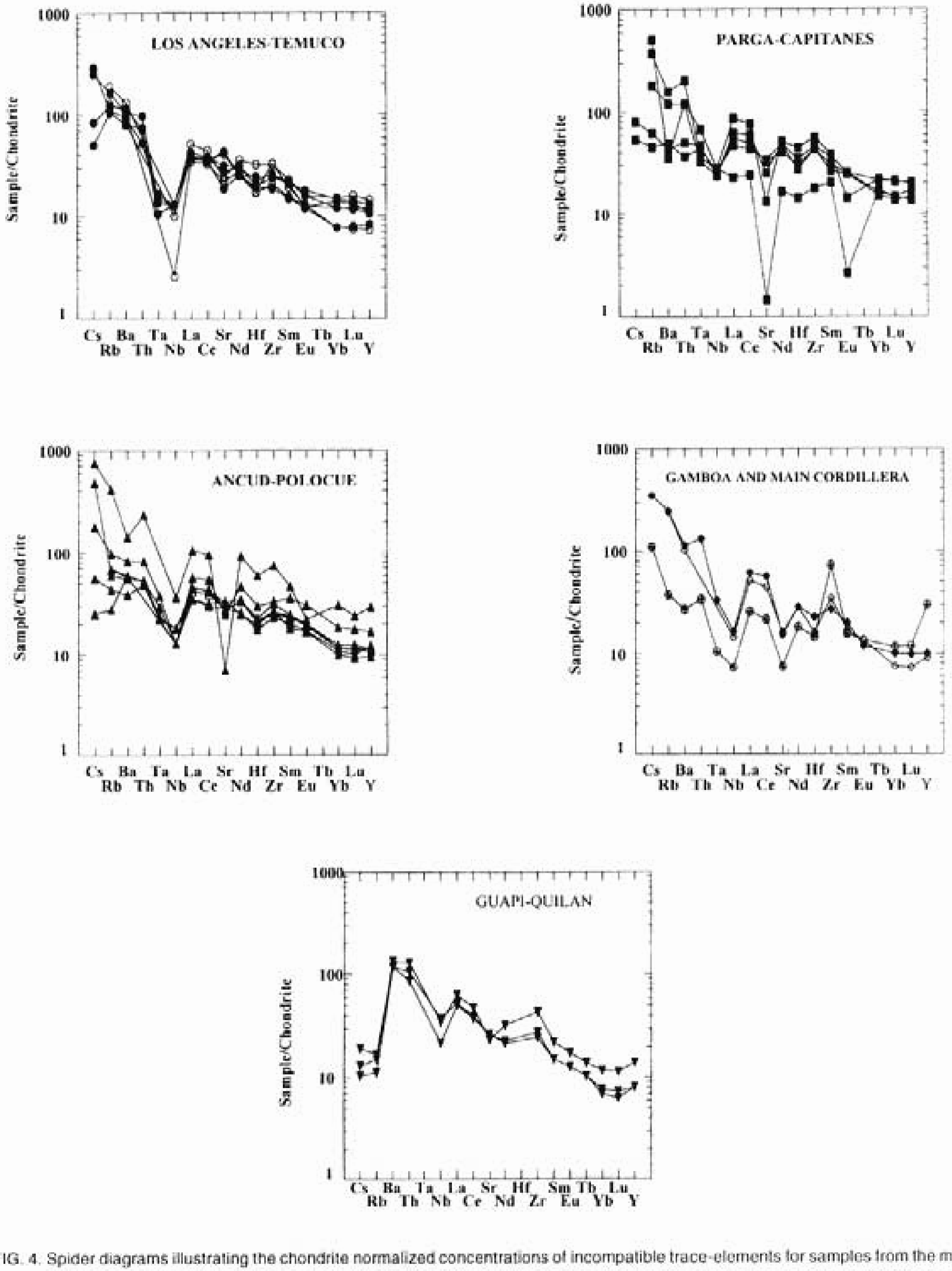


FIG. 4. Spider diagrams illustrating the chondrite normalized concentrations of incompatible trace-elements for samples from the mid-Tertiary Coastal Magmatic Belt of south-central Chile between 37 and 43.5°S. Symbols and data sources are the same as in figure 3.

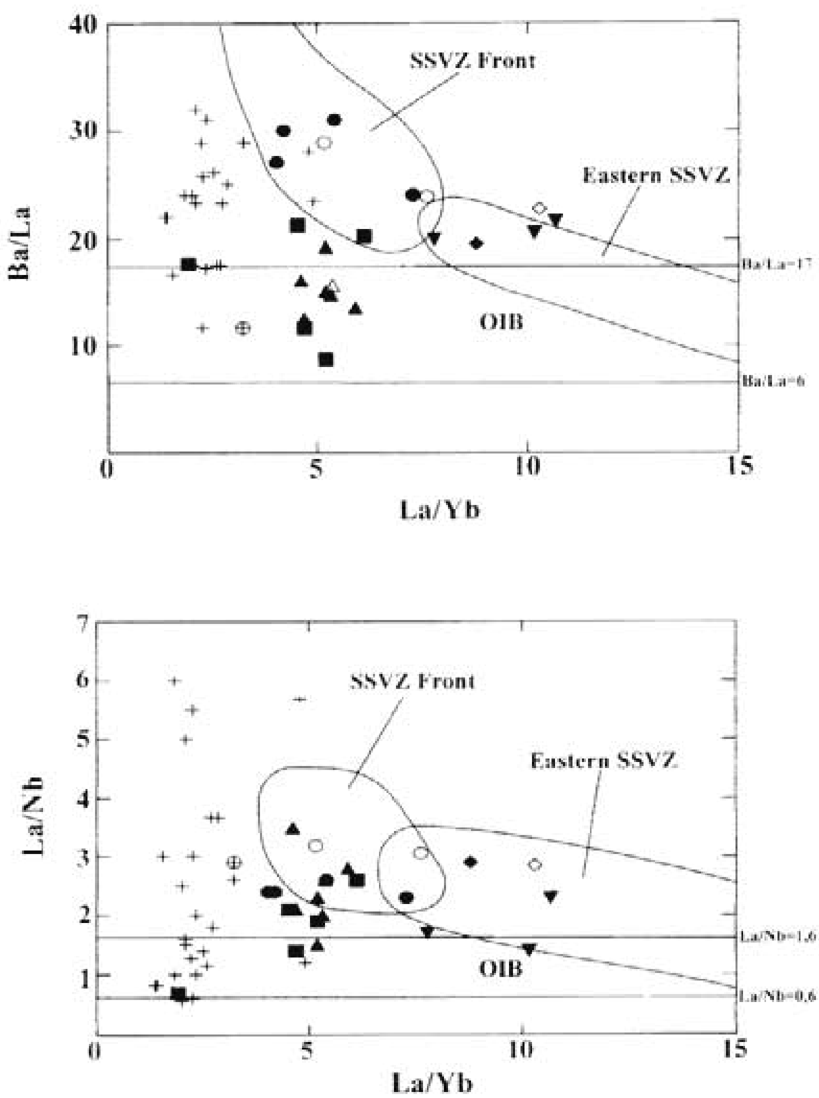


FIG. 5. Ba/La *versus* La/Yb and La/Nb *versus* La/Yb ratios for mafic and intermediate samples from the mid-Tertiary Coastal Magmatic Belt of south-central Chile between 36°S and 43.5°S. Symbols and data sources are the same as in figure 3. Fields for Andean SSVZ stratovolcanoes and Minor Eruptive Centers (MEC) from both the volcanic front and east of the front, and for ocean island basalts, are from Hickey *et al.* (1986 and 1989), Muñoz and Stern (1989), Stern *et al.* (1990), and López-Escobar and Vergara (1997).

volcanic rocks erupted from both stratovolcanoes and Minor Eruptive Centers (MEC) along the volcanic front in the southern portion of the active Andean Southern Volcanic Zone (SSVZ) at approximately similar latitude (37- 43°S; Hickey *et al.*, 1986 and 1989; López-Escobar and Vergara, 1997).

Sr, Nd (Fig. 6) and Pb isotopic ratios (Fig. 7) of these samples are also similar to both samples from this same region of the mid-Tertiary Coastal Magmatic Belt analyzed by López-Escobar and Vergara (1997), as well as to volcanic rocks erupted from along the volcanic front of the active Andean SSVZ at similar latitudes. Their $\varepsilon_{Nd(T)}$ values (+1.7 to +4.5) are lower than samples of the mid-Tertiary Coastal

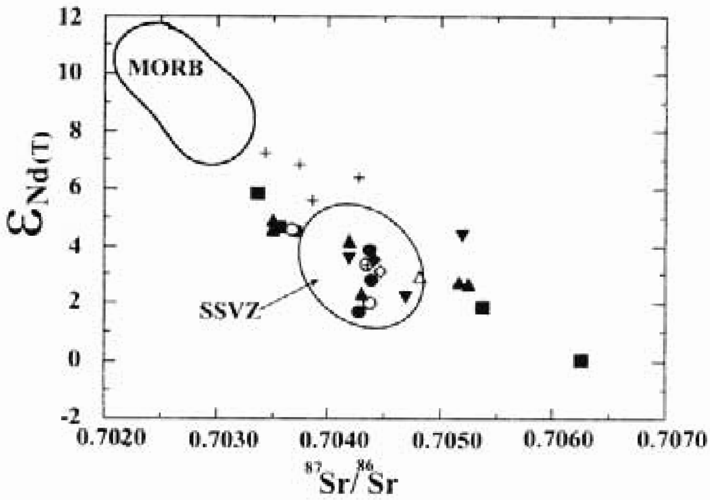


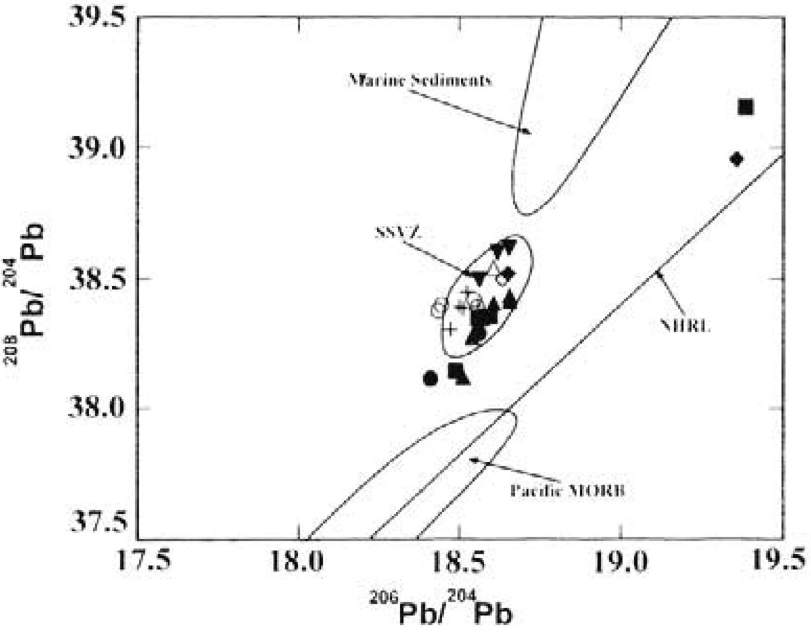
FIG. 6. Initial $^{87}Sr/^{86}Sr$ ratios *versus* $\varepsilon Nd_{(T)}$ for samples from the mid-Tertiary Coastal Magmatic Belt of south-central Chile between 36 an 43.5°S. Symbols and data sources are the same as in figure 3. Fields for Andean SSVZ stratovolcanoes and Minor Eruptive Cente (MEC) are from Hickey *et al.* (1986 and 1989), Muñoz and Stern (1989), Stern *et al.* (1990), and López-Escobar and Vergara (1997

Magmatic Belt that outcrop along the eastern margin of the Central Valley at both Colbún-Machicura (35.7°S) and Parral (36.4°S) to the north, which have $\varepsilon_{Nd(T)}$> +5, as well as relatively low La/Yb<4 (Figs. 5 and 6; Vergara *et al.*, 1997a and 1999).

BAHIA CAPITANES, ESTAQUILLAS AND CALETA PARGA (41-42°S)

A partially eroded volcanic system consisting of volcanic necks, domes, lava flows and interbedded pyroclastic and breccia layers is exposed along the Pacific coast and up to a few kilometres inland of Bahía Capitanes (41.5°S; Fig. 1), as well as on the many small island to the west of this bay (Alfaro *et al.*, 1994; Troncoso, 1999). The volcanic necks and lavas are grey to black, plagioclase+clinopyroxene±olivine bearing basaltic andesites and andesites with porphyritic to microcrystalline textures. Trachytic to intergranular groundmass consists of partially devitrified light brown glass, plagioclase microlites, clinopyroxene, and magnetite. Mafic minerals are partially altered to bowlingite and coloform silica, chlorite, and siderite. Zeolites occur in amygdules, veins and disseminated through the rocks. Hyalopylitic andesitic to dacitic breccias, interpreted as the center of a possibly submarine volcanic system (Alfaro *et al.*,1994), are formed by centimeter size reddish fragments within a tuffaceous matrix. Th originally glassy fragments, which are altered t palagonite, contain minor plagioclase and micr vesicles partially filled with calcite. Dacitic an rhyolitic domes and subvolcanic bodies, which occ east of the coast and to the south at Estaquilla have porphyritic textures with trachytic groundmas These are white due to weathering and conta plagioclase altered to sericite and mafic mineral altered to biotite.

Small outcrops of basaltic necks, vesicular lav flows, stratified pyroclastic rocks with accretiona lapilli, volcaniclastic sandstones and polymict conglomerates are also exposed over a distance about 1.5 km along the Pacific coast at Caleta Parg and Punta Puga (Fig. 1; Troncoso *et al.*, 1994 Pyroclastic rocks are crystal-rich tuffs with as plagioclase, scarce (<5%) quartz crystals, an volcanic fragments containing plagioclase and brow glass, with calcite, hematite and clays as alteratic minerals. Volcaniclastic sandstones are formed b plagioclase, ash and volcanic fragments in carbonate matrix. The pyroclastic and volcaniclast rocks and conglomerates form a 50 m thick sequenc interbedded within marine quartz sandstones ar conglomerates. The grey, plagioclase+clin pyroxene+olivine basaltic necks and lavas sho irregular columnar jointing. They have fine graine



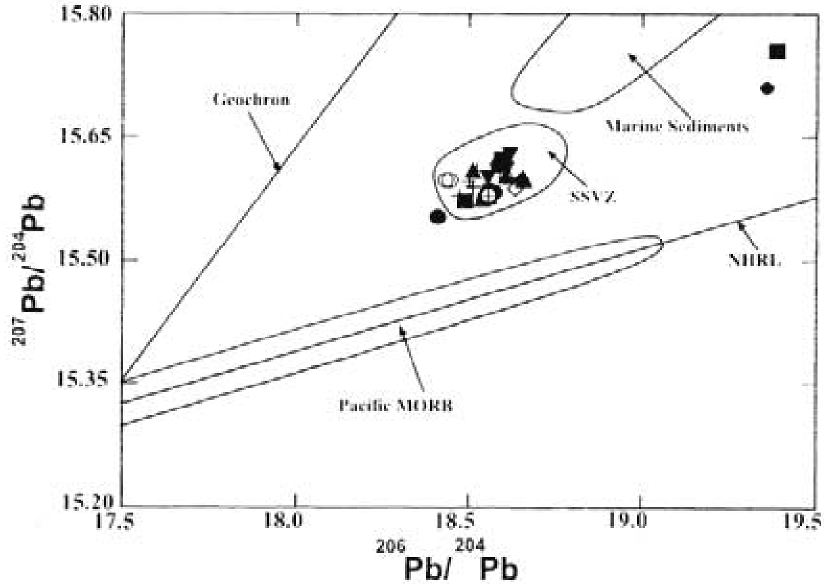


FIG. 7. $^{208}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ for samples from the mid-Tertiary Coastal Magmatic Belt of south-central Chile between 37 and 43.5°S. Symbols and data sources are the same as in figure 3. Fields for Andean SSVZ stratovolcanoes and Minor Eruptive Centers (MEC) are from Hickey *et al.* (1986, 1989); Muñoz and Stern (1989); Stern *et al.* (1990); López-Escobar and Vergara (1997). NHRL= NORTHERN HEMISPHERE REFERENCE LINE.

porphyritic to microcrystalline textures and intersertal, subophitic and microcrystalline groundmass, with aciculate ilmenite microcrysts. Mafic minerals are selectively altered to a microcrystalline aggregate of iddingsite, siderite, calcite, rutile and specularite, and plagioclase is altered to fibrous chlorite and sericite. Siderite, colloidal limonites and calcite fill vesicles.

No previous age determinations have been published for these coastal outcrops. Two new K-Ar ages for a basaltic andesite and a dacite from Bahía Capitanes range from 32.9 ± 1.6 to 27.5 ± 1.0 Ma (Table 2). No viable K-Ar ages were obtained for the samples from Caleta Parga. The alteration assemblage here is interpreted as representing interaction with seawater during or subsequent to eruption, and the degree of alteration precluded K-Ar dating.

The samples from these localities range from basalts to rhyolites. Two samples of basalt from Caleta Parga plot in the field of alkaline basalts with respect to total alkalies *versus* silica content (Fig. 3), and these samples, as well as the basaltic andesite from Bahía Capitanes, have relatively high TiO_2 (2 wt %) compared to typical calc-alkaline or tholeiitic rocks, consistent with their alkaline affinities. REE contents of these samples are higher than the andesites from the Los Angeles to Temuco area, but their La/Yb ratios (4.5 to 5.2) are similar (Figs. 4 and 5). In contrast, Ba/La (8.8 to 21.2) and La/Nb (1.4 to 2.1) ratios of these mafic samples are similar to ocean island basalts (OIB, Fig. 5; Hickey *et al.*, 1986; Stern *et al.*, 1990), and extend to significantly lower values than the samples from the Los Angeles to Temuco area, as well as compared to values for stratovolcano and MEC basalts from along the volcanic front of the active Andean SSVZ. A dacite from Bahía Capitanes has slightly higher REE, except for Eu, and similar La/Yb (6.1), Ba/La (20.2), and La/Nb (2.6), while the rhyolite from Estaquillas has significantly lower LREE and La/Yb (2.0), and an extreme negative Eu anomaly.

With respect to Sr and Nd (Fig. 6) isotopes, the basalts from Caleta Parga are similar to some samples from the Colbún-Machicura area (35.7°S; Vergara *et al.*, 1999) in the sense that they have lower $^{87}Sr/^{86}Sr$ ratios (0.70337 and 0.70356) and higher $\varepsilon_{Nd(T)}$ values (+4.7 and +5.9) than most other samples described from the mid-Tertiary Coastal Magmatic Belt or from along the volcanic front of the active Andean SSVZ, including MEC basalts (López-Escobar and Vergara, 1997). The basaltic andesite and dacite from Bahía Capitanes have higher initial $^{87}Sr/^{86}Sr$ ratios and lower initial $\varepsilon_{Nd(T)}$ and the rhyolite from Estaquillas has a significantly higher initial $^{87}Sr/^{86}Sr$ ratio, suggesting possible assimilation of Paleozoic-Triassic crust. Pb isotopic composition of the more mafic rocks are similar to magmas erupted from the active Andean SSVZ (Fig. 7), while the dacite and rhyolite have distinctly higher Pb isotopic ratios.

CHILOE (42-42.5°S)

Mid-Tertiary igneous rocks in the area of northern Chiloé Island, previously referred to as the Ancud Volcanic Complex (Vergara and Munizaga, 1974; Valenzuela, 1982; García *et al.*, 1988; Stern and Vergara, 1992) occur in and around the city of Ancud, where they are partly covered by Pleistocene glacial deposits (Heusser, 1990), and south of Ancud, where they are both interbedded with and covered by horizontal sedimentary rocks with Miocene marine invertebrate fossils. They also occur along the Pacific coast west of Ancud, at both Pumillahue and Tetas de Teguaco on the southern end of Bahía Cocotué, and as outcrops forming the coastal cliffs at Punta Polocué. These rocks include basaltic to andesitic lava flows and volcanic necks, and rhyolitic pyroclastic flows. West of Castro, at Gamboa, a series of dacitic dikes and sills are emplaced in Paleozoic-Triassic metamorphic rocks (Valdivia and Valenzuela, 1988).

Along the Pacific coast, at the southern end of Bahía Cocotué and at Punta Polocué, basaltic andesite necks and lava flows, typically with columnar jointing, have both fine grained and porphyritic textures with phenocrysts of labradorite plagioclase, clinopyroxene and olivine in a glassy groundmass. Alteration minerals include traces of iddingsite and hematite in mafic minerals, and calcite occurs in veins and fractures. Around Ancud, rocks are plagioclase+pyroxene±olivine phyric basalts and basaltic andesites with medium to fine grained porphyritic and/or aphanitic textures. Pyroclastic rocks are mainly vitric, lithic-rich rhyodacitic pyroclastic flows with fresh plagioclase, oriented fragments of both white colored and compacted black pumice, partially altered volcanic lithics, rounded clastic sedimentary fragments and carbonized wood in a recrystallized perlitic glass. The dacitic hypabyssal intrusions at Gamboa are coarse porphyritic rocks with plagioclase, quartz and minor biotite.

Vergara and Munizaga (1974) determined a K-Ar age of 40.4±1.8 Ma for the columnar neck at Punta Polocué, but later García *et al.* (1988) reported an age of 21.8 ± 1.7 Ma for a sample from the same locality. The authors have determined a new age of 24.3 ± 5.9 Ma (Table 2) for a sample from Punta Polocué, consistent with the age obtained by García *et al.* (1988) given the large error, which may be due to alteration. Three new ages determined for mafic volcanic rocks in the vicinity of Ancud range from 20.0 ± 0.9 to 22.1± 1.0 Ma (Table 2), somewhat younger than the new 23.2 ± 0.8 Ma date determined for glassy compacted pumice fragments separated from the rhyodacitic pyroclastic flow outcropping north of Ancud. A previous age determined for this same pyroclastic flow yielded a date of 25.6 ± 0.7 Ma (Stern and Vergara, 1992). A sample of the dacitic sill at Gamboa was dated as 37.2 ± 1.2 Ma.

The mid-Tertiary magmatic rocks of Chiloé range from basalts to rhyolites (Fig. 3). One basaltic andesite sample from Ancud has high TiO_2 (>2 wt%) and more alkaline affinities, similar to the samples from Caleta Parga, but other basalts and basaltic andesites are clearly subalkaline. La/Yb ratios (4.6 to 5.9) of basalts and basaltic andesites are similar to those from the Bahía Capitanes, Caleta Parga, and the Los Angeles to Temuco areas further to the north, as well as magmas erupted from along the volcanic front of the active Andean SSVZ. In contrast, Ba/La ratios (12.5 to 19.2) are similar to the samples from Bahía Capitanes and Caleta Parga, but lower than those from Los Angeles and Temuco, and from stratovolcanoes or MEC basalts located along the volcanic front of the Andean SSVZ (Fig. 5), while La/Nb ratios (1.6 to >3.5) are transitional between the values for samples from the Bahía Capitanes-Caleta Parga and the Los Angeles-Temuco areas of the mid-Tertiary Coastal Magmatic Belt. The silicic pyroclastic rocks from Ancud have elevated REE and a significant negative Eu anomaly, but similar La/Yb, Ba/La and La/Nb as the associated mafic rocks. In contrast, the dacites from Gamboa have lower HREE and higher La/Yb.

Isotopically, two basaltic andesites from Ancud have relatively low initial $^{87}Sr/^{86}Sr$ ratios (0.70354) and high $\varepsilon_{Nd(T)}$ (+4.6 and +4.9), similar to basalts from Caleta Parga and Colbún-Machicura, while other mafic samples have higher initial $^{87}Sr/^{86}Sr$ ratios and lower $\varepsilon_{Nd(T)}$ (Fig. 6). The rhyodacitic pyroclastic flow from Ancud is isotopically similar to more mafic rocks from the Ancud volcanic complex, while the two samples of dacites from Gamboa have variable Sr, Nd and Pb isotopic compositions (Fig. 7), one sample having distinctly higher Pb isotopic ratios similar to the dacite from Bahía Capitanes.

GUAPI QUILAN ISLAND (43.5°S)

Outcrops of the mid-Tertiary Coastal Magmatic Belt on both Guapi Quilán Island, and also the small group of Esmeralda Islands just south of Guapi Quilán, include volcanic necks and dikes emplaced in the metamorphic basement, and lava flows and pyroclastic deposits. The volcanic necks, dikes and lava flows are dark grey to black, aphanitic to microporphyric basaltic andesites and andesites with plagioclase, clinopyroxene, orthopyroxene, and minor olivine partially altered to iddingsite and calcite. In some areas these rocks exhibit albitization of plagioclase in association with chlorite and carbonates, suggesting interaction with seawater. In other areas, silica-pyrite alteration occurs in association with thin quartz veins. Minor pyroclastic deposits include ashfall and lapilli tuffs.

Three new K-Ar age determinations for samples from this area range from 22.0 ± 0.9 to 29.0 ± 1.1 Ma (Table 2). These three samples (Tables 1 and 3), and two other samples from these islands, are subalkaline basaltic andesites and andesites, with moderate TiO_2 (0.9 to 1.4 wt %). Their La/Yb ratios (7.1 to 10.7; Fig. 4) are higher than other mafic and intermediate rocks from the mid-Tertiary Coastal Magmatic Belt to the north, while their Ba/La (15.8 to 21.5) and La/Nb (1.3 to 2.3) ratios are similar to samples from Bahía Capitanes, Caleta Parga and Chiloé, and transitional between arc and ocean island basalts (Fig. 5). Their $^{87}Sr/^{86}Sr$ ratios, $\varepsilon_{Nd(T)}$ values, and Pb isotopic ratios are also similar to other samples from the southern portion of the mid-Tertiary Coastal Magmatic Belt (Figs. 6 and 7).

MAIN ANDEAN CORDILLERA AT LAGO RANCO (40.25°S)

Mid-Tertiary igneous and associated sedimentary rocks outcrop in the Main Andean Cordillera in a nearly continuous fashion as far south as 39°S (Fig. 1), while south of 39°S, evidence for a mid-Tertiary Main Andean Cordillera Magmatic Belt, specifically a late Oligocene to early Miocene belt, is scarce. This may be due to its removal by deep erosion, to cover produced by late Quaternary volcanic activity, or possibly that there was not extensive late Oligocene to early Miocene magmatic activity in the Main Andean Cordillera south of 39°S. There are no late Oligocene to early Miocene plutons in this portion of the southern Andes, indicating a significant hiatus in plutonism between 30 to 18 Ma (Rapela and Kay, 1988). The few spatially restricted outcrops of late Oligocene to early Miocene igneous rocks in the Main Andean Cordillera include volcanic and volcaniclastic rocks associated with continental and marine sediments deposited in small, isolated, possibly intermontane sedimentary basins (Campos *et al.*, 1998). These are cut by hypabyssal intrusions such as volcanic necks, sills, dikes, and small stocks, but not large intrusive bodies.

Outcrops of mid-Tertiary extrusive rocks south and east of Lago Ranco (Fig. 1) include a >1,000 meters thick folded sequence of porphyritic basaltic andesite, andesite and dacite lavas and partially welded tuffs, grading upwards into conglomerates, sandstones, and shales. Alteration minerals in the igneous rocks include chlorite, epidote and calcite. A representative basaltic andesite lava from this sequence has a K-Ar age of 20.7 ± 2.4 Ma (Table 2), and the sequence is intruded by Miocene granite and gabbro plutons dated between 18 and 15 Ma (Campos *et al.*, 1998). This subalkaline basaltic andesite has La/Yb, Ba/La and La/Nb ratios (Figs. 4 and 5) similar to samples from Bahía Capitanes and Chiloé in the southern portion of the Mid-Tertiary Coastal Magmatic Belt. Its La/Yb and La/Nb ratios are similar, but its Ba/La ratio is lower than magmas erupted along the volcanic front of the active Andean SSVZ. Isotopically it is similar to both other samples from the mid-Tertiary Coastal Magmatic Belt, as well as from the volcanic front of the active Andean SSVZ.

DISCUSSION

AGES

Virtually all (forty-three of forty-six) the new and previously published K-Ar age determinations for volcanic rocks from the mid-Tertiary Coastal Magmatic Belt fall within the range 29 to 18.8 Ma (Fig. 2). The three exceptions include a basaltic andesite from along the coast at Bahía Capitanes, which yielded a slightly older Oligocene age of 32.9±1.6 Ma (sample XY91; Table 2), a rhyolite along the eastern margin of the Central Valley at Colbún-Machicura (35.3 Ma; Vergara *et al.*, 1999), and the 37.2±1.6 Ma dacite sill (sample XM53; Table 2) from Gamboa, Chiloé (discussed separately below). A U-Pb age obtained in zircons from an ash fall deposit between two coal layers interbedded in a continental sedimentary sequence within the Catamutún coal mine in the Central Valley north of Osorno also yielded a late Oligocene-early Miocene age (23.5 ± 0.5 Ma; S. Elgueta and J. Urqueta[2]), as have three fisson track ages for andesites from near Parral (22.0± 8.2, 21.6±8.6 and 21.7±9.6 Ma; Vergara *et al.*, 1997b).

As a result, the authors conclude that the magmatic activity associated with the extension that formed the proto-Central Valley occurred during a single prolonged episode of 10 million years that began in the late Oligocene, after 29 Ma, and ended in the early Miocene, by 18.8 Ma (Fig. 2). Previously, López-Escobar and Vergara (1997; p. 241) suggested that the mid-Tertiary Coastal Magmatic Belt may have been formed by multiple magmatic episodes over a span of 25 million years, with 'a gradual migration, from west to east, . . . since the late Eocene'. This conclusion was based in part on a single Eocene K-Ar age (40.4 Ma; Vergara and Munizaga, 1974) obtained for a basaltic andesite from the Pacific coast at Punta Polocué, Chiloé. The authors' new K-Ar age determination for a sample from this same outcrop yielded a late Oligocene-early Miocene age of 24.3 Ma (sample XM54; Table 2), similar to that determined by García *et al.* (1988), and to other rocks from the Ancud volcanic complex, and we conclude that this outcrop is late Oligocene-early Miocene, and not Eocene in age.

The late Oligocene (29 Ma) initiation of magmatic activity in the mid-Tertiary Coastal Magmatic Belt is closely associated in age with the late Oligocene increase in both plate convergence rate, from <4 cm/yr to >10 cm/yr, and orthogonality of convergence between the Nazca and South American plates, which occurred at 27±2 Ma (Pardo-Casas and Molnar, 1987; Somoza, 1998), and not 23 Ma as stated by Cisternas and Frutos (1994) and Frutos and Cisternas (1994). Cisternas and Frutos (1994) and Frutos and Cisternas (1994) suggested that volcanic activity in the mid-Tertiary Coastal Magmatic Belt occurred prior to the initiation of high convergence rates between the Nazca and South American plates, but the data (Fig. 2) indicate that it occurred after the late Oligocene increase in trench-normal convergence rate. The relatively high rate of convergence beginning in the late Oligocene has continued to the present, with essentially orthogonal convergence during this entire time. Thus the termination in the early Miocene (18.8 Ma) of the magmatic activity in the mid-Tertiary Coastal Magmatic belt does not coincide with any obvious change in plate convergence rate or angle.

An early Miocene age (20.7 Ma) for a sample from Lago Ranco in the Main Andean Cordillera, and two other new ages of 24.6 Ma and 22.8 Ma determined by Jordan *et al.* (in press) for volcanic rocks from the Cura Mallín Formation in the Main Cordillera at 37°S, document that contemporaneous magmatic activity also occurred within the Main Cordillera, east of the mid-Tertiary Coastal Magmatic Belt. However, the spatial extent of outcrops of late Oligocene and early Miocene igneous rocks, either extrusive or intrusive, in the Main Cordillera south of 39°S is restricted, and there is no large late Oligocene to early Miocene plutonic complex in this portion of the Andes. Late Oligocene through early Miocene magmatic activity also occurred in the El Maitén Belt to the east of the current Main Andean Cordillera (Rapela *et al.*, 1988), as well as even further to the east in the Meseta de Somún Curá (Kay *et al.*, 1993, 2000). What is not clear is whether or not the mid-Tertiary magmatic activity in the Coastal, Main Cordillera, and El Maitén belts, and the Meseta de Somún Curá, consisted of spatially and/or chemically distinct igneous rocks that might be identified as fore-arc, arc or back-arc magmatic belts, or whether, as discussed below, they formed a single broad belt related to regional extension (Fig. 8).

The authors obtained an Eocene age for the dacite sill from Gamboa, west of Castro, Chiloé (37.2 ± 1.2 Ma, sample XM53; Table 2). Other late Cretaceous to early Tertiary intrusives and subvolcanic bodies have been recognised along the Coastal Cordillera near 40°S, to the west and east of Valdivia, including the Chaihuín pluton dated as 85 Ma (U-Pb in zircons) and 92 Ma (K-Ar in biotite; McDonough *et al.*, 1997), a hypabyssal basaltic-andesite exposed along the Inaque river to the north of Los Lagos (39°45'S) dated at 77 Ma (P. Duhart, J.L. Antinao, J. Clayton, M. McDonough, and S. Elgueta)[4], an altered dacitic porphyry along the Río Futa at San Ramon, dated at 52.7 Ma (K-Ar in hydrothermal sericite; Peri and Rivera, 1991), and another pluton near Lastarria (39°15'S) dated at 80 Ma (Troncoso, 1999). These late Cretaceous to early Tertiary igneous rocks are located on a tectonically uplifted block of Paleozoic-Triassic metamorphic basement lacking exposures of igneous rocks of late Oligocene and early Miocene age. These igneous rocks may represent an earlier, independent magmatic episode, distinct from that which formed the mid-Tertiary Coastal Magmatic Belt. Whether or not the outcrops at Gamboa, which also occur on an uplifted block of Paleozoic-Triassic metamorphic basement, belong to this earlier event or are related to the mid-Tertiary Coastal Magmatic Belt is uncertain.

PETROCHEMISTRY

Basalts appear to be absent in the Los Angeles to Temuco area of the Central Valley, but they do occur further to the south in the mid-Tertiary Coastal Magmatic Belt at Bahía Capitanes and Caleta Parga, as well as on the island of Chiloé. Previously, López-Escobar and Vergara (1997) concluded that andesites and dacites predominate in the Mid-Tertiary Coastal Magmatic Belt south of 37°S, but without detailed mapping of individual mid-Tertiary volcanic centers the authors suggest that there is as yet no firm basis to constrain either possible overall changes in the abundance of different rock types or other regional geochemical variations from north to south in this belt.

The new data indicate that some samples from the southern portion of the mid-Tertiary Coastal Magmatic Belt have significantly lower Ba/La (<19) and La/Nb (<1.6) ratios (Fig. 5), as well as lower initial $^{87}Sr/^{86}Sr$ ratios (<0.7035) and higher $\varepsilon_{Nd(T)}$

[4] 1998. Geología preliminar del Area Los Lagos, Chile. *In* SERNAGEOMIN, 1998. Estudio Geológico-Económico de la Xª Región Norte (Inédito). *Servicio Nacional de Geología y Minería*, Informe Registrado IR-15-98, 6 Vols.

values (>+5; Fig. 6), than magmas erupted from volcanic front of the Andean SSVZ, including both stratovolcanoes and Minor Eruptive Centers (MEC). Previously, López-Escobar and Vergara (1997) concluded that the rocks from the southern portion of the mid-Tertiary Coastal Magmatic Belt south of 37°S have trace-element contents and ratios, and isotopic compositions, similar to magmas erupted along the volcanic front of the active Andean SSVZ. For this reason, they proposed that the generation of the mid-Tertiary Coastal Magmatic Belt involved subduction related processes similar to those taking place below the western portion of the active Andean SSVZ. These processes are generally interpreted to involve dehydration of subducted oceanic lithosphere resulting in contamination and melting in the overlying mantle wedge (Hickey *et al.*, 1986 and 1989; Stern *et al.*, 1990). However, the occurrence of rocks in the mid-Tertiary Coastal Magamtic Belt with lower Ba/La and La/Nb ratios (Fig. 5), as well as lower initial $^{87}Sr/^{86}Sr$ ratios and higher $\varepsilon_{Nd(T)}$ values (Fig. 6) than magmas erupted from volcanic front of the Andean SSVZ, suggests little input of slab-derived hydrous fluids into their mantle source region.

Some samples from the mid-Tertiary Coastal Magmatic Belt also have more alkaline affinities than any rocks from the volcanic front of the active Andean SSVZ. Magmas with more alkaline affinities and lower Ba/La and La/Nb have erupted east of the active Andean volcanic front (Fig. 5; Hickey et al., 1986 and 1989; Muñoz and Stern, 1988, 1989; Stern *et al.*, 1990), but these magmas also have higher La/Yb, interpreted as indicating that as the input of slab-derived fluids decreases east of the volcanic front, the degree of mantle partial melting also decreases. However, no samples with high La/Yb (>11) ratios have been encountered within the mid-Tertiary Coastal Magmatic Belt, even among the more alkaline rocks from this belt.

As a group, the samples from the mid-Tertiary Coastal Magmatic Belt south of 36°S are distinct from those of the active Andean SSVZ arc in that they do not exhibit a negative correlation between either Ba/La or La/Nb and La/Yb (Fig. 5). For the active Andean arc, this negative correlation has been interpreted to indicate a relation between the degree of source region contamination by hydrous fluids derived from subducted oceanic crust, and the degree (percent) of mantle partial melting (Hickey *et al.*, 1986 and 1989; Stern *et al.*, 1990). It has been proposed that a greater input of hydrous slab-derived fluids, such as occurs below the Andean volcanic front compared to east of the front, results in both more contamination of the subarc mantle wedge and thus higher Ba/La and La/Nb ratios in partial melts of this wedge, and at the same time, greater degrees of mantle partial melting and thus lower La/Yb ratios in these melts.

The lack of a negative correlation between either Ba/La or La/Nb with La/Yb (Fig. 5), and the low Ba/La and La/Nb in some of the mid-Tertiary Coastal Magmatic Belt samples, suggests that dehydration of subducted slab may not have been the fundamental mechanism driving magma genesis below the proto-Central Valley between the late Oligocene and early Miocene. The fact that all the samples from the mid-Tertiary Coastal Magmatic Belt south of 37°S have Pb isotopic compositions similar to magmas erupted along the volcanic front of the active Andean SSVZ, and many have Ba/La and La/Nb ratios similar to these modern Andean arc magmas, could reflect the effects of source region contamination of the subcontinental mantle during earlier episodes of subduction of oceanic lithosphere below this portion of the southern South American continent.

The petrochemical data suggest that the genesis of the mid-Tertiary Coastal Magmatic Belt was not directly related to slab dehydration, but involved chemical heterogeneous mantle sources, including a source that resembles the asthenospheric mantle source of ocean island basalts, which is free of slab-derived components. Kay *et al.* (1993, 2000) reached a similar conclusion for late Oligocene and Miocene subalkaline and alkaline basalts from the Meseta de Somún Curá to the east of the Main Cordillera. A sample of a early Miocene basaltic andesite from the Main Andean Cordillera at 40°S is also chemically similar to rocks from the mid-Tertiary Coastal Magmatic Belt and has a relatively low Ba/La ratio compared to magmas erupted along the volcanic front of the active Andean SSVZ. This suggests that mid-Tertiary magmatic activity in the area of the Coastal and Main Cordillera, as well as further to the east, may not have been chemically distinct belts, but rather different portions of a rather broad belt of extension-related magmatic activity, which, at 42°S, extended from the Pacific coast in the west to close to the Atlantic coast in the east (Fig. 8).

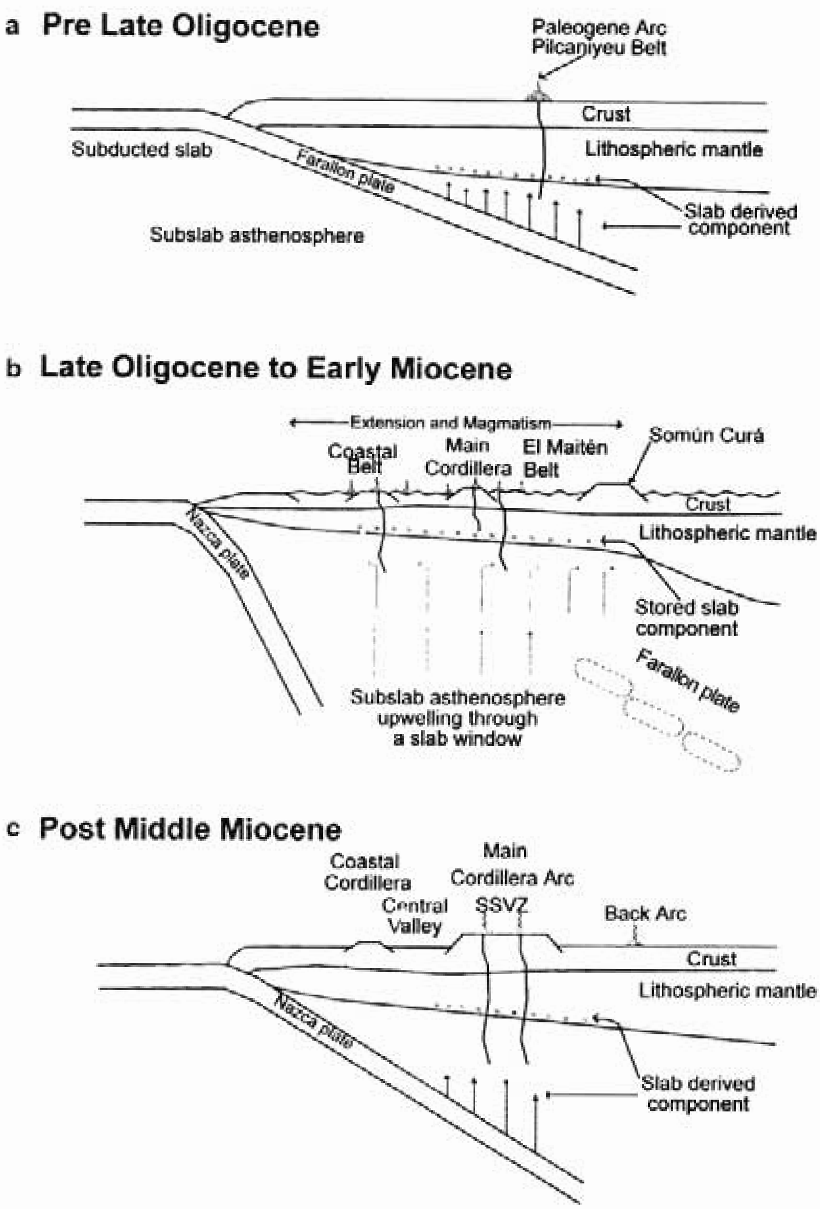


FIG. 8. Proposed schematic tectonic sections across the western margin of southern South America at 42°S, during the time period: **a-** just prior to the late Oligocene; **b-** between the late Oligocene and early Miocene; and **c-** after the mid Miocene. Prior to the late Oligocene, relatively low angle, oblique subduction of the Farallon Plate at low convergence rate (<4 cm/yr) resulted in arc volcanism which produced the Paloegene Pilcaniyeu belt east of the current continental divide (Rapela *et al.*, 1988). During the late Oligocene, more rapid (>10 cm/yr) trench-normal subduction, apparently at a steeper angle, resulted in westward migration of the volcanic front and invigorated upwelling, possibly through a slab window, and melting of subslab asthenospheric mantle uncontaminated by slab-derived components. Interaction of these asthenospheric melts with subcontinental mantle lithosphere containing stored slab-derived components, and/or the disintegrating Paleogene Farallon slab (Kay *et al.*, 1993; Kay *et al.*, in press), produced magmas with both ocean island and arc chemical affinities over a wide area extending from the Pacific coast in the west to near the Atlantic coast in the east. Late Oligocene through early to mid Miocene crustal extension occurred west of, within, and east of the Main Cordillera. Subsequently, decreasing angle of subduction returned the arc to it current position in the Main Cordillera, and caused deformation, uplift and exposure of the late Oligocene and Miocene magmatic and sedimentary rocks deposited in the proto-Central Valley, Andean intermontane, and extra-Andean basins.

GENESIS

The new and previously published data constrain the following first-order geological, chronological and petrochemical observations concerning the genesis of the mid-Tertiary Coastal Magmatic Belt south of 36°S.

- This formation of this belt involved a significant westward migration of magmatic activity from its current and previous location in the Main Cordillera, which occurred in conjunction with a broadening of the locus of magmatic activity to the east as well (Fig. 8).
- The formation of this magmatic belt was associated with extension and the early stages of development of continental and subsequently marine sedimentary basins west of the current Main Cordillera, and extension also occurred both within and well to the east of the Main Cordillera (Fig. 8).
- Magmatic activity in this belt, as well as contemporaneous magmatic activity both in and to the east of the Main Andean Cordillera, involved melting of heterogeneous mantle sources, including asthenospheric mantle uncontaminated by slab-derived fluids (Figs. 5 and 6).
- The episode of late Oligocene extension and magmatic activity west of (Fig. 2), within, and to the east of the current Main Andean Cordillera began at essentially the same time as a significant increase in the trench-normal convergence rate between the Nazca and South American plates.

It has been suggested that an increased rate of plate convergence should result in both decreased subduction angle (Luyendynk, 1970; Ruff and Kanamori, 1980) and trench-normal compression in the overriding plate (Uyeda and Kanamori, 1979; Ruff and Kanamori, 1980). However, the close correlation in time of the approximately three-fold increase in the late Oligocene trench-normal convergence rate between the Nazca and South American plates with both the initiation of extension and the westward migration of the volcanic front are inconsistent with these predictions. Jordan *et al.* (in press) reach a similar conclusion, and note that 'existing models do not offer a consensus opinion of what exactly would have happened to the subducted slab and asthenosphere wedge when convergence rate increased'. They cited studies which suggest that there is no correlation between convergence rate and the state of stress in the overriding plate (McCaffrey, 1997), and that the geometry of subduction may depend on the rate of motion of the overriding South American plate, which did not change, rather than relative convergence rate between the Nazca and South American plates (Uyeda and Kanamori, 1979; Scholz and Campos, 1995). Exactly how the geometry of subduction below the southern Andes changed in the late Oligocene cannot be determined, but the westward migration of the zone of volcanic activity that produced the mid-Tertiary Coastal Magmatic Belt appears to be related to an increase rather than a decrease in subduction angle (Fig. 8).

Jordan *et al.* (in press) suggested that, as a result of both the significant increase in the late Oligocene plate convergence rate and change in convergence direction from more to less oblique between the Nazca and South American plates, 'transient circulation patterns within the asthenospheric wedge may have been abnormally complex', possibly resulting in an 'invigorated asthenospheric circulation'. Kay *et al.* (1993, Kay *et al.*, in press) also suggested transient asthenospheric upwelling 'related to adjustments in mantle flow patterns during plate reorganization at ~27±2 Ma' as an explanation for the generation of basalts with ocean island chemical affinities erupted during the formation of the Meseta Somún Curá. The transient nature of the changes in both the subduction geometry and the asthenospheric mantle response to the late Oligocene increase in the trench-normal plate convergence rate is consistent with the fact that, by the mid to late Miocene, magmatic activity in the mid-Tertiary Coastal Magmatic Belt, as well as the Meseta Somún Curá, ceased and Andean magmatic activity returned to its previous and current locus in the Main Cordillera. However, the end of magmatic activity in the mid-Tertiary Coastal Magmatic Belt and its return its current locus in the Main Cordillera occurred without any associated change in the late Miocene plate convergence rate or direction. The chronologic constraints on magmatic activity in the mid-Tertiary Coastal Magmatic Belt (Fig. 2) suggest that, at least, 10 million years were required for a new equilibrium subduction geometry to be established.

The authors propose that the generation of the mid-Tertiary Coastal Magmatic Belt resulted from transitory processes of changing subduction geometry and invigorated mantle circulation caused by the three-fold increase in late Oligocene trench-normal convergence rates between the Nazca and

South American Plates. In this model, the fundamental cause of magmatic activity in the mid-Tertiary Coastal Magmatic Belt would not be slab dehydration, but upwelling of asthenospheric mantle in response to increased trench-normal convergence rate. The variable trace-element and isotopic composition of mid-Tertiary Coastal Magmatic Belt magmas, which in some but not all cases overlap the compositions of magmas erupted from along the volcanic front of the active Andean SSVZ, could reflect the interaction between melts derived from upwelling asthenospheric mantle and the subcontinental mantle lithosphere previously contaminated by slab-derived fluids (Stern *et al.*, 1990; Gorring and Kay, in press).

Kay *et al.* (1993; Kay *et al.*, in press) suggested that arc-like chemical signatures in some Meseta Somún Curá lavas are derived from a 'disintegrating slab associated with Paleogene subduction'. To account for the possible physical presence, during the late Oligocene, of the slab associated with Paleogene subduction below the Meseta de Somun Curá, the authors propose that the transient period of invigorated mantle upwelling that produced the mid-Tertiary Coastal Magmatic Belt may have occurred through an asthenospheric slab-window (Thorkelson and Taylor, 1989; Hole *et al.*, 1995; Thorkelson, 1996) formed between the older, pre-late Oligocene subducted Farallon oceanic lithosphere, and the younger subducting Nazca plate ocean lithosphere (Fig. 8). In the southernmost Andes, the development of a series of slab windows in association with the subduction of the Chile Ridge, and a reduction in convergence rates from approximately 10 to 2 cm/yr, has been invoked to explain the expanding zone of late Miocene and Pliocene Patagonian plateau volcanism, with variable but generally ocean island basalt chemical affinities (Ramos and Kay, 1992; Gorring *et al.*, 1997; Gorring and Kay, in press), and also the Quaternary magmatic activity with mid-ocean ridge chemical affinities on Peninsula Taitao, well west of the active Andean SSVZ (Mpodozis *et al.*, 1985; Forsythe *et al.*, 1986). In contrast, the tectonic changes that occurred across the boundary between the Nazca and South American plates during the late Oligocene involved an increase, not a decrease, in plate convergence rates, and did not involve ridge subduction. However, based on the westward migration of the volcanic front during the late Oligocene, oceanic lithosphere appears to have been subducted at a significantly greater angle below South American than prior to the late Oligocene (Fig. 8). This could have resulted in a slab window opening between the new, more steeply subducting Nazca plate oceanic lithosphere and the older, more slowly and less steeply dipping Farellon plate oceanic lithosphere. Eventually, after a period of at least 10 million years, the initially steep subduction angle of the more rapidly subducting slab flattened, closing the slab window and returning the arc to its current location in the Main Cordillera (Fig. 8).

Possible causes for extension in the fore-arc, arc and back-arc regions of convergent plate boundaries have been extensively debated (Sonder and Jones, 1999; Jordan *et al.*, in press). Furlong *et al.* (1982) suggested that rapid changes in convergence velocities across convergent plate boundaries generate changes in the profile of the subducted slab which provide an enabling mechanism for a transient episode of extension that ends once the subducting slab reaches its new equilibrium geometry. This suggestion was supported by Hynes and Mott (1985), who demonstrated that increased convergence rate between the Pacific and Indian plates during the Pliocene produced an episode of extension behind both the Tonga and Kermadec arcs. They concluded that this resulted from a migration of the trench due to changes in subduction profile, causing slab rollback (Dewey, 1980), as a consequence of the increase in convergence rates. Slab rollback, possibly combined with subduction erosion (Stern, 1991), is required through time to accommodate the westward drift of South America relative to the position of the trench boundary with the Farallon/Nazca plate (Garfunkel *et al.*, 1986). Rates of subduction erosion and trench rollback along this plate boundary may have varied through time as sporadically as other processes involved in producing the different episodes of extension versus compressive deformation and uplift in the evolution of the South American continental-oceanic convergent plate boundary margin. The changes in subduction geometry and the transient period of invigorated asthenospheric circulation which we propose as responsible for the magmatic activity that generated the mid-Tertiary Coastal Magmatic Belt may have also resulted in the late Oligocene and early Miocene extension across the southern South American continental margin by inducing an episode of slab rollback and trench migration.

Jordan *et al.* (in press) suggested other mechanisms that might have enabled the increased rate of convergence to produce extension, including increased flux of water into the intraplate zone, resulting in increased pore pressure at the base of the overriding South American lithosphere, which in turn caused a decrease in the topographic slope (Davis *et al.*, 1983), perhaps by extension, of the forearc region. However, late Oligocene extension occurred not only in the Andean forearc, but in the Main Cordillera and back-arc region as well. Alternatively, Jordan *et al.* (in press) suggested that heating of the lithosphere, due to the invigorated asthenospheric circulation and the resulting magmatic activity, could have caused uplift and extension across the continental margin.

Whatever the fundamental cause of late Oligocene extension across the southern South American continental margin, what is significant is that this extension was a transient event, as was the magmatic activity which generated the mid-Tertiary Coastal Magmatic Belt. Extension began at essentially the same time as the three-fold increase in late Oligocene trench-normal convergence rate between the Nazca and South American plates, and ended in the early to mid Miocene (Martínez and Pino, 1979; S. Elgueta and J. Urqueta[2]; Jordan *et al.*, in press). The sediments and volcanic rocks deposited in the late Oligocene and early Miocene basins west of, within, and east of the Main Cordillera were subsequently deformed and uplifted, presumably due to compression associated with the decrease in subduction angle that returned the magmatic activity to its current locus in the Main Cordillera (Fig. 8).

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REFERENCES

Alfaro, G.; Vukasovic, M.; Troncoso, R.; Cisternas, M.E. 1994. Aeromagnetometría en la ubicación de cuerpos volcánicos en el ambito de la Cordillera de la Costa Sur: El volcanismo Terciario de Punta Capitanes, Decima Región. *In Congreso Geológico Chileno, No 7, Actas*, Vol. 1, p. 556-561. Concepción.

Campos, A.; Moreno, H.; Muñoz, J.; Antinao, J.L.; Clayton, J; Martin, M. 1998. Area Futrono-Lago Ranco, 1:100.000. *Servicio Nacional de Geología y Minería, Serie Mapas Geológicos*, No. 8.

Cande, S.C.; Leslie, R.B. 1986. Late Cenozoic tectonics of the Southern Chile Trench. *Journal of Geophysical Research*, Vol. 91, p. 471-496.

Chotin, P. 1975. Los Andes meridionales et la termination du basin Andin de Lonquimay (Chili) et de Neuquén (Argentine) (lat. 38°45' S). PhD Thesis (Unpublished), *Université Pierre et Marie Curie*, 306 p.

Cisternas, M.E.; Frutos, J. 1994. Evolución tectónico-paleogeográfico de la cuenca terciaria de los Andes del sur de Chile (37°30'-40°30' L.S). *In Congreso Geológico Chileno, No. 7, Actas*, Vol. 1, p. 6-12. Concepción.

Davis, D.M.; Suppe, J.; Dahlen, F.A. 1983. Mechanics of fold-and-thrust belts and accretionary wedges. *Journal of Geophysical Research*, Vol. 88, p. 1153-1172.

Delpino, D.; Deza, M. 1995. Mapa geológico y de recursos minerales de la Provincia del Neuquén. *Dirección Nacional del Servicio Geológico*. Buenos Aires.

Dewey, J.F. 1980. Episodicity, sequence and style at convergent plate boundaries. *In* The Continental Crust and Its Mineral Deposits (Strangway, D.W.; editor). *Geological Association of Canada, Special Paper*, No. 20, p. 553-573.

Farmer, G.L.; Broxten, D.E.; Warren, R.G.; Pickthorn, W. 1991. Nd, Sr, and O isotopic variations in metaluminous ash-flow tuffs and related volcanic rocks at the Timber Mountain/Oasis Valley Caldera Complex, SW Nevada, implications for the origin and evolution of large-volume silicic magma bodies. *Contributions to Mineralogy and Petrology*, Vol. 109, p. 53-68.

Forsythe, R.D.; Nelson, E.P.; Kaeding, M.E.; Carr, M.J.; Hervé, M.; Mpodozis, C.; Soffia, J.M.; Harambour, S. 1986. Pliocene near trench magmatism in southern

Chile: a possible manifestation of ridge subduction. *Geology*, Vol. 14, p. 23-37.

Frutos, J.; Cisternas, M.E. 1994. Análisis tectónico-estructural de los Andes del sur de Chile durante el Cenozoico. *In Congreso Geológico Chileno, No. 7, Actas*, Vol. 1, p. 32-37. Concepción.

Furlong, K.P.; Chapman, D.S.; Alfeld, P.W. 1982. Thermal modeling of the geometry of subduction with implications for the tectonics of the overriding plate. *Journal of Geophysical Research*, Vol. 87, p. 1,786-1,802.

García, A.; Beck, M.; Burmester, R.; Munizaga, F.; Hervé, F. 1988. Paleomagnetic Reconnaissance of the Region de Los Lagos, Southern Chile, and its tectonic implications. *Revista Geológica de Chile*, Vol.15, No 1, p. 13-30.

Godoy, E.; Kato, T. 1990. Late Paleozoic serpentinites and mafic schists from the Coastal Range accretionary complex, central Chile: their relation to aeromagnetic anomalies. *Geologische Rundschau*, Vol. 79, No. 1, p. 121-130.

Gorring, M.L.; Kay, S.M. In press. Mantle processes and sources of Neogene slab window magmas from southern patagonia, Argentina. *Journal of Petrology*.

Gorring, M.L.; Kay, S.M.; Zeitler, P.K.; Ramos, V.A.; Rubiolo, D.; Fernández, M.I.; Panza, J.L. 1997. Neogene Patagonian plateau lavas: Continental magmas associated with ridge collision at the Chile Triple Junction. *Tectonics*, Vol. 16, p. 1-17.

Hynes, A.; Mott, J. 1985. On the causes of back-arc spreading. *Geology*, Vol. 13, p. 387-389.

Hervé, F.; Pankhurst, R.J.; Drake, R.; Beck, M.E. 1995. Pillow metabasalts in a mid-tertiary extensional basin adjacent to the Liquiñe-Ofqui fault zone: the Isla Magdalena area, Aysén, Chile. *Journal of South American Earth Sciences*, Vol. 8, p. 33-46.

Heusser, C. 1990. Chilotan piedmont glacier in the southern Andes during the last glacial maximum. *Revista Geológica de Chile*, Vol. 17, No. 1, p. 3-18.

Hickey, R.L.; Frey, F.A.; Gerlach, D.C.; López-Escobar, L. 1986. Multiple sources for basaltic arc rocks from the Southern Volcanic Zone of the Andes (34°-41°S): Trace element and isotopic evidence for contributions from subducted oceanic crust, mantle and continental crust. *Journal Geophysical Research*, Vol. 91, No. 6, p. 5963-5983.

Hickey-Vargas, R.; Moreno, H.; López Escobar, L.; Frey, F. 1989. Geochemical variations in Andean basaltic and silicic lavas from the Villarrica-Lanín volcanic chain (39.5°S): an evaluation of source heterogeneity, fractional cristallization and crustal assimilation. *Contributions to Mineralogy and Petrology*, No. 103, p. 361-386.

Hole, M.J.; Saunders, A.D.; Rogers, G.; Sykes, M.A. 1995. The relationship between alkaline magmatism, lithospheric extension and slab window formation along destructive plate margins. *Geological Society of London, Special Publication*, No. 81, p. 265-285.

Jordan, T.E.; Burns, W.M.; Veiga, R.; Pángaro, F.; Copeland, P.; Kelley, S.; Mpodozis, C. In press. Extension and basin formation in the southern Andes caused by increased convergence rate: A mid-Cenozoic trigger for the Andes. *Tectonics*.

Karzulovic, J.; Hausser, H.; Vergara, M. 1979. Edades K/Ar en rocas volcánicas e intrusivas del área de los proyectos hidroeléctricos Colbún-Machicura, Melado, ENDESA. *In Congreso Geológico Chileno, No. 2, Actas*, Vol. 4, p. J127-J133. Arica.

Kay, S.M.; Ardolino, A.A.; Frachi, M.; Ramos, V.A. 1993. El origen de la meseta de Somún Curá: distribución y geoquímica de sus rocas volcánicas máficas. *In Congreso Geológico Argentino, No. 12* y *Congreso de Exploración de Hidrocarburos, No. 2*, Vol. 4, p. 236-248.

Kay, S.M.; Ardolino, A.A.; Gorring, M.L.; Ramos, V.A. In press. The Patagonian Somuncura large igneous province: interaction of a late Oligocene hotspot-like anomaly with a subducted slab. *Journal of Petrology*.

Kelm, U.; Cisternas, M.E.; Helle, S.; Méndez, D. 1994. Diagenetic character of the Tertiary basin between Los Angeles and Osorno. *Revista Geológica de Chile*, Vol. 21, No. 2, p. 241-252.

López-Escobar, L.; Frey, F.A.; Vergara, M. 1976. Andesites from central-south Chile: Trace elements abundances and Petrogenesis. *In AIVCEI Proceedings Symposium on Andean and Antarctic Volcanology Problems* (González-Ferrán, O.; editor), p. 725-761.

López-Escobar L.; Vergara, M. 1997. Eocene-Miocene Longitudinal Depression and Cuaternary volcanism in the Southern Andes, Chile (33-42.5°S). Revista *Geológica de Chile*, Vol. 24, No. 2, p. 227-244.

Luyendynk, B.P. 1970. Dips of downgoing lithospheric plates beneath island arcs. *Geological Society of America, Bulletin*, Vol. 81, p. 3411-3416.

Martínez, R.; Pino, M. 1979. Edad, paleoecología y sedimentología del Mioceno marino de la Cuesta Santo Domingo, Valdivia, X Region. *In Congreso Geológico Chileno, No. 2, Actas*, Vol. 2, p. C311-C325. Arica.

McCaffrey, R. 1997. Influences of recurrance times and fault zone temperatures on the age-rate dependence of subduction zone seismicity. *Journal of Geophysical Research*, Vol. 102, p. 22/839-22/854.

McDonough, M.; Duhart, P.; Crignola, P. 1997. Naturaleza del alzamiento del basamento costero y la apertura de la cuenca Osorno-Llanquihue, Xa Región: nuevos antecedentes sísmicos y observaciones de terreno. *In Congreso Geológico Chileno, No. 8, Actas*, Vol. 2, p. 164-168. Antofagasta.

McDonough, M.; Duhart, P.; Herrero, C.; Van der Velden, A.; Cook, F.; Martin, M.; Ugalde, H.; Villeneuve, M; Mpodozis, C. In press. Accretionary tectonics and basin evolution on the southwestwern margin of gondwana, southern Chile: implications of new crustal seismic and geochronological results. *Tectonics*.

Mpodozis, C.; Hervé, M.; Nasi, C.; Soffia, J.; Forsythe, R.; Nelson, E. 1985. El magmatismo Plioceno de la Península Tres Montes y su relación con la subducción del Punto Triple de Chile Austral. *Revista Geológica de Chile*, No. 25-26, p. 13-28.

Muñoz, J. 1997. Sistemas estructurales Cenozoicos en la Región de los Lagos de Chile. Interpretación de Lineamientos en Imagen Radarsat. *In Congreso Geológico Chileno, No. 8, Actas*, Vol. 1, p. 190-194. Antofagasta.

Muñoz, J.; Stern, C.R. 1988. The Quaternary volcanic belt of the southern continental margin of South America: transverse structural and petrochemical variations across the segment between 38°S and 39°S. *Journal of South American Earth Sciences*, Vol. 1, p. 147-161.

Muñoz, J.; Stern, C.R. 1989. Alkaline magmatism within the segment 38-39°S of the Plio-Quaternary volcanic belt of the southern South American continental margin. *Journal of Geophysical Research*, Vol. 94, p. 4/545-4/560.

Muñoz, J.; Duhart, P.; Crignola, P.; Farmer, G.L.; Stern, C.R. 1997. The mid-Tertiary coastal magmatic belt, south-central Chile. *In Congreso Geológico Chileno, No. 8, Actas*, Vol. 3, p. 1,694-1,698. Antofagasta.

Nullo, F. E.; Franchi, M.; González, P.; Herrero, J. C.; Reinoso, M. S. 1993. Mapa Geológico de la Provincia de Río Negro. *Dirección Nacional del Servicio Geológico*. Buenos Aires.

Nyström, J.; Parada, M.A.; Vergara, M. 1993. Sr-Nd isotope compositions of Cretaceous to Miocene volcanic rocks in central Chile: a trend towards a MORB signature and a reversal with time. *Second ISAG, Extended Abstracts*, p. 21-23. Oxford.

Pardo-Casas, F.; Molnar, P. 1987. Relative motion for the Nazca (Farallon) and South America plates since late Cretaceous time. *Tectonics*, Vol. 6, p. 233-248.

Peri, M.; Rivera, S. 1991. Mineralización aurífera en Ramón, Valdivia, Región de Los Lagos, Chile. *In Congreso Geológico Chileno, No. 6, Actas*, Vol. 1, p. 166-168. Viña del Mar.

Ramos, V.A.; Kay, S.M. 1992. Southern Patagonian plateau basalts and deformation: Backarc testimony of ridge collision. *Tectonophysics*, Vol. 205, p. 261-282.

Ramos, V.A.; Neimeyer, H.; Skarmeta, J.; Muñoz, J. 1982. The magmatic evolution of the Austral patagonian Andes. *Earth Science Reviews*, Vol. 18, p. 411-443.

Rapela, C.W.; Kay, S.M. 1988. Late paleozoic to recent magmatic evolution of northern Patagonia. *Episodes*, Vol. 11, p. 175-182.

Rapela, C.W.; Spalletti, L.A.; Merodio, J.C.; Aragón, E. 1988. Temporal evolution and spatial variation of early Tertiary volcanism in the Patagonian Andes. *Journal of South American Earth Sciences*, Vol. 1, No. 1, p. 75-88.

Rubio, X. 1993. Geología regional y estratigrafía del Terciario de la cuenca de Labranza, IX Región. Memoria de Título (Inédito), *Universidad de Chile, Departamento de Geología*, 132 p.

Ruff, L.; Kanamori, H. 1980, Seismicity and the subduction process. *Physics of the Earth and Planetary Interiors*, Vol. 23, p. 240-252.

Scholz, C.H.; Campos, J. 1995. On the mechanism of seismic decoupling and back-arc spreading at subduction zones. *Journal of Geophysical Research*, Vol. 100, p. 22103-22115.

Servicio Nacional de Geología y Minería. 1982. Mapa Geológico de Chile (Escobar, F.; editor). *Servicio Nacional de Geología y Minería*.

Somoza, R. 1998. Updated Nazca (Farallon) -South America relative motions during the last 40 My: implications for mountain building in the central Andean region. *Journal of South American Earth Sciences*, Vol. 11, p. 211-215.

Sonder, L.J.; Jones, C.H. 1999. Western United States extension: How the west was widened. *Annual Reviews of Earth and Planetary Sciences*, Vol. 27, p. 417-462.

Spalletti, L.A.; Dalla-Salda, L. 1996. A pull apart volcanic related Tertiary Basin, an example from the Patagonian Andes. *Journal of South American Earth Sciences*, Vol. 9, p. 197-206.

Stern, C.R. 1991. Role of subduction erosion in the generation of Andean magmas. *Geology*, Vol. 19, No. 1, p. 78-81.

Stern, C.R.; Vergara, M. 1992. New age of the vitrophyric rhyolite-dacite from Ancud (42°S), Chiloé, Chile. *Revista Geológica de Chile*, Vol. 19, No. 2, p. 249-251.

Stern, C.R.; Frey, F.A.; Futa, K.; Zartman, R.E.; Peng, Z.; Kyser, T.K. 1990. Trace element and Sr, Nd, Pb and O isotopic composition of Pliocene and Quaternary alkali basalts of the Patagonian plateau lavas of southernmost South America. *Contributions to Mineralogy and Petrology*, Vol. 104, p. 294-308.

Stern, C.R.; Muñoz, J.; Troncoso, R.; Duhart, P.; Crignola, P.; Farmer, G.L. 2000. The Mid-Tertiary Coastal Magmatic Belt in south-central Chile: The westernmost portion of an extensional event related to late Oligocene changes in plate convergence rate and subduction geometry. *In Congreso Geológico Chileno, No. 9, Actas*, Vol. 2, p. 693-696. Puerto Varas.

Tebbens, S.F.; Cande, S.C. 1997. Southeast Pacific tectonic evolution from early Oligocene to Present. *Journal of Geophysical Research*, Vol. 102, No. B6, p. 12061-12084.

Thiele, R.; Beckar, I.; Levi, B.; Nyström, J.O.; Vergara, M. 1991. Tertiary andean volcanism in a caldera-graben setting. *Geologische Rundschau*, Vol. 80, p. 179-186.

Thorkelson, D.J. 1996. Subduction of diverging plates and principles of slab window formation. *Tectonophysics*, Vol. 255, p. 47-63.

Thorkelson, D.J.; Taylor, R.P. 1989. Cordilleran slab windows. *Geology*, Vol. 17, p. 833-836.

Troncoso, R.; Cisternas, M.E.; Alfaro, G.; Vukasovic, M.1994. Antecedentes sobre el volcanismo Terciario, Cordillera de la Costa, X Región, Chile. *In Congreso Geológico Chileno, No. 7, Actas*, Vol. 1, p. 205-209, Concepción.

Troncoso, R. 1999. Caracterización petrográfica y geoquímica del cinturón volcánico de la costa en el ámbito de las cuencas terciarias del sur de Chile (37°00'-41°45'S). Graduation Thesis (Inédito), *Universidad de Concepción*, 120 p.

Ugalde, H.; Yañez, G.; Muñoz, J. 1997. Dominios magnéticos en la región de Los Lagos. *In Congreso Geológico Chileno, No. 8*, Vol. 1, p. 283-286. Antofagasta.

Uyeda, S.; Kanamori, H. 1979. Back-arc opening and the mode of subduction. *Journal of Geophysical Research*, Vol. 84, p. 1049-1061.

Valdivia, S.; Valenzuela, E. 1988. Volcanitas riodacíticas de Gamboa, Isla de Chiloé, X Región, Chile. *In Congreso Geológico Chileno, No. 5, Actas*, Vol. 3. 261-273. Santiago.

Valenzuela, E. 1982. Estratigrafía de la Boca Occidental del Canal de Chacao, X Región, Chile. *In Congreso Geológico Chileno, No. 3, Actas*, Vol. 1, p. A343-A376.

Vergara, M. 1982. Andesitas subvolcánicas miocénicas entre Los Angeles y Temuco: su petrología y mineralogía. *In Congreso Geológico Chileno, No. 3, Actas*, Vol. 2, p. 202-233. Concepción.

Vergara, M.; Munizaga, F. 1974. Age and evolution of the Upper Cenozoic andesitic volcanism in central-south Chile. *Geolocical Society of America, Bulletin*, Vol. 85, p. 603-606.

Vergara, M.; López-Escobar, L.; Hickey-Vargas, R.M. 1997a. Geoquímica de las rocas volcánicas miocenas de la cuenca intermontana de Parral y Ñuble. *In Congreso Geológico Chileno, No. 8*, Actas, Vol. 2, p. 1570-1573. Antofagasta.

Vergara, M.; Moraga, J.; Zentilli, M. 1997b. Evolución termotectónico de la cuenca terciaria entre Parral y Chillán: análisis por trazas de fisión en apatitas. *In Congreso Geológico Chileno, No. 8, Actas*, Vol. 2, p. 1,574-1,578. Antofagasta.

Vergara, M.; Morata, D.; Hickey-Vargas, R.M.; López-Escobar, L. 1999. Geoquímica de las rocas volcánicas del Terciario del área de Colbún, Precordillera de Linares, Chile Central (35°35'-36°60'S). *Revista Geológica de Chile*, Vol. 26, No. 1, p. 23-41.

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