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Geochemical variations in Cenozoic back-arc basalts at the border of La Pampa and Mendoza provinces, Argentina

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ABSTRACT

Back-arc volcanism was active in central-western Argentina (provinces of Mendoza and La Pampa) from the Miocene through historic times. The rocks of 39 monogenetic volcanoes located in this area were studied in order to define their geochemical characteristics. The dominant rock texture is porphyritic, with intergranular, pilotaxitic and hyalophitic groundmasses. The most frequent phenocrysts are olivine followed by olivine–plagioclase–clinopyroxene. Their SiO_2 content varies between 42.3 and 51.2 wt.%, the most abundant rocks are trachybasalts, followed by basalts and basanites, all of them alkaline. The rocks display enrichment of incompatible elements that varies according to the geographic location and age. There is an increase in incompatible element concentrations from the southern and central to the northern zones. Also, in the northern part of the study area, the behavior of incompatible elements varies with time; the incompatible element ratios of the Plio–Pleistocene rocks show arc signature, while the rocks of the Miocene De la Laguna volcano show intraplate affinity. We conclude for this sector that the mantle source region was modified after the generation of Miocene magmas by subduction-related fluids. These fluids are related to a late Miocene episode of subhorizontal subduction, i.e., after the generation of the rocks of De la Laguna volcano.

1. Introduction

Back-arc basalts from Patagonia in Argentina (Palaeocene–Holocene) constitute one of the largest Cenozoic continental basaltic provinces on earth (Kay et al., 2004). The outcrops of the so-called Patagonian Basaltic Province cover a surface of ca. 2,00,000 km^2, stretching between 35°S and 52°S. The origin of these basalts has been related to mechanical perturbations of the subcontinental mantle, as a consequence of subduction of the oceanic lithosphere below the South American continental plate (Skewes and Stern, 1979). On the other hand, back-arc magmatism of northern Patagonia (Somuncurá Plateau) has been related to the presence of transitory hot spots (Kay et al., 1993), to slab-induced shallow asthenospheric upwelling caused by slab rotation (De Ignacio et al., 2001), and to multiple upwelling of a hydrous melt derived from up-warped mantle transition zone (Orihashi et al., 2006; Honda et al., 2006). Farther north, back-arc basalts in Mendoza and La Pampa provinces have been considered as indicators of extensional events produced after the main compressive phase during the Tertiary and probably generated by mechanical and thermal modifications of the upper mantle produced by subduction (Bermúdez et al., 1993). By the way, Kay (2002) and Kay et al. (2004, 2006) related the eruption of the extensive plateau lavas of northern Neuquén and southern Mendoza (35°S–38°S) to the melting of hydrated mantle after a temporary low-angle subduction episode in the late Miocene (Kay and Mancilla, 2001).

There are several contributions dealing with the geochemistry of Patagonian basalts (e.g., Stern, 2004; Kay et al., 2004, 2006, and references therein), and the basaltic volcanism of Mendoza (Bermúdez et al., 1993; Saal et al., 1995; Nullo et al., 2002), but none about the geochemistry of the basalts from the study area reported in this contribution. Stern et al. (1990), based on the trace elements content and isotope ratios, divided the Pliocene to Quaternary basalts of the Southern Volcanic Zone (Patagonia, 34°S–52°S) in cratonic and transitional. These authors indicated that the transitional basalts possess arc-like geochemical features acquired during the generation of these basalts, or in a previous contamination episode; on the other hand the cratonic basalts have a geochemical signature with strong similarities to ocean island basalts. In this sense, Kay et al. (2004) showed that the Pliocene to Recent back-arc magmas north of 38°S have an intraplate-like chemistry with little to no arc-like features.

Slightly south of this study area, the basalts of the Central Southern Volcanic Zone (37°–41°30′S) show, progressively east-

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wards of the volcanic front, a decrease in the Ba/La, La/Nb, and Ba/Nb ratios. This could be the result of a decrease in the input of slab-derived fluids into the mantle source of those magmas located behind the volcanic front, probably as a consequence of progressive dehydration of the down-going slab (Futa and Stern, 1988; Stern, 2004). By the way, alkali basalts from the back-arc region, derived by low degrees of partial mantle melting, exhibit lower values of the Ba/La, La/Nb, and Ba/Nb ratios, similar to those of ocean island basalts, i.e., without evidence of slab-derived components (Stern et al., 1990; Gorring and Kay, 2001). To the northwest of the study area, in the Llancanelo Volcanic Field (back-arc 35°–36°15′S), Bermúdez et al. (1993) pointed out the presence of arc components at the basalt source during the Chapualitense (Pliocene–Pleistocene) eruptive epoch. This differs from the basalts of the Puentelitense (Pleistocene) basaltic epoch, which show a transitional character. These authors also stated that the arc components stop appearing in the Tromenlitense (Holocene) eruptive epoch in the Payún Matru Volcanic Field (back-arc 36°S–37°S). Likewise, Saal et al. (1995) found temporal geochemical variations in Plio–Quaternary alkaline lavas erupted 50–250 km behind the volcanic front (35°S–37°S). For the volcano Nevado area, these authors indicated that arc geochemical signature in lavas decreases with decreasing eruption age, and for the first time correlated these trends with an increase of the angle and/or rate of subduction of the Nazca plate. This increase in the angle of subduction must have occurred after a period of slab flattening that happened during the upper Miocene, as proposed for the south of Mendoza by Ostera et al. (2000, 2006) and Kay and Mancilla (2001).

This study is based on the survey of the 39 eruptive centers located in the area near the boundary between the provinces of La Pampa and Mendoza. In this region there is a large basalt field formed by lava flows and numerous associated pyroclastic cones. They represent the easternmost expression of the extra-Andean back-arc volcanism north of Patagonia and south of 35°S. The volcanic centers of this study lie 460–540 km east of the Chile trench.

The objective of this work is to present new geochemical data of major and trace element contents, and Sr isotope ratios of the rocks that constitute the Cenozoic basaltic eruptive centers placed along the eastern margin of the Argentine extra-Andean back-arc volcanic zone, between 36°S and 37°30′S and east of 68°40′W (provinces of La Pampa and Mendoza, Figs. 1 and 2). Moreover, we contrast our data with those of Patagonian basalts and basement rocks, in a first attempt to understand the geochemical variations in the magmas and the possible causes of such variations.

2. Geological setting

In the northern part of the study area the volcanoes are over the northwestern part of the Las Matras Block (Sato et al., 2000; Llambías et al., 2003), and the eruptive centers of the central and southern zones are located along the eastern margin of the Neuquén Basin (Jurassic–Paleogene). The Las Matras Block is composed of middle Proterozoic tonalites and trondhjemites, Ordovician limestone (San Jorge Formation), and quartz sandstones of Upper Carboniferous age (Agua Escondida Formation) (Llambías et al., 2003). The units of the Las Matras Block are intruded and covered by rocks of Permian to Lower Triassic age grouped in the Choiyoi Group (Llambías et al., 1993). The rocks of the Choiyoi Group are widespread in the northern area of this study, and are mainly rhyolitic in composition (Fig. 2). In the southern area of this study, the rocks of the Choiyoi Group constitute the basement of the Neuquén Basin. There, the exposed rocks are mainly sandstones assigned to the late Cretaceous by Holmberg (1962). Widespread over all the area there are evaporites, alluvial, and principally aeolian deposits of Holocene age.

Volcanism in the extra-Andean back-arc zones of Mendoza and La Pampa has been active since the Miocene (González Díaz, 1979) up to prehistoric times (Groeber, 1946; Inbar and Risso, 2001). During the Pliocene–Holocene – between 35°S and 38°S – large volumes of basalt generated the volcanic fields of Llancanelo, Payún Matru, Chachahuen and Auca Mahuida. These were the most important lava flow fields in Patagonia during this period (Kay, 2002). The products of these flows in Llancanelo and Payún Matru were grouped in the Andino-Cuyana Basaltic Province by Bermúdez and Delpino (1989). Their outcrops cover an area of approximately 15,900 km^2 (Bermúdez et al., 1993) in the provinces of Mendoza and La Pampa. Llancanelo and Payún Matru volcanic fields are formed by two large Tertiary andesitic-trachytic composite volcanoes (Nevado and Payún Matru), with widespread lava flows, and numerous cinder cones mostly concentrated around the volcanoes. For the Pliocene/Holocene time span, Bermúdez et al. (1993) recognized three periods of highest activity, calling them Chapualitense (upper Pliocene–lower Pleistocene), Puentelitense (Pleistocene) and Tromenlitense (Holocene) eruptive epochs.

In this contribution, for the basaltic rocks we adopt the lithostratigraphic units defined by Bertotto (2003), summarized as follows. The oldest basaltic rocks are those of the La Parva (Oligocene) (#25 in Fig. 2) and De la Laguna (Miocene) (#19 in Fig. 2) volcanic necks, which are included in the La Parva Basalt. Narciso et al. (2001) included the rocks of La Parva volcano in the La Parva Formation (Oligocene–Miocene).

The name Chapúa Group is used – following Bermúdez et al. (1993) – to group the basalt eruptions of the Pliocene and early Pleistocene that occurred during the Chapualitense eruptive epoch. This unit includes lava flows widespread in the study area and several eroded monogenetic cones. The rocks of this unit exposed in the area near Agua Escondida were previously assigned to the Pleistocene and included in the Morado Alto (González Díaz, 1972) and Chapúa (Narciso et al., 2001) formations. The eruptive centers that compose the Chapúa Group are Loma Chica Oeste (1), Loma Chica Este (2), Loma Chica Sur (3), El Oscuro (4), Negro 3 (5), Negro 2 (6), Morado 2 (7), Chato (8), Negro 1 (9), Agua de Torres (10), Chato Segundo (11), Del Chivo (12), Los Corrales (13), El Lindero (14), El Peludo (15), Loma Jagüel del Moro (20), Puntudo (21), Amarillo (22), La Negra (23), Tordillo (24), Morado 1 (26), Tapa (27), Los Carrizales (28), Escorial (31), Huanul (33), Rial (38), Morado 3 (39). In parenthesis is indicated the number of each center in Fig. 2.

Included in the Puente Group (Pleistocene) are the rocks generated during the Puentelitense eruptive epoch defined by Bermúdez et al. (1993) for Mendoza, which in the studied area include pahoehoe basalt lava flows (El Mollar Basalt) and monogenetic volcanoes. The El Mollar Basalt is composed of olivine basalt flows exposed in the northwestern sector of the department of Puelén and southwestern sector of the department of Chical Co. These flows were included in the El Puente Formation (Holocene) by Narciso et al. (2001). We include in the Puente Group the following eruptive centers: De Díaz 1 (16), De Díaz 2 (17), De Díaz 3 (18), Del Nido (29), Ñire Co (30), Agua Poca (32), El Pozo (34), La Yegua (35), La Blanca (36) and El Águila (37); in parenthesis is indicated the number of each center in Fig. 2.

3. Analytical methods

X-ray fluorescence (XRF) chemical analyses (whole rock) for major elements and some trace elements were made for samples from 36 eruptive centers. Major elements in samples AP61, N29 and A46 were analyzed by Fusion-ICP, and trace elements by ICP–MS (Bertotto, 2000). Selected samples of each area were analyzed using ICP–MS methods, and $^{87}Sr/^{86}Sr$ ratios were obtained from seven.

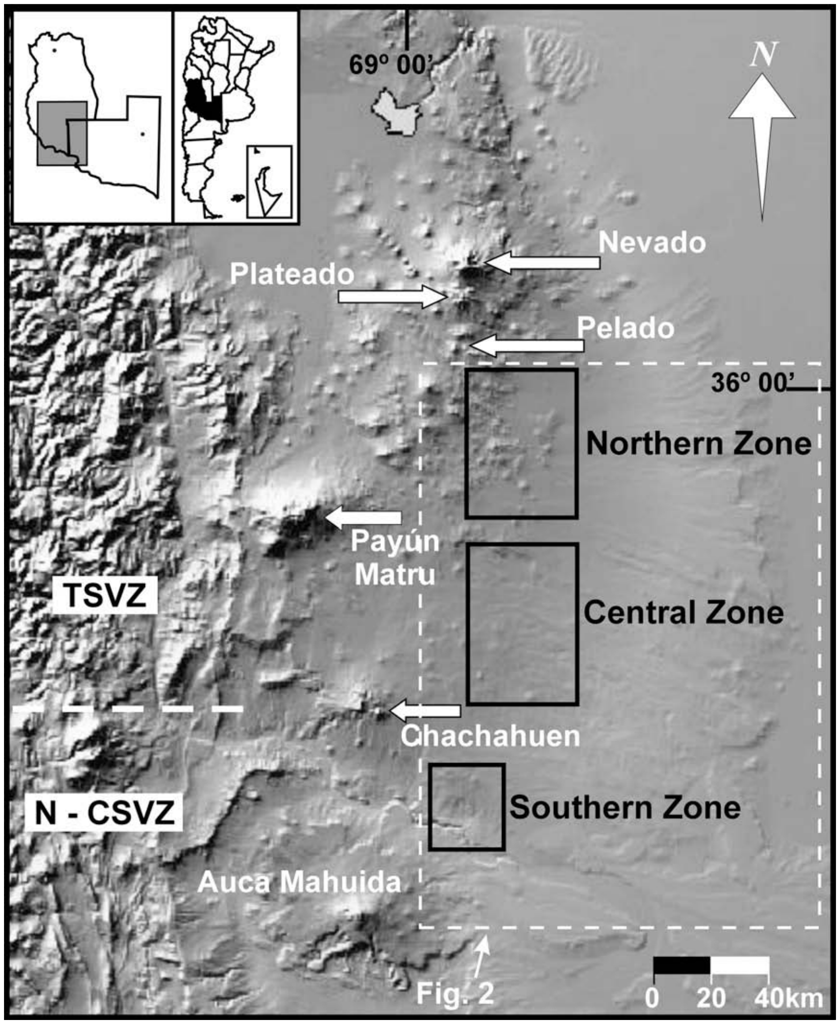

Fig. 1. Satellite image of the border zone between La Pampa, Mendoza and Neuquén provinces, with the studied zones, the Upper Tertiary arc volcanoes Nevado–Plateado–Pelado, Payún Matru and Chachahuen. Also shown is the basaltic volcanic complex Auca Mahuida.

Samples of the volcanoes Ñire Co (Ñ4), Tapa (TA6), Morado 1 (M100), Los Carrizales (CA4), La Parva (PA10), La Negra (NE6), Tordillo (TO7), Amarillo (AM7), Jagüel del Moro (JM4), Puntudo (PU7), Loma Chica Este (LE2), Loma Chica Oeste (LO1), Loma Chica Sur (SN1) and De Díaz 3 (DZ13) were analyzed at the Dipartimento di Scienze della Terra of the Università degli Studi di Modena e Reggio Emilia, Modena, Italy, using a Philips PW1480 XRF. Rock samples of the eruptive centers De la Laguna (LA19), Negro 3 (NO7), Chato (CH7), El Oscuro (OS9), Morado 2 (M4), Chato Segundo (CS2), Del Chivo (DC8), Los Corrales (C6), Agua de Torres (AT9), El Lindero (LI2), Negro 1 (NA2), Negro 2 (NL13), El Peludo (P9), De Díaz 1 (DA1), De Díaz 2 (DB6), Huanul (HU6), La Blanca (B9), El Águila (AG8), Morado 3 (MO14), Del Pozo (PO3), La Yegua (Y9) and Rial (RI4) were analyzed by XRF at the Universidade Federal do Rio Grande do Sul (Porto Alegre, Brazil) with a Rigaku RIX 2000. In both cases, analyses are considered accurate to within 2–5% for major elements and within 10% for trace elements. FeO was determined as total iron oxide (Fe_2O_3).

Analyses of bulk-rock trace elements were provided by Activation Laboratories Ltd. (ActLabs), Canada, for samples of the volcanoes Morado 1 (M100), Ñire Co (Ñ4), Huanul (HU6), La Blanca (B9), Rial (RI4), Los Corrales (C6), De la Laguna (LA19), Morado 2 (M4) and Negro 1 (NA2). Samples from localities Tapa (TA6), Puntudo (PU7) and La Parva (PA10) were analyzed at ACME Analytical Laboratories Ltd., Canada. In both cases, the method used was Fusion-ICP/MS with detection limits between 0.01–5 ppm. The analyses of Escorial (A46), Del Nido (N29) and Agua Poca (AP61) are from Bertotto (2000).

The $^{87}Sr/^{86}Sr$ ratio was obtained for seven samples. The extraction of natural Sr through cation exchange columns was performed at the Centro de Investigaciones Geológicas, La Plata, Argentina. The isotopic ratios were measured using a VG 354 mass spectrometer with multiple and single collector systems at the Centro de Pesquisas Geocronológicas, Universidade de São Paulo, Brazil.

4. Petrography

Petrographic characterization of the basaltic rocks that constitute the studied volcanoes was carried out by Bertotto et al. (2005). The rocks show a vesicularity varying from absent to greater than 50%; at times it grades into amygdaloidal because of the infilling of carbonates (and minor quartz, sulphates and zeolites) in the vesicles.

Porphyritic texture is dominant, followed by glomeroporphyritic, with intergranular, pilotaxitic, hyalophitic to hyalopilitic, and intersertal groundmasses, in decreasing order of abundance. The most frequent association of phenocrysts is olivine followed by olivine–plagioclase–clinopyroxene, olivine–clinopyroxene and

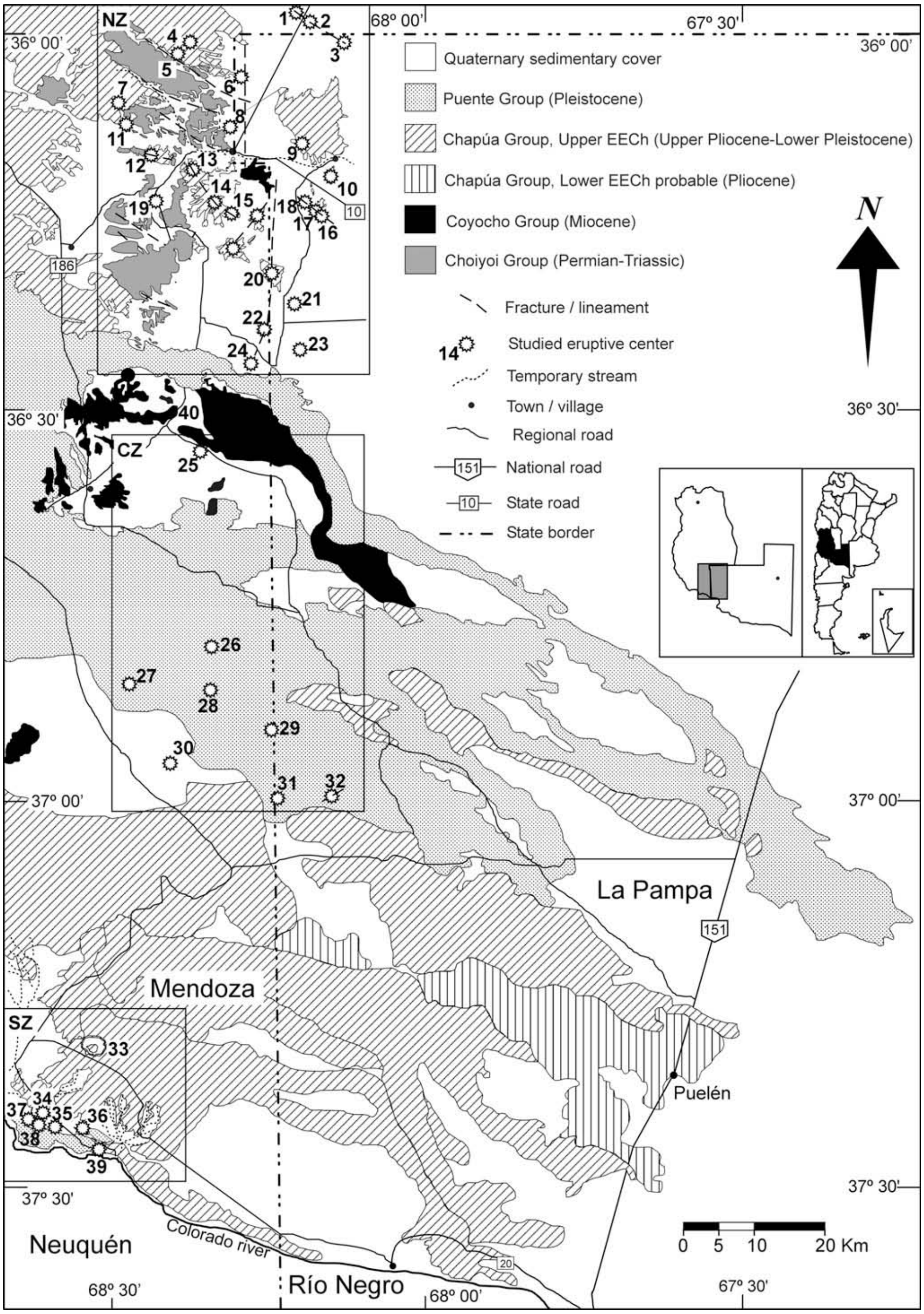

Fig. 2. Geological map of study area and volcanoes sampled (modified from Bertotto, 2003). Northern Zone (NZ): 1, Loma Chica Oeste; 2, Loma Chica Este; 3, Loma Chica Sur; 4, El Oscuro; 5, Negro (3); 6, Negro (2); 7, Morado (2); 8, Chato; 9, Negro (1); 10, Agua de Torres; 11, Chato segundo; 12, Del Chivo; 13, Los Corrales; 14, El Lindero; 15, El Peludo; 16, De Díaz (1); 17, De Díaz (2); 18, De Díaz (3); 19, De la Laguna; 20, Loma Jagüel del Moro; 21, Puntudo; 22, Amarillo; 23, La Negra; 24, Tordillo. Central Zone (CZ): 25, La Parva; 26, Morado (1); 27, Tapa; 28, Los Carrizales; 29, Del Nido; 30, Ñire Co; 31, Escorial; 32, Agua Poca. Southern Zone (SZ): 33, Huanul; 34, El Pozo; 35, La Yegua; 36, La Blanca; 37, El Águila; 38, Rial; 39, Morado (3). Also included a Miocene lava flow: 40, El Cenizo.

olivine–plagioclase. The groundmass is made up of plagioclase, olivine, clinopyroxene, opaques, and brownish glass. Accessory minerals are apatite (included in plagioclase) and feldespathoid (nepheline).

Phenocrysts of olivine are mainly subhedral and to a lesser extent euhedral, with a maximum size of 6.8 mm. They are commonly replaced partially by low temperature iddingsite (+/− bowlingite) and, in some cases, olivine have embayed and skeletal textures. Plagioclases are subhedral and reach a maximum length of 7.6 mm (average 3.6 mm). They show albite and albite-Carlsbad twins, and rarely have oscillatory zoning. Those of the groundmass are swallow-tailed. Clinopyroxenes are subhedral to anhedral, brown to weakly purplish and show oscillatory and sectorial (hour glass) zoning, with a maximum size of 2.8 mm. Opaque minerals are polygonal (equidimensional and prismatic), in many cases with jagged edges, and some of them show acicular ends.

Olivine xenocrysts with kink bands and reaction rims are present in rocks of the Negro 1, El Tordillo and Loma Jagüel del Moro centers. Xenocrysts of quartz have been identified in some samples of Loma Jagüel del Moro, Amarillo, Negro 2, Negro 3 and Ñire Co and xenocrysts of plagioclase at Los Carrizales and Morado 3. Likewise, felsic xenoliths (from acid to intermediate volcanic rocks and quartzites) are present as inclusions in rocks from Morado 2, Agua Poca, Rial and La Blanca. Plagioclase xenocrysts show reaction rims and sieve texture, and quartz xenocrysts show reaction rims. The felsic xenocrysts and xenoliths reach up to 0.6% of modal volume.

The lavas from three of the studied localities (Agua Poca, Huanul and De la Laguna) carry ultramafic (upper mantle) xenoliths (Bertotto, 2000, 2002a,b).

5. Geochemistry

For geochemical treatment of data, the samples were grouped according to their geochemical affinities into three assemblages: Northern Zone, Central Zone and Southern Zone (See Fig. 2 for details).

5.1. Major elements

The rocks of the Northern Zone show a variation in weight percent SiO_2 content from 42.3 (NA2) to 51.2 (JM4) wt.%, although most exhibit a range between 45.3 and 48.7 wt.% SiO_2. A similar variation in range is shown by the rocks from the Southern Zone (SiO_2 = 45.0–50.1 wt.%). This SiO_2 content is less than that in samples from the Central Zone (SiO_2 = 48.5–50.0 wt.%) (Table 1). According to these contents, most rocks can be classified as basic, except those from the Negro 1 (NA2) and De la Laguna (LA19) volcanoes, which are ultrabasic. Based on the TAS diagram (Le Maitre et al., 1989), the rocks are trachybasalts, basalts and basanites (Fig. 3, Table 1), and they plot in the alkaline fields of Macdonald (1968) and Irvine and Baragar (1971).

The magnesium number (Mg# = molar MgO/MgO + FeOtot) oscillates between 0.52 (JM4) and 0.68 (NO7) in rocks from the Northern Zone. In rocks from the Central Zone the range is 0.42 (CA4)–0.56 (AP61), and in those from the Southern Zone these values span between 0.45 (Y9) and 0.60 (HU6, AG8 and RI4) (Fig. 4, Table 1). The lowest values are for rocks from Los Carrizales, La Parva, La Yegua, Ñire Co and Morado 3. The highest values (0.67–0.68) are for rocks from Morado 2 (M4) and Negro 3 (NO7). Rocks from all the three zones exhibit a negative correlation of Al_2O_3, TiO_2, Na_2O and SiO_2 with respect to Mg# (Fig. 4). K_2O in samples from Central Zone and Southern Zone shows a positive correlation and for the Northern Zone, there is a dispersion in of K_20 values that do not correlate with Mg# (Fig. 4). The CaO content is relatively constant with increase of Mg# for all samples considered, although there are slight negative trends within each zone (Fig. 4).

Normative minerals were calculated with KWareMAGMA software (Wohletz, 2001) using a ratio $Fe_2O_3/FeO = 0.25$ (from ratios reported by Rollinson, 1993). This calculation suggests that samples are nepheline normative with a range from 0.27% (N29) to 18.1% (NA2), and olivine normative with a range from 9.8% (Y9) to 24.6% (NO7). These results emphasize the alkalinity of these rocks, in agreement with the character of the youngest basalts (Pleistocene) of the Nevado volcano area (Saal et al., 1995).

5.2. Trace elements

Results of trace-element analyses are listed in Table 2 and plotted in Figs. 5 and 6. The REE distribution pattern normalized to PM (primitive mantle, Sun and McDonough, 1989) is similar for the three zones studied, although the REE slopes vary in each case. The steepest REE pattern is shown by the sample from the De la Laguna volcano ($La/Yb_N = 18.9$) and is followed by the patterns of samples from the Northern Zone (La/Yb_N = 8.6–11.0). The flattest REE patterns are those from the Southern and Central zones with La/Yb_N ratios in the ranges of 5.9–10.2 and 5.6–9.1, respectively (Fig. 5). Sample LA19 is outstanding due to its greater content of REE, followed by samples C6 and NA2 from the Northern Zone, and RI4 from the Southern Zone. Overall, rocks from the Northern Zone are richer in REE when compared to those from Southern and Central Zones (Fig. 5). In the case of the Central Zone, there is a small positive Eu anomaly (1.05–1.35). $Eu/Eu^* = (2 \times Sm_N)/(Sm_N + Gd_N)$.

Fig. 6 depicts the trace element concentrations normalized to PM. For comparison, we include data from basaltic rocks from the volcanic arc at 38°40′S (Llaima volcano, Hickey et al., 1986), and from cratonic and transitional environments from Patagonia (Stern et al., 1990, and references therein). Rocks from the Northern Zone show concentrations that fall within those of transitional basalts; the distribution pattern presents features similar to those of basalts from volcanic arcs, i.e., a strong negative Nb–Ta anomaly and a negative Ti anomaly. Although the sample from De la Laguna shows concentrations and a distribution pattern generally similar to those of cratonic basalts, it presents some features similar to those of subduction related basalts, i.e., positive Th anomaly, and negative Ti anomaly. Rocks from the Central Zone show concentrations and patterns similar to those of transitional basalts, with some tendency towards cratonic, e.g., positive Nb–Ta anomaly and negative Th anomaly. Within this group, early Miocene rocks (PA10 and CE15) show similar patterns, except that they exhibit lower values of Cs, Rb and Ba when compared to the average of Central Zone. On the other hand, samples from Southern Zone show concentrations and patterns in a range similar to those of transitional basalts from Patagonia.

The Th/Ta ratio used in Patagonian basalts as an indicator of subduction enriched mantle source is significantly higher in rocks from the Northern Zone (8.3) than in those from De la Laguna (2.9), and from the Southern Zone (1.9) and Central Zone (1.5). On the other hand, Ba/Nb ratio increases from the Central Zone (11.7–19.1 average 14.3) to the Southern Zone (14.5–17.9 average 16.2) and NZ (39–53.1 average 45.5). The lowest Ba/Nb ratio (8.9) value is at De la Laguna. A similar pattern is observed in the La/Nb ratio, which increases from the Central Zone (0.5–1.1 average 0.8) to the Southern Zone (0.9–1.0 average 1.0) and the Northern Zone (1.8–2.6 average 2.1); sample LA19 shows a La/Nb ratio of 1.1, similar to those in the Central Zone. Considering the La/Nb and Ba/Nb ratios, rocks from the Central Zone and Southern Zone show similar values to the lowest values exhibited by transitional basalts (i.e., they show a trend towards cratonic basalts). The majority belong in the range of ocean island basalts (OIB) (Hickey et al., 1986; Wilson, 1989). The same ratios show that the basalts from the Northern Zone have values similar to the Andean volcanic arc basalts (Hickey et al., 1986). In the case of De la Laguna, the La/Yb, Ba/La, Ba/Nb and Cs/Rb ratios are similar to those of the cratonic basalts from Patagonia.

The rocks of the three zones exhibit $Ti/Y_N > 1$ (LA19 = 1.3; Northern Zone = 1.2–1.5; Southern Zone = 1.6–1.9 and Central Zone = 1.9–3.0) ratios and high Nb/Zr and Nb/Y ratios, compared to those from mid-ocean ridge basalts.

5.3. Isotopes

Table 3 shows $^{87}Sr/^{86}Sr$ (whole rock) ratios of the basaltic rocks studied herein. Although the data still do not allow comparisons between the different areas studied, it becomes clear that rocks from the Central Zone are more isotopically enriched with respect to the rest.

Table 1
Major element analyses (wt.%) of selected volcanic rocks.

	Northern Zone																		
Volcano	L.Ch. Oeste	L.Ch. Este	L.Ch. Sur	El Oscuro	Negro 3	Negro 2	Morado 2	Chato	Negro 1	Agua de Torres	Chato sgdo	Del Chivo	Los Corrales	Lindero	El Peludo	De Díaz 1	De Díaz 2	De Díaz 3	De la Laguna
Numbers in Fig. 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Sample	LO1	LE2	SN1	OS9	NO7	NL13	M4	CH7	NA2	AT9	CS2	DC8	C6	Li2	P9	DA1	DB6	DZ13	LA19
Rock	TB (H)	TB (H)	TB (H)	TB (H)	B	B	B	TB (H)	BN	BN	TB (PTB)	B	TB (PTB)	B	BN	TB (H)	B	TB (H)	BN
SiO_2	47.90	47.91	48.20	47.39	45.52	47.80	48.51	47.42	42.27	46.36	45.25	47.59	47.46	48.66	45.44	46.24	47.43	47.23	42.68
TiO_2	1.98	1.97	2.03	1.54	1.66	1.50	1.23	1.77	1.47	1.77	1.38	1.31	1.36	1.39	1.61	1.60	1.69	1.77	2.27
Al_2O_3	17.49	17.45	17.00	14.84	13.81	15.28	15.39	16.38	14.19	16.07	15.23	16.25	15.84	15.40	15.09	15.17	14.28	16.11	14.75
Fe_2O_3tot	9.99	9.99	10.29	11.21	11.27	10.42	10.02	10.88	12.67	10.72	11.31	10.28	10.24	9.97	11.19	10.57	10.82	10.27	12.06
MnO	0.15	0.15	0.15	0.16	0.17	0.15	0.15	0.16	0.20	0.16	0.18	0.16	0.16	0.15	0.18	0.16	0.15	0.15	0.20
MgO	6.04	6.23	6.4	10.02	12.19	8.83	10.49	6.31	11.68	6.83	10.08	8.72	9.42	9.01	8.29	9.23	10.23	8.39	9.99
CaO	10.54	10.48	10.29	9.22	9.86	10.58	9.24	10.72	11.46	10.98	11.00	10.82	10.04	10.39	11.52	11.16	10.17	10.63	11.19
Na_2O	4.11	4.13	3.89	3.80	3.04	3.32	3.15	4.19	3.96	4.31	3.49	3.01	3.52	3.07	4.19	3.64	3.26	3.71	4.36
K_2O	1.29	1.26	1.34	1.29	1.43	1.60	1.41	1.56	1.64	2.13	1.60	1.38	1.52	1.49	1.86	1.54	1.45	1.31	1.02
P_2C_5	0.51	0.44	0.42	0.54	1.05	0.52	0.41	0.60	0.46	0.67	0.47	0.47	0.46	0.48	0.62	0.70	0.51	0.45	1.48
LOI	–	–	–	1.20	0.60	1.20	0.06	0.50	0.30	1.20	0.30	1.00	0.50	1.20	1.00	1.10	0.60	–	1.70
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Mg#	0.54	0.55	0.55	0.64	0.68	0.63	0.67	0.53	0.65	0.56	0.64	0.63	0.65	0.64	0.59	0.63	0.65	0.62	0.62

	Northern Zone					Central Zone								Southern Zone						
Volcano	L.J. Moro	Puntudo	Amarillo	La Negra	El T ordillo	La Parva	Morado 1	Tapa	Los Carriz	Del Nido	Ñire Co	Escorial	Agua Poca	Huanul	El Pozo	La Yegua	La Blanca	El Águila	Rial	Morado 3
Numbers in Fig. 2	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Sample	JM4	PU7	AM7	NE6	TO7	PA10	M100	TA6	CA4	N29*	Ñ4	A46*	AP61*	HU6	PO3	Y9	B9	AG8	RI4	MO14
Rock	TB (H)	B	TB (H)	B	B	TB (H)	TB (H)	B	TB (H)	TB (H)	TB (H)	TB (H)	TB (H)	BN	TB	B	TB (H)	B	TB (PTB)	B
SiO_2	51.16	48.50	47.74	47.60	48.44	49.16	48.54	48.67	49.37	49.96	49.38	49.75	49.30	45.05	48.66	50.14	46.61	47.25	49.25	49.31
TiO_2	1.55	1.47	1.67	1.30	1.60	2.28	2.12	2.33	2.09	1.75	2.11	1.94	1.86	1.86	1.94	1.86	2.17	1.88	1.86	2.18
Al_2O_3	17.96	17.26	17.52	17.63	16.68	17.82	17.80	17.77	17.43	15.70	18.22	17.18	15.19	14.64	16.71	16.41	15.88	15.35	15.60	16.83
Fe_2O_3tot	8.99	9.99	10.11	9.54	10.10	10.51	10.91	10.90	11.52	11.67	10.32	10.57	12.10	12.80	11.16	11.20	12.70	11.99	10.62	11.49
MnO	0.14	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.15	0.15	0.14	0.15	0.15	0.17	0.14	0.13	0.16	0.15	0.13	0.14
MgO	4.96	8.23	7.26	9.38	8.92	4.10	5.46	5.76	4.28	7.15	4.40	5.12	7.82	9.68	5.70	4.68	5.78	8.94	8.00	4.93
CaO	9.95	9.58	9.42	9.59	9.11	10.30	9.38	9.33	9.12	8.13	9.34	9.51	8.00	9.32	9.66	10.37	10.81	9.30	8.45	9.72
Na_2O	3.87	4.13	4.24	3.73	3.99	4.17	4.25	3.94	4.65	3.72	4.52	3.90	3.71	4.15	4.11	3.79	4.30	3.41	3.74	3.78
K_2O	1.3	0.46	1.52	0.75	0.72	1.21	1.08	1.00	1.06	1.46	1.23	1.45	1.50	1.81	1.46	1.09	1.21	1.35	1.77	1.19
P_2C_5	0.13	0.23	0.37	0.32	0.31	0.30	0.33	0.15	0.33	0.30	0.35	0.42	0.38	0.52	0.44	0.32	0.38	0.37	0.58	0.43
LOI	–	0.7	–	–	–	1.5	–	0.1	–	0.59	–	0.32	0.67	0.10	0.20	1.00	0.04	0.60	0.06	0.30
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Mg#	0.52	0.62	0.59	0.66	0.64	0.44	0.50	0.51	0.42	0.55	0.46	0.49	0.56	0.60	0.50	0.45	0.47	0.60	0.60	0.46

B, basalt; TB, trachybasalt; BN, basanite; H, hawaiite; PTB, potassic trachy basalt.
*, ICP; otherwise XRF analyses. LOI, loss of ignition; "–", not analyzed.
Mg# = MgO/MgO + FeOtot (Fe_2O_3tot = Fe_2O_3tot × 0.8998).
Analyses are recalculated to 100% on a volatile-free basis. No samples with duplicated analyses.

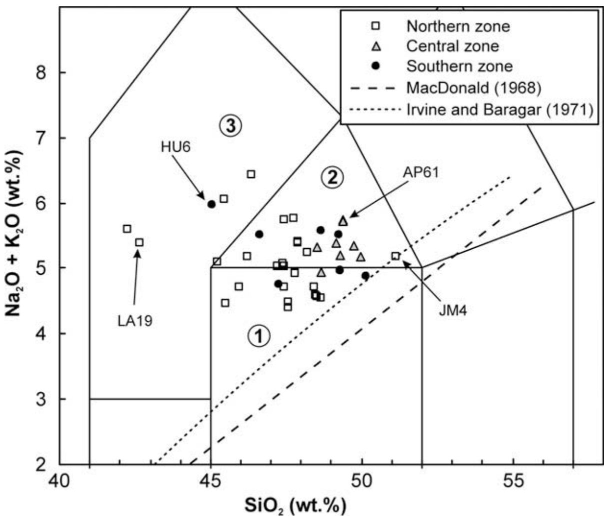

Fig. 3. Total alkali–silica diagram (Le Maitre et al., 1989) for the studied rocks. Fields: 1, basalts; 2, trachybasalts; 3, basanites/tefrites. Boundary line between alkaline and subalkaline fields after Macdonald (1968) (dashed straight line), and Irvine and Baragar (1971) (dotted curve). Samples: open squares, Northern Zone; gray-filled triangles, Central Zone; filled circles, Southern Zone. Arrows indicate xenoliths localities (LA19, HU6 and AP61) and a sample with possible upper crust contamination (JM4).

Most of the new data on rocks from the Late Pliocene–Pleistocene show a range of variation similar to those of the same age from Payunia (Kay et al., 2004). On the other hand, the sample from De la Laguna shows a value similar to those of more isotopically depleted lavas from the early Miocene of the Neuquén Basin (Kay et al., 2004).

6. Discussion

The low Mg# values (0.42–0.45) of the rocks from Los Carrizales, La Parva, La Yegua, Ñire Co and Morado 3 indicate a greater degree of magmatic differentiation than for the basalts from the other localities. Eleven samples have greater than 9% MgO. Only one (NO7) has a Mg# consistent with being in equilibrium with mantle olivine (Mg# = 0.68–0.75, Wilson, 1989).

According to several authors (e.g., Pearce, 1983) the source of subduction-related magmas is a subcontinental lithosphere that has been enriched in Sr, K, Rb, Ba and Th by subduction-related fluids. Zanetti et al. (1999), among others, have shown that LREE enrichments and negative HFSE anomalies in mantle rocks can be attributed to subduction-related silicate melts or water-rich fluids. These melts or fluids are depleted in Nb and Ta and enriched in Pb, Sr, Ba and alkalis.

According to Kilian et al. (1998), Kilian and Stern (2002), Stern (1989) and Laurora et al. (2001), the Patagonian mantle shows evidence of slab–related metasomatism. In addition, Stern et al. (1990), Gorring and Kay (2001) and Rivalenti et al. (2004), determined that mantle sources of Patagonia back-arc basalts record an eastward decrease of slab components. In the volcanic arc, at the latitude of this study, Hickey et al. (1986) considered the subducted oceanic crust as the most probable source for the enrichment of Pb, U, Th, alkali and alkaline earth elements compared with REE and HFSE found in arc rocks.

Increases in Th/Ta, Ba/Nb and La/Nb ratios from the Central Zone to the Northern Zone reported in this study may be explained as the result of an increase of the influence of elements supplied by the Nazca plate from the Central Zone to the Southern Zone and still further towards the Northern Zone. Rocks from the *Northern Zone* (except LA19) show La/Nb and Ba/Nb ratios similar to the basalts erupted by Andean stratovolcanoes to the east of the volcanic

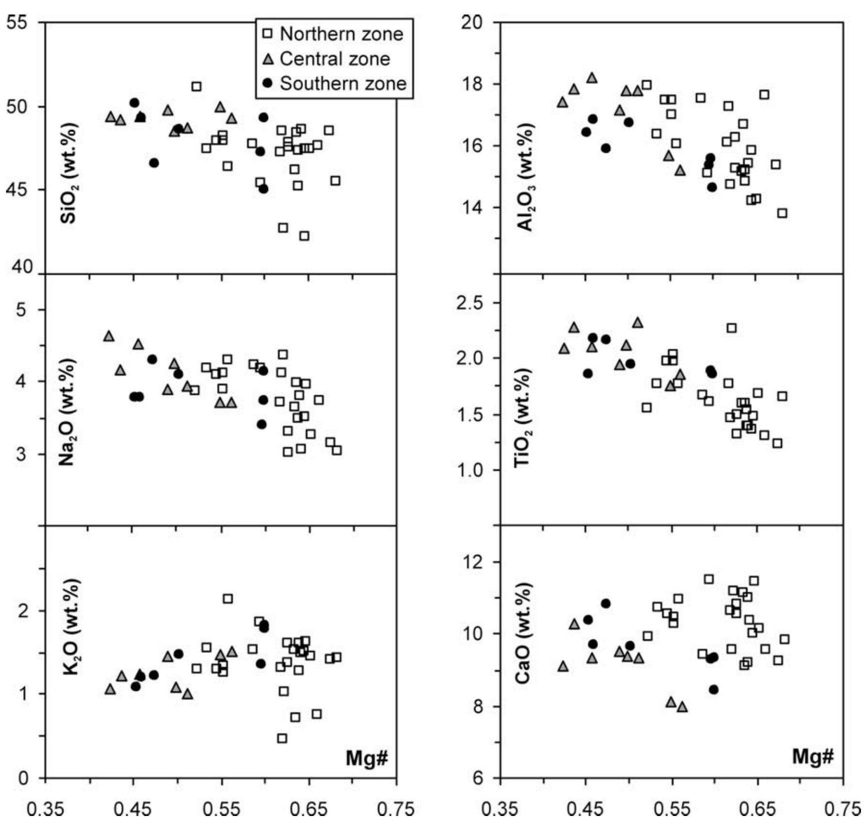

Fig. 4. SiO_2, Al_2O_3, Na_2O, TiO_2, K_2O and CaO (wt.%) versus Mg# variation diagrams for the studied rocks. Symbols as in Fig. 3.

Table 2
Trace element analyses (in ppm) of selected volcanic rocks.

	Northern Zone																		
Volcano	L.Ch. Oeste	L.Ch. Este	L.Ch. Sur	El Oscuro	Negro 3	Negro 2	Morado 2	Chato	Negro 1	Agua de Torres	Chato Sgdo	Del Chivo	Los Corrales	Lindero	El Peludo	De Díaz 1	De Díaz 2	De Díaz 3	De la Laguna
Numbers in Fig. 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Sample	LO1	LE2	SN1	OS9	NO7	NL13	M4*	CH7	NA2*	AT9	CS2	DC8	C6*	Li2	P9	DA1	DB6	DZ13	LA19*
Rock	TB (H)	TB (H)	TB (H)	TB (H)	B	B	B	TB (H)	BN	BN	TB (PTB)	B	TB (PTB)	B	BN	TB (H)	B	TB (H)	BN
V	266	263	274	–	–	–	256	–	288	–	–	–	273	–	–	–	–	263	270
Cr	180	200	180	–	–	–	417	–	438	–	–	–	270	–	–	–	–	327	243
Ni	60	63	63	–	–	–	172	–	197	–	–	–	137	–	–	–	–	178	167
Pb	15	15	12	–	–	–	8.14	–	15	–	–	–	14	–	–	–	–	13	6.35
Cs	–	–	–	–	–	–	1.79	–	1.54	–	–	–	2.04	–	–	–	–	–	0.66
Rb	48	48	50	51	41	38	40	32	31	45	34	25	39	32	35	32	30	54	20
Ba	916	659	743	–	–	–	565	–	558	–	–	–	594	–	–	–	–	780	545
Sr	1096	1016	1068	791	869	862	791	824	928	837	856	873	856	861	954	889	859	1086	1110
Th	–	–	–	–	–	–	5.55	–	5.75	–	–	–	6.30	–	–	–	–	–	11.66
Nb	18	17	21	14	24	12	13	13	12	19	9	11	11	12	20	21	24	26	61
Ta	–	–	–	–	–	–	0.62	–	0.58	–	–	–	0.71	–	–	–	–	–	3.96
Zr	177	170	179	151	170	146	124	154	123	172	146	155	125	146	184	173	176	134	275
Hf	–	–	–	–	–	–	3.29	–	3.16	–	–	–	3.20	–	–	–	–	–	5.74
Y	21	19	19	24	26	25	21	25	24	27	25	25	23	22	25	25	22	20	35
La	33	28	30	–	–	–	24	–	26	–	–	–	29	–	–	–	–	38	68
Ce	60	59	58	–	–	–	51	–	55	–	–	–	58	–	–	–	–	65	132
Pr	–	–	–	–	–	–	6.26	–	6.76	–	–	–	6.84	–	–	–	–	–	14.7
Nd	29	30	29	–	–	–	26	–	28	–	–	–	28	–	–	–	–	31	56
Sm	–	–	–	–	–	–	5.47	–	5.87	–	–	–	5.81	–	–	–	–	–	10.28
Eu	–	–	–	–	–	–	1.75	–	1.79	–	–	–	1.84	–	–	–	–	–	3.30
Gd	–	–	–	–	–	–	5.34	–	5.57	–	–	–	5.65	–	–	–	–	–	9.13
Tb	–	–	–	–	–	–	0.75	–	0.80	–	–	–	0.81	–	–	–	–	–	1.25
Dy	–	–	–	–	–	–	3.92	–	4.10	–	–	–	4.14	–	–	–	–	–	6.19
Ho	–	–	–	–	–	–	0.71	–	0.76	–	–	–	0.74	–	–	–	–	–	1.10
Er	–	–	–	–	–	–	1.96	–	2.09	–	–	–	2.08	–	–	–	–	–	3.01
Tm	–	–	–	–	–	–	0.28	–	0.30	–	–	–	0.30	–	–	–	–	–	0.41
Yb	–	–	–	–	–	–	1.80	–	1.86	–	–	–	1.87	–	–	–	–	–	2.58
Lu	–	–	–	–	–	–	0.28	–	0.28	–	–	–	0.28	–	–	–	–	–	0.38

(*continued on next page*)

Table 2 (*continued*)

	Northern Zone					Central Zone								Southern Zone						
Volcano	L.J. Moro	Puntudo	Amarillo	La Negra	El Tordillo	La Parva	Morado 1	Tapa	Los Carriz.	Del Nido	Nire Co	Escorial	Agua Poca	Huanul	El Pozo	La Yegua	La Blanca	El Aguila	Rial	Morado 3
Numbers in Fig. 2	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Sample	JM4	PU7*	AM7	NE6	TO7	PA10*	M100*	TA6*	CA4	N29*	N4*	A46*	AP61*	HU6*	PO3	Y9	B9*	AG8	RI4*	MO14
Rock	TB (H)	B	TB (H)	B	B	TB (H)	TB (H)	B	TB (H)	TB (H)	TB (H)	TB (H)	TB (H)	BN	TB(H)	B	TB (H)	B	TB (PTB)	B
V	253	242	239	236	244	209	235	220	206	212	253	208	170	208	–	–	237	–	212	–
Cr	163	281	262	315	356	123	174	151	111	289	117	67	255	286	–	–	106	–	271	–
Ni	64	126	125	197	202	29	55	60	31	144	56	42	205	192	–	–	74	–	134	–
Pb	7	0.50	7	9	12	0.90	5.12	0.90	8	BDL	16	BDL	BDL	BDL	–	–	BDL	–	28	–
Cs	–	1.60	–	–	–	0.30	BDL	0.10	–	–	0.51	–	–	0.83	–	–	BDL	–	0.87	–
Rb	48	16	81	34	62	13	17	13	32	25	24	28	28	30	27	15	18	25	37	20
Ba	597	460	576	586	637	232	332	274	388	477	366	432	447	358	–	–	231	–	474	–
Sr	963	918	883	1010	1038	716	576	611	497	573	632	708	630	558	617	586	505	550	700	556
Th	–	3.80	–	–	–	1.80	1.97	1.40	–	3.02	2.69	2.79	2.87	3.09	–	–	1.80	–	3.61	–
Nb	14	12	16	10	17	20	22	22	21	31	19	31	38	25	17	14	14	15	27	19
Ta	–	0.70	–	–	–	1.50	1.37	1.40	–	1.82	1.22	1.61	2.16	1.68	–	–	0.95	–	1.79	–
Zr	110	124	184	185	135	146	145	127	222	183	149	151	172	145	171	136	116	151	174	147
Hf	–	4	–	–	–	3.90	3.66	3.30	–	4.30	3.64	3.60	4.00	3.29	–	–	2.92	–	3.97	–
Y	16	20	22	22	18	20	23	17	24	18	25	21	18	23	26	24	24	23	24	27
La	18	20	29	32	29	17	18	12	21	17	20	21	19	23	–	–	15	–	26	–
Ce	31	44	52	63	56	37	39	26	38	34	43	42	37	46	–	–	33	–	52	–
Pr	–	5.49	–	–	–	4.72	4.75	3.30	–	3.78	5.22	4.74	4.09	5.36	–	–	4.12	–	6.11	–
Nd	20	25	28	30	28	20	21	16	25	18	22	22	19	22	–	–	18	–	25	–
Sm	–	5.60	–	–	–	5.10	4.88	3.70	–	4.32	5.09	5.49	4.47	4.68	–	–	4.51	–	5.47	–
Eu	–	1.69	–	–	–	1.74	1.78	1.66	–	1.40	1.78	1.81	1.71	1.62	–	–	1.67	–	1.93	–
Gd	–	4.60	–	–	–	4.75	5.39	3.74	–	4.07	5.55	4.85	4.23	4.99	–	–	5.27	–	5.58	–
Tb	–	0.68	–	–	–	0.73	0.83	0.60	–	0.65	0.85	0.77	0.66	0.77	–	–	0.80	–	0.84	–
Dy	–	3.84	–	–	–	3.85	4.31	3.39	–	3.57	4.32	4.17	3.60	4.04	–	–	4.24	–	4.21	–
Ho	–	0.72	–	–	–	0.68	0.78	0.62	–	0.65	0.79	0.76	0.63	0.77	–	–	0.77	–	0.76	–
Er	–	1.89	–	–	–	1.85	2.09	1.64	–	1.84	2.20	2.22	1.80	2.11	–	–	2.11	–	2.10	–
Tm	–	0.27	–	–	–	0.25	0.29	0.23	–	0.24	0.32	0.28	0.23	0.31	–	–	0.30	–	0.29	–
Yb	–	1.70	–	–	–	1.42	1.81	1.48	–	1.60	1.93	1.84	1.49	1.98	–	–	1.78	–	1.80	–
Lu	–	0.23	–	–	–	0.23	0.27	0.23	–	0.23	0.28	0.28	0.22	0.30	–	–	0.27	–	0.26	–

B, basalt; TB, trachybasalt; BN, basanite; H, hawaiite; PTB, potassic trachybasalt.
*, ICP; otherwise XRF analyses (no samples with duplicated analyses). "–", not analyzed; BDL, below detection limit.

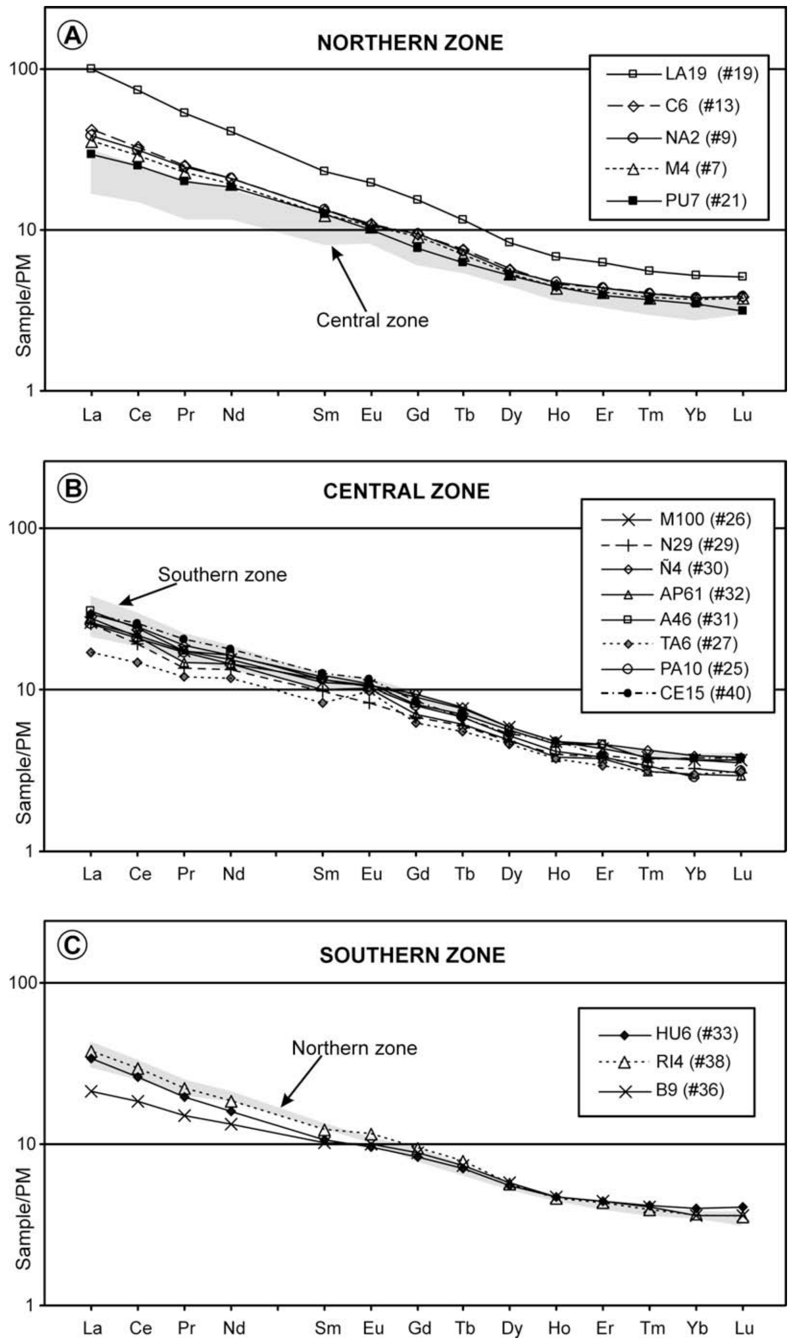

Fig. 5. REE concentrations normalized to primitive mantle (Sun and McDonough, 1989) of the rocks studied. Following each sample number is indicated the number of the locality in Fig. 2. (A) Northern Zone (LA19, C6, NA2, M4 and PU7), for comparison is included the field of variation of rocks from the Central Zone. (B) Central Zone, (M100, N29, Ñ4, AP61, A46, TA6 and PA10) included is an unpublished analysis of a Miocene lava flow (CE15) and the field of variation of rocks from the Southern Zone. (C) Southern Zone (HU6, RI4 and B9) compared with the range of variation of rocks from the Central Zone (shaded field).

front (Hickey et al., 1986; Stern et al., 1990). Additionally, the normalized patterns of the rocks of the Northern Zone exhibit negative anomalies of Nb and Ta with respect to Th and Ce, and enrichment of LILE (Cs, Rb, Ba and Th) normally interpreted as characteristic features of the volcanic arc rocks (Pearce, 1996). An alternative source for the elements that imprinted the "arc-like" character of the rocks of the Northern Zone could have been assimilation of upper crust rocks melted during ascent of the basaltic magma. To constrain this possibility, we have compared the compositions of sample LA19 (De la Laguna) of cratonic "uncontaminated" character and C6 (Los Corrales) of "arc-like" features, with crustal rocks belonging to Choiyoi (Llambías et al., 2003), Co La Ventana (Cingolani and Varela, 1999) and Las Matras units (Sato et al., 2000). De La Laguna is located at 7 km from Los Corrales volcano and both have similar MgO content (Fig 2, Table 1). Sample C6 represents the Pleistocene volcanoes of the Northern Zone and LA19 is of Miocene age. Calculations have shown that for cratonic magmas of type LA19 more than 80% assimilation of upper crustal rocks, of Co La Ventana, Las Matras or Choiyoi type, is required to get contents of Nb–Ta similar to those of sample C6. In addition to this unrealistic high value of assimilation, Sr isotopes do not show clear signs of contamination by continental crust rocks (Fig. 7).

On the basis of available data, we interpret the tendency of the analyzed rocks of the Northern Zone to display compositions sim-

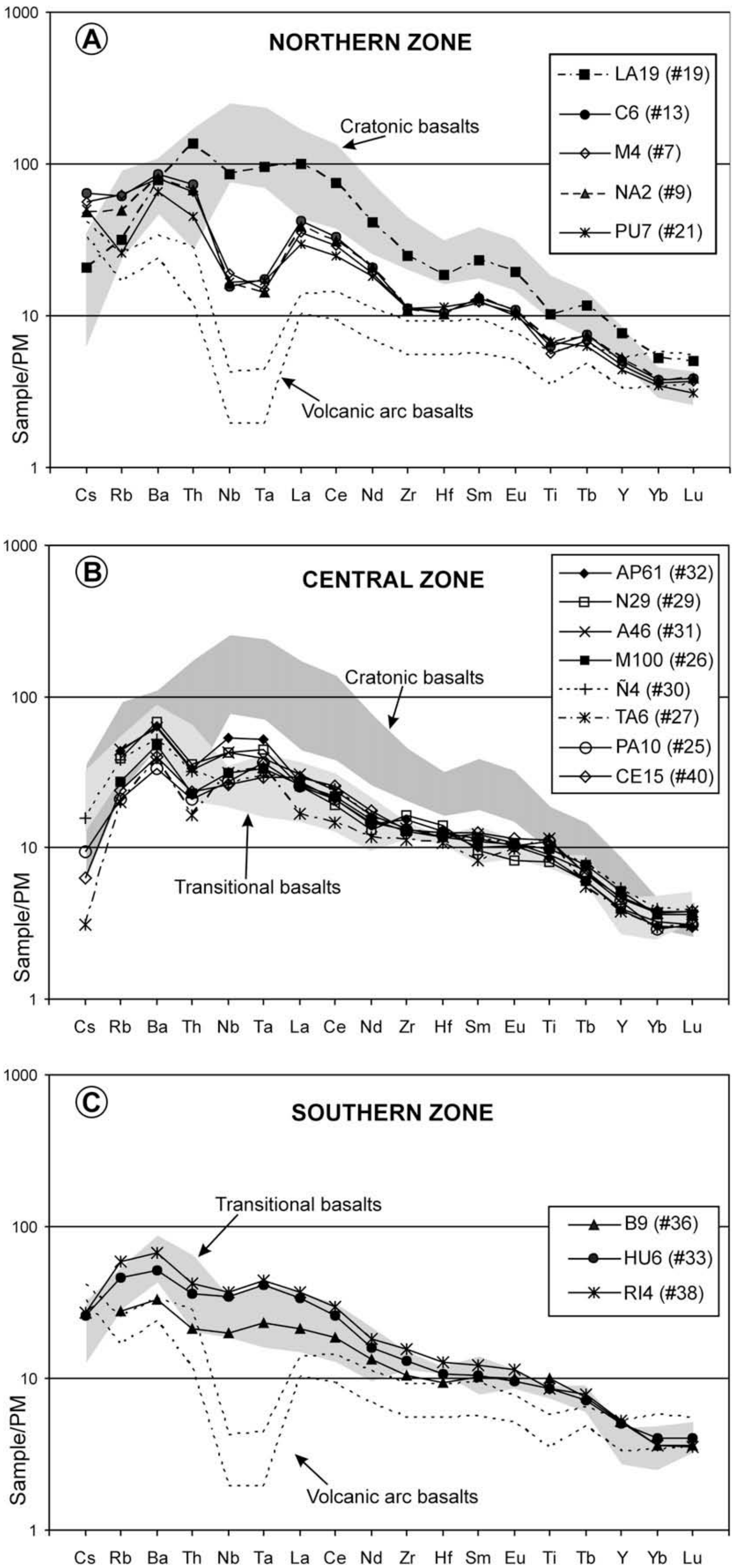

Fig. 6. Multi-element concentration patterns normalized to primitive mantle (Sun and McDonough, 1989). Following each sample number is indicated the number of the locality in Fig. 2. (A) Rocks from the Northern Zone (LA19, C6, NA2, M4 and PU7), compared with Cratonic basalts of Patagonia and Andean volcanic arc basalts. (B) Rocks from the Central Zone (M100, N29, Ñ4, AP61, A46, TA6 and PA10 also included an unpublished analysis of a Miocene lava flow, CE15), compared with basalts from Cratonic and Transitional settings of Patagonia. (C) Rocks from the Southern Zone (HU6, RI4 and B9) compared with Cratonic basalts of Patagonia and Andean volcanic arc basalts. Values of Cratonic and Transitional basalts after Stern et al. (1990, and references therein), and values of Andean volcanic arc basalts are of Llaima volcano (Hickey et al., 1986).

Table 3
Values of $^{87}Sr/^{86}Sr$ obtained from basaltic rocks.

Volcano	De la Laguna*	Los Corrales	Negro 1	Morado 2	Huanul*	Morado 1	Ñire Co
Zone	N	N	N	N	S	C	C
Sample	LA19	C6	NA2	M4	HU6	M100	Ñ4
$^{87}Sr/^{86}Sr$	0.70318	0.70349	0.70379	0.70396	0.70384	0.70414	0.70428
Error	0.000012	0.000026	0.000016	0.000022	0.00002	0.000019	0.000023

N: Northern; S: Southern; C: Central.
* Rocks bearing ultramafic xenoliths.

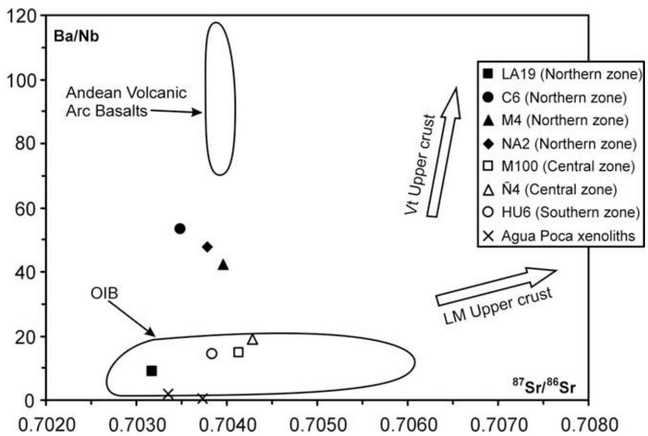

Fig. 7. Ba/Nb versus $^{87}Sr/^{86}Sr$ diagram for seven selected rocks of the Northern Zone (LA19, C6, M4 and NA2), Central Zone (M100 and Ñ4) and Southern Zone (HU6). For comparison are shown Agua Poca xenoliths and fields of Andean volcanic arc basalts (Antuco 37°30′S and Llaima 38°36′S volcanoes, Hickey et al., 1986) and ocean island basalts (OIB, Wilson, 1989). The arrows point to compositions of crustal rocks that form the crystalline basement of the neighboring regions: "Vt" Co La Ventana Fm. type (Cingolani and Varela, 1999), and "LM" Las Matras type (Sato et al., 2000).

ilar to those of the volcanic arc (Figs. 6 and 7) as an indication of a source contamination similar to that of the arc basalts, that is by subduction-related fluids. It should be pointed out that these eruptive centers are latitudinally closer to the Neogene "arc volcanoes" (Nevado, Plateado and Pelado) than those of the other areas (Fig. 1).

We do not discard the possibility of upper crustal contamination; we envision that the effect on the composition of the studied rock is slight. Rocks of volcanoes Loma Jagüel del Moro, Amarillo, Morado 2, Negro 2 and Negro 3 contain to 0.6% (modal volume) inclusions of felsic minerals, some of these with reaction rims. Sample JM4 has a SiO_2 content 3–4% higher and MgO content 1–2% lower compared to other rocks from the Northern Zone (Table 2, Fig. 3). We have evaluated the possibility that the felsic inclusions could have changed the composition of sample JM4 to higher SiO_2 and lower MgO contents. Our results indicate that with 15–20% of assimilation of upper crustal rocks, sample JM4 loses 3–4% of SiO_2 and gains 1–2% of MgO, reaching the mean values of the other rocks of the Northern Zone.

Ratios of incompatible elements (La/Yb, Ba/La, Ba/Nb and Cs/Rb) of the rocks from the *De la Laguna* volcano in the Northern Zone are in the range of intraplate basalts suggesting affinities with the cratonic basalts of Stern et al. (1990), unlike the rest of the samples from this region. From the low $^{87}Sr/^{86}Sr$ ratio and the high MgO (6.3–12.2%, except JM4 MgO = 5.0%) it is unlikely that upper crustal assimilation could have played a major role in changing the composition of the basaltic magmas from the Northern Zone. Therefore, we consider that the main geochemical characteristics of the magmas from this zone reflect the composition of the original source. Based on this, two different magma sources can be differentiated in the Northern Zone, one for the Miocene lavas (De La Laguna volcano, LA19) with intraplate signatures and another for Pleistocene lavas with arc-like enrichment. We suggest that the mantle source of Pleistocene magmas was contaminated by subduction-related fluids. Keeping in mind the Pleistocene age of these rocks and the Miocene age and the intraplate character of LA19, at least two possibilities exist for the incorporation of subduction-related fluids into the magma source: (1) these fluids could have originated in an episode of subhorizontal subduction that happened in the upper Miocene, after the generation of the rocks of De la Laguna volcano. This reduction in the subduction angle of the Nazca plate was proposed for the South of Mendoza by several authors (Ostera et al., 2000, 2006; Kay and Mancilla, 2001; Kay et al., 2004). Its influence was of regional importance according to its distribution in the rocks analyzed in the Northern Zone (Fig. 2); (2) these fluids could have been added by a subduction episode previous to the Miocene, but in this case the existence of mantle heterogeneities in source regions separated by only 7 km is required (between C6 and LA19). The first option is considered more likely because the wide distribution of magmas with arc-like features in the Northern Zone (Fig. 2) suggests that the influence of the subduction components was of regional character.

Rocks of the *Southern Zone* are clearly transitional (classification of Stern et al., 1990), whether considering their pattern design or the incompatible element ratios. Stern et al. (1990) observed in transitional basalts some influence of the subducting plate, a feature separating them from the cratonic basalts. In the case of rocks of the Southern Zone, they could have been influenced by an enrichment originated in the stages in which subhorizontal subduction prevailed and in which the Chachahuen volcanic arc was generated 5–7 Ma ago (Kay and Mancilla, 2001).

In the *Central Zone*, there is a lesser influence of elements supplied by the Nazca plate; these rocks have incompatible elements ratios like the transitional basalts of Stern et al. (1990), and trend towards cratonic basalts (i.e., with ratios completely different from those of rocks from the volcanic arc). These are the lavas geographically most distant from the Neogene volcanic centers to the east of the front (approximately 70 km east of the Payún Matru volcano and 40 km east of the Chachahuen complex, Fig. 1). As it happens in the Northern Zone, the rocks from the Central Zone show few signs of crustal contamination. Inclusions of felsic minerals representing up to 0.5% in volume have been identified in samples of Agua Poca, Los Carrizales and Ñire Co.

Nb/Zr and Nb/Y ratios and REE patterns of the basalts included in this study indicate low degrees of partial melting of an enriched mantle source, as previously reported for basalts from other parts of Patagonia by Stern et al. (1990), Kay et al. (2004) and Massaferro et al. (2006). All the studied samples show depletion of HREE compared to LREE, and Ti/Y_N ratios are >1 in the three areas. This is interpreted to be as a result of melting in the garnet zone, although with a degree of melting insufficient to melt all the garnet (Pearce, 1996). This interpretation is based on the following features: LREE have greater bulk partition coefficients than HREE, and Y is more compatible than Ti during melting of a garnet lherzolite (Pearce, 1983); as a result the melt generated has HREE/LREE and Ti/Y ratios greater than 1. The high Nb/Zr and Nb/Y ratios compared to those of mid-ocean ridge basalts agree with low degrees of melting of an earlier non-depleted mantle source (Pearce, 1996; Dorendorf et al., 2000). Partial melting degrees of 3% to 5% (Huanul) and 2% to 4% (Agua Poca) were obtained for the peridotites included in rocks from these volcanoes (Bertotto, 2003).

The range of the $^{87}Sr/^{86}Sr$ ratios (0.70318–0.70428) agrees with Stern et al. (1990), who stated that the plateau basalts from Patagonia show a range in Sr isotope composition that is larger than in the lavas from the Andean orogenic arc. Stern et al. (1990) attributed this characteristic to a greater partial melting degree of the arc lavas and their possible sub-arc homogenization as suggested by Gerlach et al. (1983).

Rocks from the De la Laguna (Northern Zone), Agua Poca (Central Zone) and Huanul (Southern Zone) carry ultramafic (upper mantle) xenoliths (Bertotto, 2000, 2002a,b). Geophysical investigations indicate that the upper mantle is located 40 km below the surface of the zones treated here (Martínez et al., 1994; Nocioni, 1997). Additionally, geochemical analyses of minerals from mantle xenoliths at Agua Poca indicate that they were equilibrated at 45–65 km depth, and in the case of xenoliths from Huanul, the depth of equilibrium varies from 45 to 70 km (Bertotto, 2003). This indicates that the basaltic magma constituting these three volcanoes ascended rapidly to the surface from at least 40–45 km deep, preventing settling of the ultramafic xenoliths.

7. Concluding remarks

The majority of the studied rocks are basic trachybasalts, basalts and basanites that belong to the alkaline series. These rocks are the result of low degrees of melting of a garnet-bearing mantle source. The Mg# varies between 0.42 and 0.68, with only one of the samples showing a composition indicative of equilibrium with mantle olivine composition.

There is a decrease in the influence of arc-related elements in the Northern compared to the Southern and Central zones. In the case of the Northern zone, this influence bears a clear relation with the age of the rocks; namely the De la Laguna volcanic rocks (Miocene) do not show significant arc-element enrichment in comparison to what occurs with Plio–Pleistocene rocks from the same area. From geochemical evidence it can be concluded that the source regions of magmas from the Northern zone were modified by subduction-related fluids. These variations are in agreement with an eastward migration of the slab fluid metasomatism in response to a reduction in the angle of subduction in the late Miocene.

The ultramafic xenoliths hosted by the lavas of three volcanoes suggest magma generation at deep levels in the mantle and high ascent rates.

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