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Geochemistry of mafic Paleocene volcanic rocks in the Valle del Cura region: Implications for the petrogenesis of primary mantle-derived melts over the Pampean flat-slab

Vanesa D. Litvak *, Stella Poma

Consejo Nacional de Investigaciones Científicas y Técnicas, Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria Pabellón II, C1428EHA, Argentina

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A B S T R A C T

Mafic volcanism of Paleocene age was recently reported in the Valle del Cura region and the El Indio Belt in the aphanitic and very homogenous well-preserved lavas flows of the Río Frío Basalts unit. These are high-K basalts, with high Fe_2O_3 and TiO_2 contents that imply an alkaline tendency and show typical intra-plate-type patterns on a MORB normalized trace elements plot. Sr and Nd isotopic ratios evidence a mantle affinity. The chemistry indicates that these rocks are high temperature melts that result from a low degree of melting of an enriched portion of lithospheric mantle, with no contamination from crustal derived components. The alkaline back-arc Las Máquinas Basalts of Lower Miocene age are derived from more primitive magmas closer to the original source. Mantle composition was relatively constant from Paleocene to Lower Miocene in the studied latitudes over the Pampean flat-slab. Both mafic units share the isotopic trend of pre-Miocene mafic lavas from the Central Andes that were not affected by crustal contamination. Post-Miocene mafic lavas show a strong influence from crust-related processes.

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R E S U M E N

Nuevas manifestaciones de volcanismo máfico de edad Paleocena fueron reconocidas recientemente en la región del Valle del Cura/Faja del Indio e incluidos en la unidad Basaltos Río Frío, los que corresponden a flujos lávicos afaníticos muy homogéneos y bien preservados. Se clasifican como basaltos de alto-K, con altos contenidos de Fe_2O_3 y TiO_2 y de tendencia alcalina; las relaciones isotópicas de Sr y Nd evidencian una afinidad mantélica para los mismos. De acuerdo a su comportamiento químico, estas rocas provienen de fundidos de alta temperatura de origen profundo, producto de bajo grado de fusión de porciones enriquecidas del manto litosférico, sin contaminación de componentes corticales. Junto con los Basaltos Las Máquinas, de edad Miocena Temprana y afinidad química de retroarco, corresponden a los magmas mas primitivos del área, concluyendo así que la composición del manto fue relativamente constante desde el Paleoceno al Mioceno Temprano a las latitudes en estudio, sobre el segmento de subducción horizontal Pampeano. Ambas unidades máficas presentan el mismo comportamiento isotópico que las lavas máficas pre-Miocenas de los Andes Centrales, las cuales no fueron afectadas por contaminación cortical, mientras que las lavas máficas post-Miocenas muestran una fuerte influencia de procesos corticales.

1. Introduction

The Valle del Cura region, on the Pampean flat-slab, is considered the continuity in Argentina of the El Indio metallogenetic belt located in Chile. It is one of the best-studied regions in the Andean principal cordillera in recent years because of the presence of world-class ore deposits, such as El Indio, Pascua-Lama, and Veladero. The region is characterized by a thick sequence of Tertiary volcanic and volcaniclastic arc-like rocks that are associated with both Au–Ag–Cu-rich epithermal and porphyry-type mineral deposits (Maksaev et al., 1984; Nasi et al., 1990; Kay et al., 1987, 1988, 1991; Ramos et al., 1989; Bissig et al., 2001; Litvak, 2004; Litvak and Poma, 2005; Litvak et al., 2007). The origin of these ore deposits is linked to the evolution of the magmatic rocks,

* Corresponding author.
E-mail addresses: vane@gl.fcen.uba.ar (V.D. Litvak), stella@gl.fcen.uba.ar (S. Poma).

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hydrothermal activity, host rock composition, and the tectonic regime in the region. Previous studies have largely emphasized the geochemical and tectonic evolution of acid to mesosilicic volcanic-arc and back-arc related magmatic rocks from the Eocene to late Miocene as an aid in deciphering the Tertiary crustal evolution of the main cordillera (Kay et al., 1991, 1999; Bissig et al., 2003; Litvak et al., 2007).

However, mantle composition was difficult to infer due to the lack of primary uncontaminated mafic magmas. Mafic lavas were only recognized in the area as small basaltic volcanic necks of retroarc affinities linked to the main Upper Oligocene–Lower Miocene volcanic arc (Ramos et al., 1989). Mafic volcanism of Paleocene age was recently reported in the area and defined as the Río Frío Basalts unit (Litvak and Page, 2002). As mafic volcanic rocks are the best petrological tool for studying the processes that occur in the mantle, the reconnaissance of these Paleocene basaltic rocks allows the evaluation of the mantle composition and genesis of primary mafic melts.

The purpose of this paper is to present the results of new geologic mapping (1:100,000) and geochemistry data for Paleocene mafic rocks in the Valle del Cura region, and to evaluate the petrogenesis of these rocks and mantle composition in this sector of the Pampean flat-slab in the Paleocene. Comparison of these data with locally and regionally related mafic igneous rocks puts new constraints on the Early Tertiary magmatic and tectonic evolution of the main Andean cordillera over the Pampean flat-slab segment.

2. Geological setting of the Valle del Cura

The Valle del Cura is located on the volcanically inactive Pampean flat-slab segment of the southern Central Andes (Fig. 1). The Miocene shallowing of the Nazca plate has been attributed to the collision of the Juan Fernández Ridge on the Nazca plate against the trench (Pilger, 1981, 1984; Yañes et al., 2001). Kay and Mpodozis (2002) explained that the arrival of the east–west trending segment of the ridge under the Valle del Cura region corresponds to the eruption of the middle Miocene (12–10 Ma) volcanic rocks. This perturbation increased the shallowing of the subduction zone on the Pampean flat-slab, resulting in changes in the magmatic and tectonic style of the region. The Valle del Cura region, together with the El Indio belt, host a number of mineralized hydrothermal systems; they form a north-trending block limited by high angle reverse faults (Maksaev et al., 1984; Jones et al., 1996; Martin et al., 1997b). The geology of the Valle del Cura region includes a Permo-Triassic basement formed of sedimentary, plutonic, and volcanic rocks, which are unconformably overlain by Tertiary sedimentary and volcanic rocks (Kay et al., 1987, 1988; Ramos et al., 1989; Bissig et al., 2001; Litvak, 2004; Litvak and Page, 2002; Litvak and Poma, 2005).

The study area corresponds to the Argentinian slope of the El Indio belt/Valle del Cura region. As shown in Fig. 2, it includes the southernmost area of Valle del Cura, where the mafic lavas are well exposed. The Cenozoic stratigraphy of the Valle del Cura is characterized by a series of Paleocene to Upper Miocene magmatic and sedimentary sequences. On the Argentine side of the international border, most geological studies were more reconnaissance in nature (Groeber, 1951; Ramos et al., 1987, 1989; Nullo, 1988; Kay et al., 1991; Otamendi et al., 1994). A more precise stratigraphy, along with new isotopic ages, has been presented recently (Limarino et al., 1999; Bissig et al., 2001; Litvak and Page, 2002; Litvak et al., 2004, 2007; Litvak and Poma, 2005). These studies show that the stratigraphic units can be correlated across the international border. The volcanic stratigraphy is well documented on the Chilean side of the border (Maksaev et al., 1984; Nasi et al., 1990; Kay et al., 1987; Martin et al., 1997a,b; Bissig et al., 2001). Table 1 summarizes the main Tertiary stratigraphic units that describe the Cenozoic volcanic history of the Valle del Cura region. There are eight volcanic and volcaniclastic units from the Lower Paleocene to Upper Miocene, with compositional variation including basalts, andesites, and rhyolites.

The oldest Tertiary magmatic rocks, which are the main objective of this work, are lava flows of basaltic composition that crop out in the Río Frío Creek (Figs. 2 and 3a). Litvak and Page (2002) reported a K/Ar (whole rock) age of 55.9 ± 1.9 Ma for these rocks and named them the Río Frío Basalts. As reported by the authors, they are well-preserved lava flows interbedded with red conglomerates, forming an anticline structure whose axis is parallel to the NE-trending normal faulting that affects the sequence (Fig. 2). Río Frío Basalts are aphanitic and homogenous; though the basal levels are more massive than the upper ones, which present vesicular structure and abundant fractures that are generally infilled with secondary minerals. Due to their fine and homogenous grain size, they develop concentric weathering (Fig. 3b). Interbedded red beds are matrix-supported conglomerates, with highly abundant basalt and volcanic sandstone clasts. Under the microscope, the predominant texture of the basalts is aphiric, with an intergranular groundmass formed by plagioclase microlites, with olivine, pyroxene, and opaque minerals in the interstices. In a few cases, clinopyroxene and/or olivine, frequently altered to iddingsite, are present as microphenocrysts of microporphyric varieties (Fig 4a). Aphiric varieties sometimes show a pilotaxic groundmass, while samples with relatively larger grain size develop ophitic to subophitic textures (Fig 4b and c).

The only mafic lavas previously reported as a basaltic volcanic unit are the Las Máquinas Basalts defined and described by Ramos

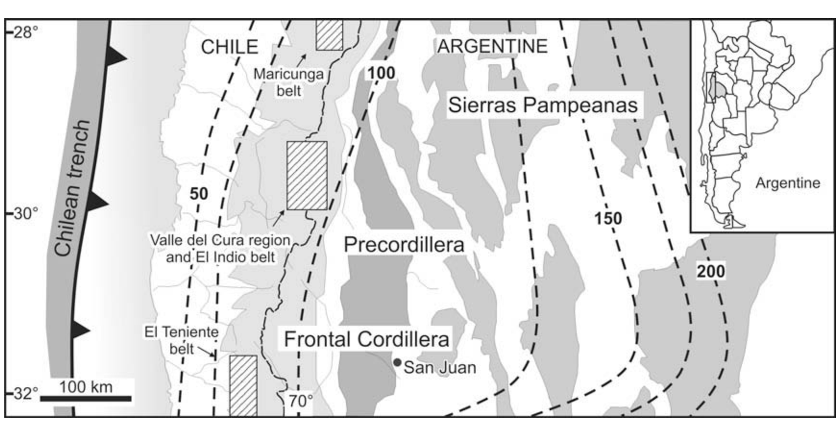

Fig. 1. Location of Valle del Cura region and the El Indio belt over the Pampean flat-slab segment, Southern Central Andes. Dashed lines show subducted slab depth.

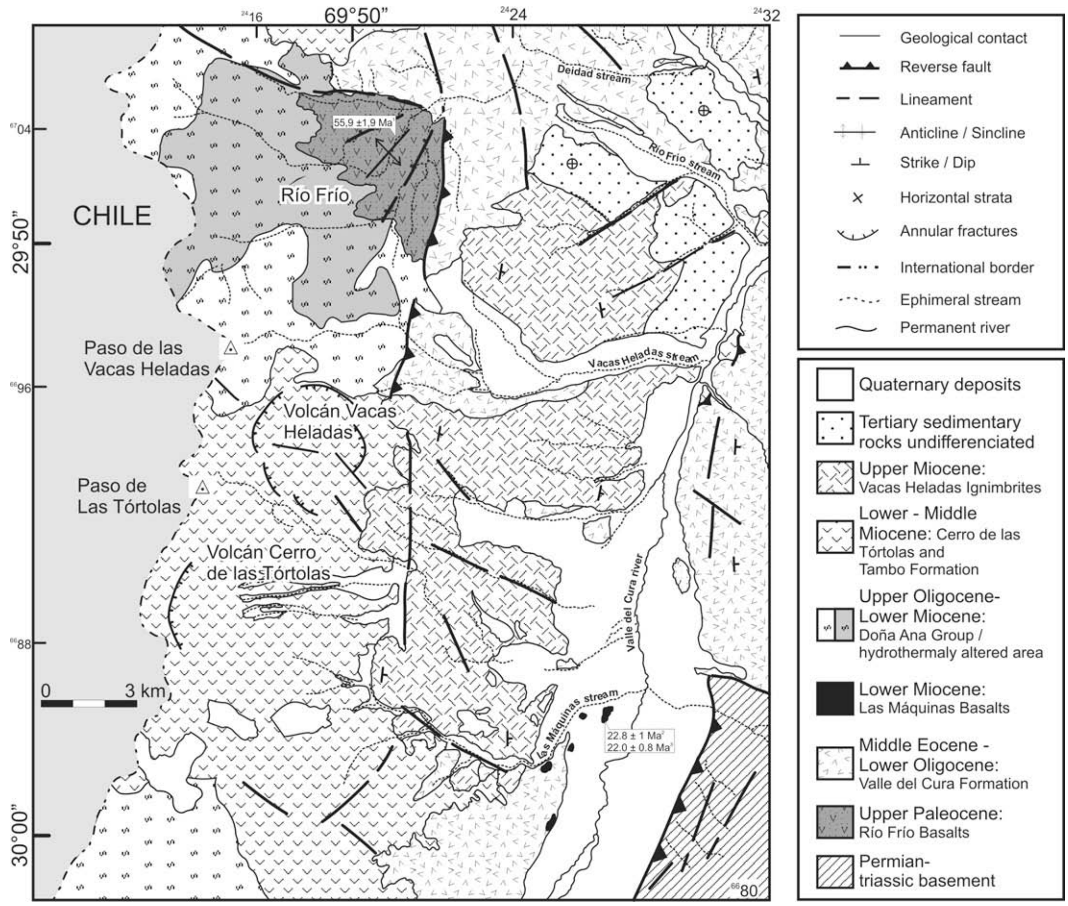

Fig. 2. Geological map of southern Valle del Cura region in Frontal Cordillera, San Juan province, Argentina (modified from Litvak (2004)).

Table 1
Main Tertiary stratigraphic units that describe Valle del Cura region Paleogene and Neogene volcanic history (Maksaev et al., 1984; Kay et al., 1987; Ramos et al., 1989; Nasi et al., 1990; Martin et al., 1997a; Limarino et al., 1999; Bissig et al., 2001; Litvak and Page, 2002; Litvak et al., 2004; Litvak and Poma, 2005).

Age	Stratigraphic units		
PLIOCENE			
MIOCENE			Vacas Heladas Ignimbrites (dacitic tuffs)
MIOCENE	Cerro de las Tórtolas Formation (andesites and dacites)	Tambo Formation (dacitic tuffs)	
MIOCENE	Doña Ana Group: Escabroso Formation (mainly andesites, basandesites and volcanic breccias)		
MIOCENE / OLIGOCENE	Doña Ana Group: Tillito Formation (mainly rhyolites, dacictic tuffs and volcanic breccias)		Las Máquinas Basalts
OLIGOCENE / EOCENE	Valle del Cura Formation (rhyolites and rhyolitic ignimbrites)		
PALEOCENE	Basaltos Río Frío (basalts)		

et al. (1989) and Kay et al. (1991). Whole rock K/Ar analysis yielded ages of 22.8 ± 1.1 Ma (Ramos et al., 1989; Kay et al., 1991) and 22.0 ± 0.8 Ma (Litvak et al., 2005). They crop out as small volcanic necks at the southern extreme of the Valle del Cura near the Máquinas creek, where they intrude older volcaniclastic units. They are mainly aphanitic rocks, but under the microscope they show porphyritic textures with a high abundance of olivine phenocrysts within an intergranular groundmass. Together with the Río Frío Basalts they constitute the most primitive rocks in Valle del Cura. However, their geochemistry, together with some petrographic and stratigraphic features, show a very different magmatic history for each unit.

3. Geochemistry of Paleocene basalts

New major and trace elements, plus isotope data, are presented in Tables 2 and 3 for Río Frío Basalts. All of the samples are basalts and were taken at Río Frío Creek; sample locations are given in the tables. Earlier published data from Las Máquinas Basalts (Ramos et al., 1989), and new analyses, are included in the tables for easier comparison.

Most of the analyses were done at Cornell University. Major elements were measured on a JEOL-733 Superprobe electron microprobe on glasses made from rock powders, trace element analyses were carried out by INAA methods, and Sr and Nd isotopes were analyzed on a multi-collector VG Sector 54 thermal ionization mass spectrometer. Other major element analyses were done by X-ray fluorescence in the Instituto de Geología y Minería of the University of Jujuy, Argentina. Details of all the methodologies used are described in Appendix I.

3.1. Major elements

Río Frío Basalts are the most basic rocks that crop out in the Valle del Cura. They are geochemically very homogeneous with a silica content that varies from 48 to 52%. Their alkali content is also high ($Na_2O + K_2O$ between 5.2% and 6.9%) but the most conspicu-

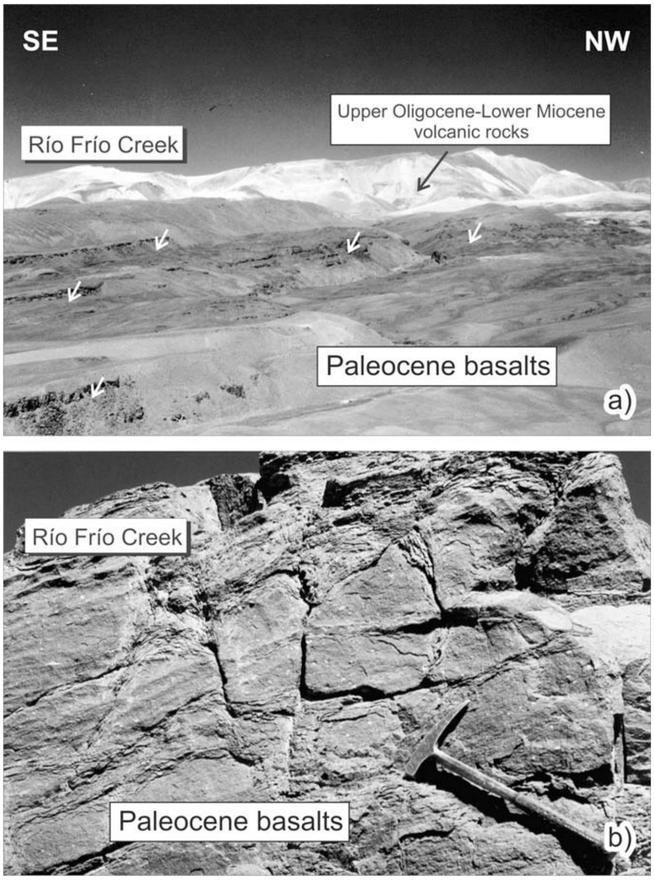

Fig. 3. (a) General view of Río Frío Basalts outcrops at Río Frío Creek. Small arrows indicate different basaltic levels, brighter tones corresponds to the interbedded red conglomerates. (b) Detail of the concentric weathering develop on the basalts due to their homogeneous grain size.

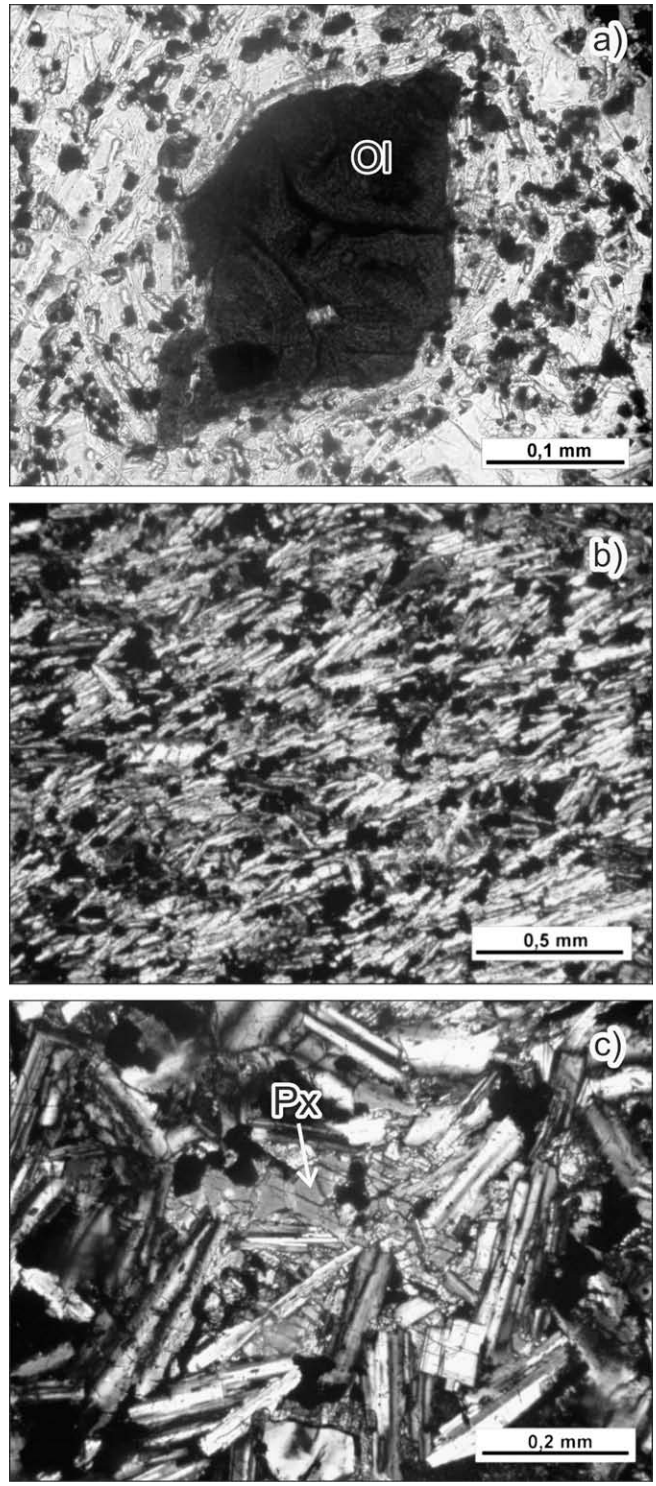

Fig. 4. Microphotographs of Río Frío Basalts. (a) Olivine altered to iddingsite in microporphyric varieties. Plain polarized light. (b) Aphiric varieties with pilotax groundmass. Cross polarized. (c) Subophitic texture in coarser grain size basalts, with fresh clinopyeroxene (Px). Cross polarized.

ous features are their high Fe_2O_3 (>11%) and TiO_2 (2.4–3%) contents, which imply an alkaline tendency. Only sample RF45b varies from the homogeneous pattern of the whole sequence, not only in the major but also in trace element chemical behavior. It is the more differentiated of the samples (52.34% SiO_2), with the highest values of K_2O and Na_2O and the lowest of FeO and MgO of all the basalts, and major element contents that are consistent with its chemical classification as a basaltic trachyandesite. Moreover, it has vesicles filled with secondary minerals, such as carbonates.

Río Frío samples plot in the trachybasalt field in the total alkali vs. silica (TAS) diagram (Fig. 5a), and correspond to the high-K field in K_2O vs. SiO_2 diagram (Fig. 5b, Le Maitre et al., 1989). An alkaline tendency shown by its Fe_2O_3 and TiO_2 content is also seen in the Irvine and Baragar (1971) discrimination diagram (Fig. 5a). Las Máquinas Basalts are also included in these plots for comparison.

3.2. Trace elements

Paleocene Río Frío Basalts show trace element patterns on MORB normalized spider diagrams that are typical of intraplate mafic magmas, as seen in Fig. 6 where samples are plotted according to their silica content. They define a negative slope from the enriched incompatible elements, such as Ta, Nb and Hf, toward the less enriched compatible ones, such as Y and Yb, which are depleted with respect to MORB. Emphatic enrichment of Th, Ta, Hf and TiO_2 with respect to MORB, as shown in this plot, is typical of intraplate alkaline basalts, which implies a significant contribution of incompatible elements from an enriched mantle.

Río Frío samples plot in the transition between E-MORB (Enriched MORB)/tholeiitic intraplate basalts and the intraplate alkaline basalts fields of the tectonic discrimination plot of Wood (1980) (Fig. 7). Their low La/Ta ratios (14–16) are also consistent with their intraplate nature.

Plots in Fig. 8 show the correlation between different incompatible elements of Río Frío Basalts samples. The ratio between two

Table 2
Major elements data for Paleocene Río Frío Basalts and Lower Miocene Las Máquinas Basalts from Valle del Cura.

Unit	Río Frío Basalts								Las Máquinas Basalts		
Sample	RF14	RF42[b]	RF17[b]	RF22	RF50[b]	DI049	RF56	RF45b[b]	TOR9B[a]	TOR9A[a]	MQ8[b]
SiO_2	48.69	48.93	48.94	49.62	49.88	50.06	51.03	52.34	49.38	48.56	50.38
TiO_2	2.97	2.93	3.00	2.92	3.21	3.03	2.40	2.09	1.63	1.36	1.58
Al_2O_3	17.03	15.74	16.53	17.21	15.48	16.16	17.88	17.941	17.94	18.97	17.18
Fe_2O_3	14.13	11.37	12.03	13.14	12.35	11.88	12.99	10.78	11.50	10.13	10.00
MnO	0.17	0.16	0.11	0.17	0.18	0.12	0.11	0.10	0.16	0.15	0.18
MgO	3.55	4.17	4.03	3.74	3.85	3.09	3.01	0.79	5.73	5.90	5.62
CaO	7.74	6.29	7.52	7.74	6.82	8.10	7.71	6.82	10.74	11.25	10.49
Na_2O	3.82	4.61	3.92	4.10	3.88	4.01	4.12	4.24	3.07	2.69	3.03
K_2O	1.40	2.00	1.45	1.83	1.40	1.55	1.65	2.72	0.98	0.83	1.07
P_2O_5	0.57	0.50	0.49	0.66	0.51	0.53	0.60	1.29	–	–	0.28
LOI	–	2.80	1.84	–	2.68	1.86	–	2.63	–	–	0.37
Total	98.66	99.51	99.85	99.83	100.23	100.39	100.21	100.211	101.13	99.84	99.52
La	30.1	29.1	32.5	34.6	29.0	32.2	28.7	48.2	13.5	11.3	13.1
Ce	69.2	61.2	73.1	79.5	63.9	72.6	64.7	111.9	29.9	25.8	27.6
Nd	42.4	39.6	42.0	52.8	37.9	35.5	41.0	70.0	18.0	15.9	15.1
Sm	8.6	8.6	9.9	10.3	8.4	9.9	8.7	15.5	4.4	3.7	4.0
Eu	2.79	2.63	3.10	3.39	2.63	2.99	2.76	4.56	1.41	1.17	1.34
Tb	1.27	1.271	1.34	1.39	1.17	1.32	1.20	2.07	0.75	0.60	0.68
Yb	2.35	2.11	2.41	2.37	2.07	2.1	2.18	3.28	2.08	1.74	1.92
Lu	0.305	0.272	0.309	0.299	0.262	0.3050	0.281	0.418	0.290	0.243	0.261
Sr	653	556	696	748	595	712	681	621	415	520	509
Ba	393	486	405	449	358	467	381	737	231	208	203
Cs	3.2	1.4	1.	69.2	2.6	4.5	0.9	5.5	29.0	1.0	8.3
U	0.9	0.9	1.0	1.1	1.1	1.1	1.3	1.8	0.3	0.3	0.4
Th	3.3	2.5	3.4	3.3	2.7	3.4	3.1	4.4	1.1	1.0	1.2
Hf	5.5	5.2	5.8	6.2	5.2	5.9	5.3	8.1	2.6	2.0	2.6
Ta	1.94	1.84	2.03	2.39	2.08	2.17	1.91	2.96	1.00	0.87	0.81
Sc	17.4	16.1	19.1	15.3	17.6	18.7	1.9	12.2	34.2	29.5	30.2
Cr	6	5	12	10	5	6	4	4	66	112	54
Ni	23	252	23	25	26	28	23	7	21	41	20
Co	45	38	42	40	48	48		18	41	40	31
Ba/La	13.1	16.7	12.4	13.0	12.3	14.5	13.2	15.3	17.1	18.4	15.5
La/Sm	3.5	3.4	3.3	3.4	3.4	3.13	3.3	3.1	3.0	3.0	3.2
La/Yb	12.8	13.8	13.5	14.6	14.0	13.9	13.2	14.7	6.5	6.5	6.8
Sm/Yb	3.7	4.1	4.1	4.4	4.1	4.3	4.0	4.7	2.1	2.1	2.1
Ba/Ta	202	265	199	188	172	215	199	249	232	240	249
La/Ta	15.5	15.9	16.0	14.5	13.9	14.8	15.0	16.3	13.6	13.0	16.1
	29°49′27″	29°47′32″	29°49′34″	29°49′42″	29°47′38″	29°49′19″	29°48′10″	29°47′59″			29°57′51″
Location	69°50′09″	69°51′26″	69°49′47″	69°49′17″	69°47′33″	69°50′09″	69°49′22″	69°49′23″	Las Máquinas Creek		69°45′31″

[a] These samples corresponds to Ramos et al. (1989).
[b] Major elements of these samples were analyzed by XRF in Universidad of Jujuy, Argentina; the others, in an electron microprobe at University of Cornell, USA. All of the trace elements were analyzed by INAA at University of Cornell, USA. See methodology details in Appendix I.

Table 3
Isotopic data for an aphiric subofitic basalt from Paleocene Río Frío Basalts unit.[a]

Río Frío Basalts	$^{87}Sr/^{86}Sr$	Error	$1^{43}Nd/^{144}Nd$	Error	εNd
Sample RF56	0.7036784	0.0007	0.5128727	0.0009	4.6

[a] εNd was calculated with a CHUR value of 0.512638; error are expressed in 2σ.

incompatible elements with a similar bulk partition coefficient does not change during a fractionated crystallization, and varies only slightly during the partial melting process (Rollinson, 1993). If the ratio of the two incompatible elements is linear, it may indicate the concentration ratios of the elements in the source; any change in this ratio might be explained by heterogeneity in the source as a result of processes such as mixing or assimilation. Fig. 8 shows that the element pairs La–Ce, Ta–La, and La–Nd show the best linear correlations.

3.3. Isotopic data

Analyzed Río Frío Basalts sample RF56 corresponds to the one dated by K/Ar in 55.9 ± 1.9 Ma (Litvak and Page, 2002), which comes from one of the lava flows in the Río Frío Creek (Fig. 2). It is a subophitic basalt, which includes plagioclase, clinopyroxene, and olivine as main mineralogical phases (Fig. 4c). This basalt, representative of the entire Paleocene unit, has an isotopic $^{87}Sr/^{86}Sr$ ratio of 0.70368 and a $^{143}Nd/^{144}Nd$ value of 0.51287, with an εNd of 4.6. The results indicate a mantle affinity as the source for these basalts.

4. Paleocene vs. Lower Miocene mafic volcanism in Valle del Cura

Paleocene Río Frío Basalts and Lower Miocene Las Máquinas Basalts represent mafic volcanism in Valle del Cura. Both units correspond to the most primitive volcanism in the area; their petrography and chemical composition are useful indicators of mantle evolution during the Tertiary.

Major and trace element chemical features described above for the Río Frío Basalts unit confirm the alkaline intraplate trend of this magmatism. Trace element correlation diagrams evidence a common source for Río Frío Basalts and show no evidence of any process that might have affected a partial melting origin from that source, which corresponds to an enriched portion of the mantle, as reflected by its trace and major element chemical composition. Isotope data show that Paleocene mafic lavas originated from mantle-

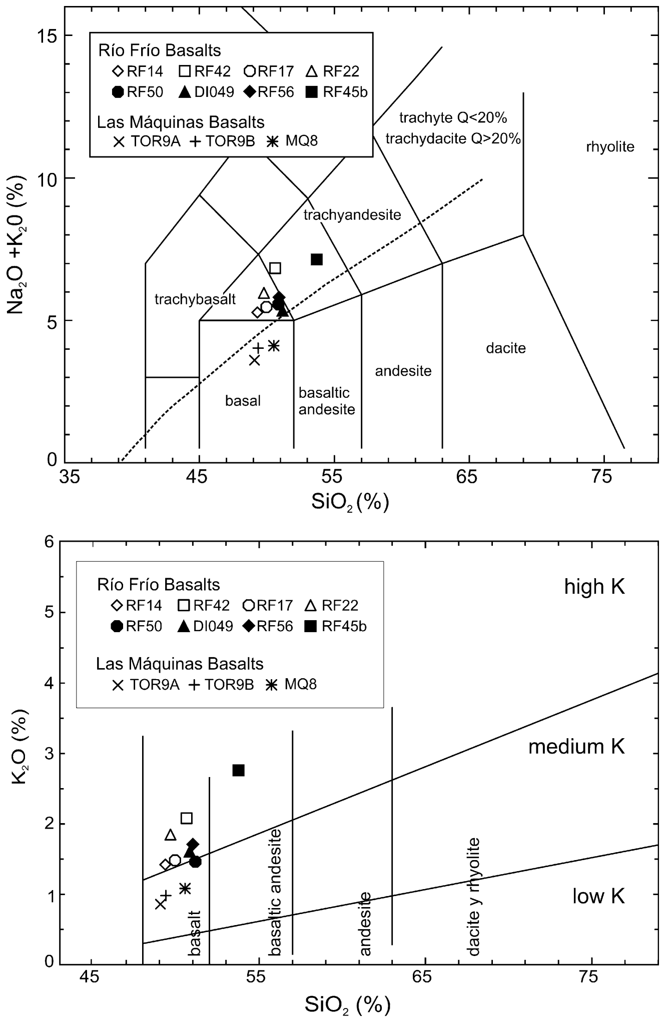

Fig. 5. (a) Total alkaline vs. silica (TAS) classification diagram for Río Frío and Las Máquinas Basalts dashed line corresponds to alkaline–subalkaline division of Irvine and Baragar (1971). (b) K_2O vs. SiO_2 diagram (Le Maitre et al., 1989) for Río Frío and Las Máquinas Basalts.

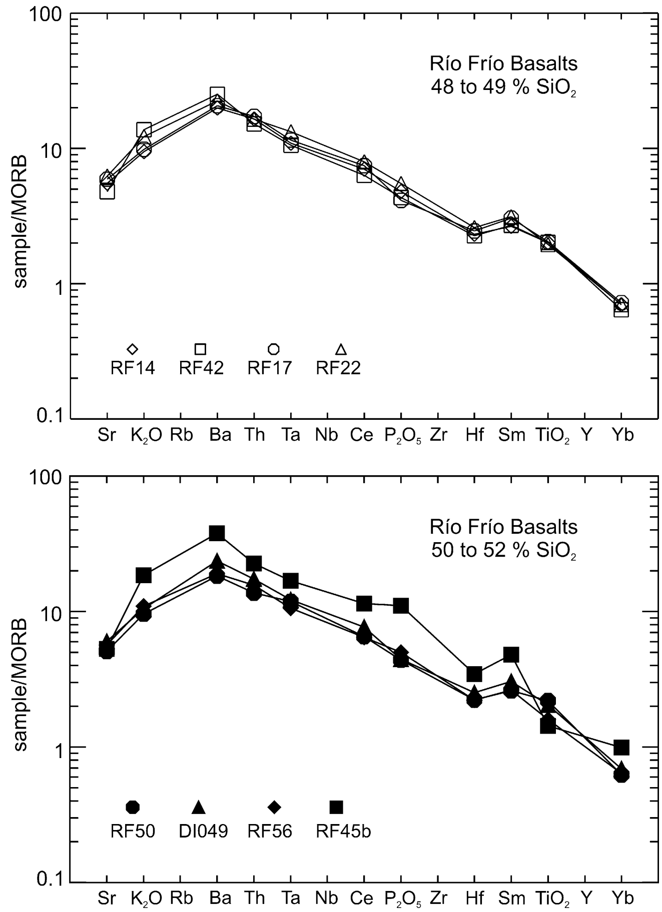

Fig. 6. Trace element spider diagrams with an intraplate-type pattern for Paleocene Río Frío Basalts. MORB normalization values taken from Pearce (1983).

derived melts with no contamination of crust-derived components. On the other hand, trace element characteristics of the Lower Miocene Las Máquinas Basalts show enrichment in incompatible elements, shown by their high La/Ta and Ba/Ta ratios as described by Kay et al. (1991); they also plot in the alkaline intraplate basalts field in the Wood (1980) tectonic discrimination plot (Fig. 7). Kay et al. (1991) also mention that FeO/MgO ratios in the Lower Miocene basalts suggest olivine fractionation in them, resulting in the high abundance of olivine phenocrysts. Ramos et al. (1989) and Kay et al. (1991) conclude that Las Máquinas Basalts are alkaline olivine-rich magmas, with Ba/La ratios consistent with a closer position to a volcanic arc. Although both groups have similar alkaline affinity, a detailed comparison between them exposes significant differences that allow evaluation of the evolution from their sources and thus, the genesis of these mafic volcanic rocks.

In major elements, the Río Frío Basalts and Las Máquinas Basalts have their most significant differences in their K_2O, Fe_2O_3 and TiO_2 contents. Paleocene basalts have higher K_2O concentrations than the Lower Miocene rocks and fall into the trachitic field in the TAS diagram (Fig. 5b), and in the high-K field in the Le Maitre et al. (1989) plot (Fig. 5a). In contrast, Lower Miocene volcanic rocks are classified as basalts in the TAS diagram and correspond to the medium-K field (Figs. 5). Fe_2O_3 and TiO_2 contents are high

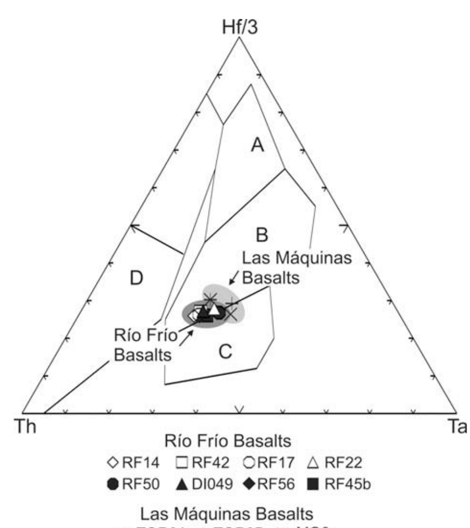

Fig. 7. Wood (1980) tectonic discrimination diagram for Río Frío and Las Máquinas Basalts. (A) N-type MORB; (B) E-type MORB and within plate tholeites; (C) alkaline within plate basalts; and (D) volcanic arc basalts.

in both basaltic units, which indicates their alkaline tendency, but Río Frío Basalts concentrations of both major elements are higher – % TiO_2 is double – showing a higher enrichment in incompatible elements for Paleocene basalts, both groups having the

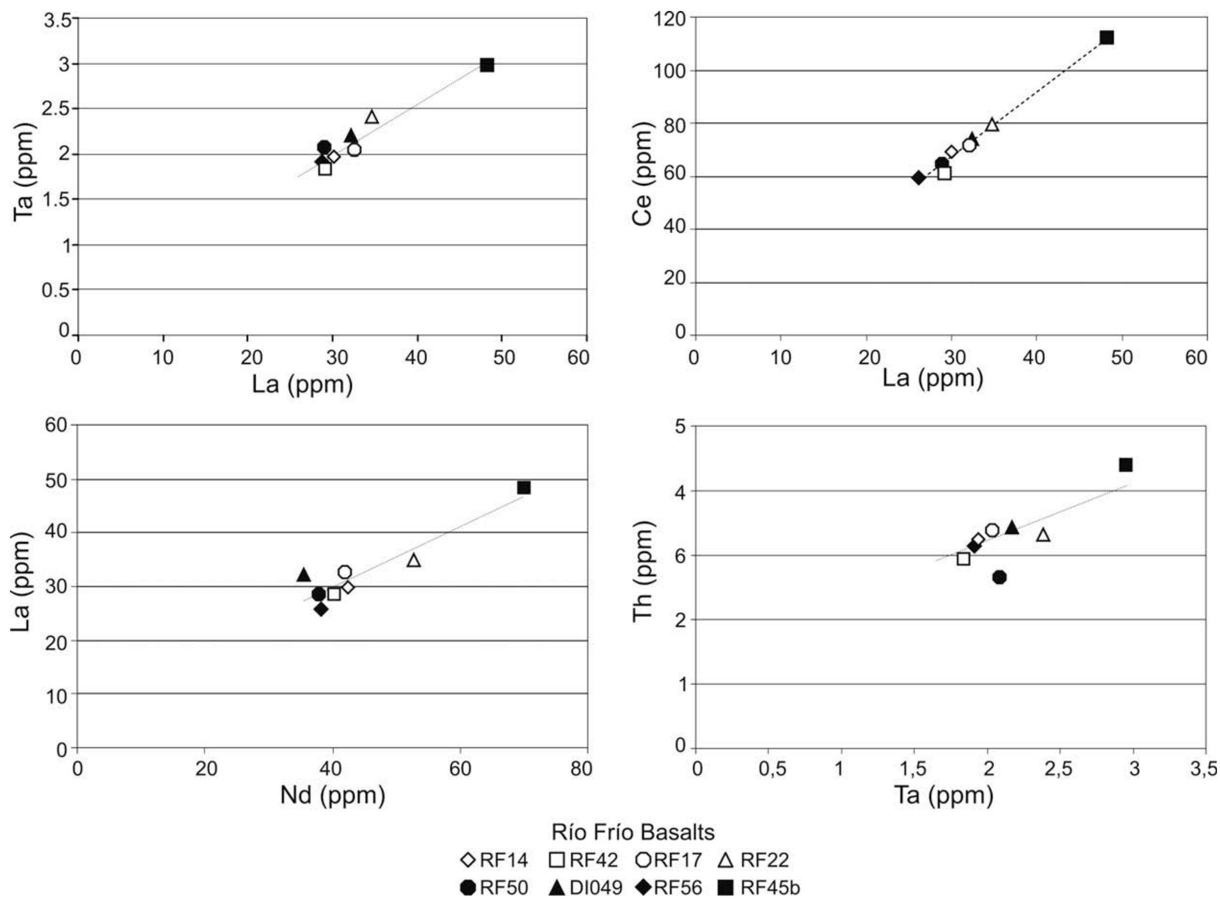

Fig. 8. Trace elements correlation diagram (La–Ce, Ta–La, La–Nd y Th–Ta) for Río Frío Basalts. Linear correlation between shown trace elements evidence a common source for Paleocene basaltic rocks.

same silica content. The Río Frío Basalts Mg# values range between 20 and 29; with only the more differentiated sample RF45b exceeding this range. The Las Máquinas Mg# values are higher, varying from 36 to 39. According to these Mg# values, both groups of basalts are close to primary compositions of mantle melts (Rollinson, 1993).

Incompatible trace elements also show a wider enrichment range for Río Frío Basalts. In the Th/Yb vs. Ta/Yb diagram (Fig. 9) both units plot in the non-subduction setting basalt (MORB/within plate) array of Pearce (1983), which evidences a similar source for these basalts that corresponds to an enriched primitive mantle, typical for an intraplate setting. However, Paleocene basalts are more enriched in incompatible elements such as Sr, Rb, Th, Ta, Nb, Ce, and Hf, as they plot in a more extreme position within the array than Lower Miocene ones.

The same situation is shown in Fig. 11, where La/Ba and La/Th ratios for both basaltic units are plotted to discriminate between orogenic and MORB derived andesite (Gill, 1981). The figure shows not only an E-MORB geochemical affinity for both Paleocene and Lower Miocene basalts, but also a higher content of incompatible elements for the older basaltic unit. The La/Ba plot (Fig. 10a) shows that Las Máquinas Basalts samples have a slight tendency towards the orogenic andesites field due to a higher Ba content (relative to La) in these basalts compared to those from Río Frío ones. Ba is an element derived from fluids associated with the subducted slab and/or subducted sediments; its presence is associated with arc-related settings (Kay, 1977; Gill, 1981). This distinguishing feature of Las Máquinas Basalts can be explained according to Ramos et al. (1989) and Kay et al. (1991), who pointed out that these basalts are contemporaneous and probably closely related with the main volcanic arc volcanism.

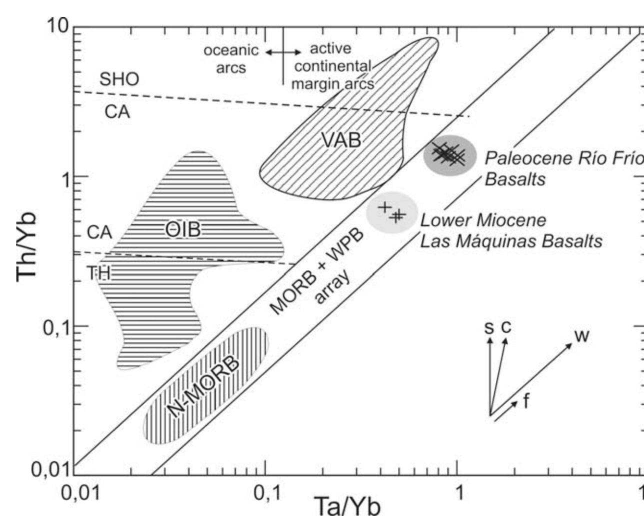

Fig. 9. Th/Yb vs. Ta/Yb correlation diagram of Pearce (1983) for Río Frío and Las Máquinas Basalts. Both units plot in the non-subduction setting basalts (MORB/within plate) array. Identified fields correspond to: OIB, ocean island basalts; VAB, volcanic arc basalts; N-MORB; TH. Dashed lines divides fields of tholeitic (TH), calcalkaline (CA) and shoshonitic (SHO) compositions.

Trace elements such as Ta, Th and Hf, are of particular interest for evaluating mafic magmas, because the Ta/Hf ratio is a good indicator of mantle enrichment, while the Th/Hf ratio is useful

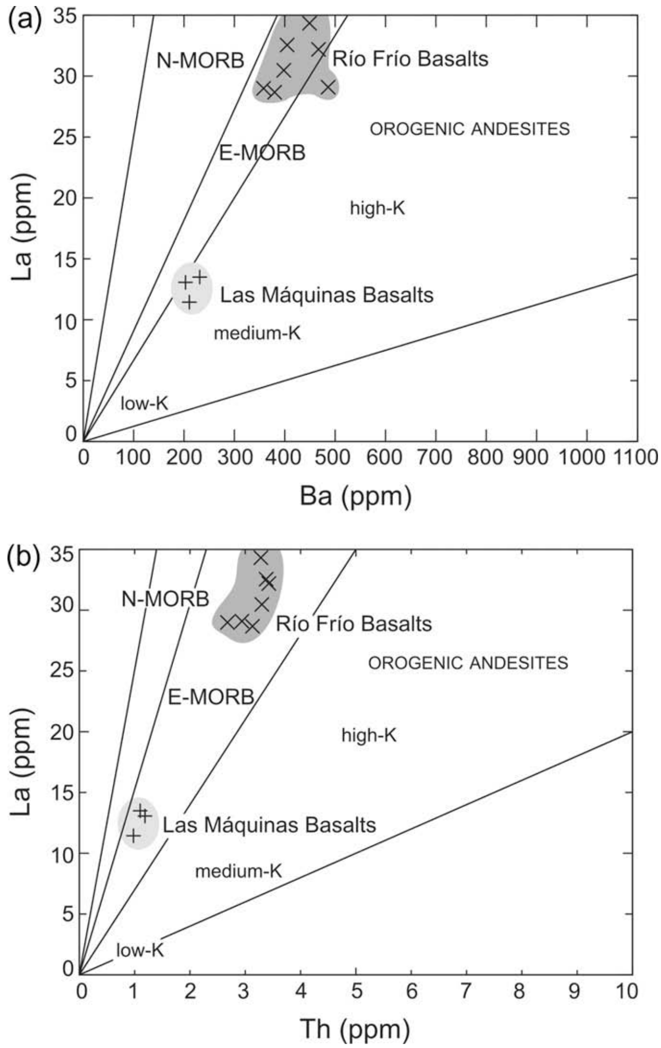

Fig. 10. (a) La/Ba and (b) La/Th for Río Frío and Las Máquinas Basalts (Gill, 1981). Both groups plot within E-type MORB basalts field. In (a) Las Máquinas Basalts have tendency towards the orogenic andesites field that evidence a volcanic arc influence.

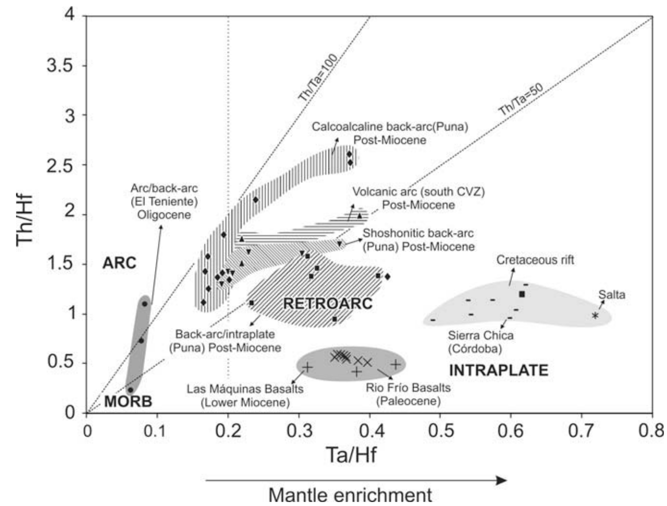

Fig. 11. Th/Hf vs. Ta/Hf diagram for Río Frío and Las Máquinas Basalts; these ratios are good indicators of mantle enrichment relative to subduction component contribution (based on Kay, 2001). Data from Puna, Salta and El Teniente are taken from Kay et al. (1994, 1999) and from Sierra Chica from Lagorio (2003). Ta/Hf values for Río Frío and Las Máquinas Basalts evidence contributions from an incompatible-enriched mantle.

as a relative measure for slab-related component contributions. Th and Hf are high field strength elements with similar chemical behavior. Ta is sensitive to oxidation and replaces Ti, but Hf does not; so high Ta/Hf ratios are related to intraplate enriched mantle sources, while low values reflect depleted MORB signatures and arc sources (Kay, 2001). Ta/Hf values for Río Frío and Las Máquinas Basalts (0.3 and 0.5) evidence more intraplate-like mantle enrichment than arc or MORB derived contributions (Fig. 11).

Intraplate volcanism might be associated with extensional tectonic settings that allow the melts, previously formed at depth, to rise rapidly towards the surface. Pearce (1996) explained that one of the most conspicuous features of intraplate basalts is that the only incompatible elements not enriched (relative to MORB) are the ones which are incorporated in garnet; as a result, Ti is typically enriched whereas Y and Yb are depleted in intraplate basalts. Ti and Y have the same fractionation coefficient for melting of a spinel lherzolite, but Y has a much higher one for melting of a garnetiferous lherzolite. As a result, any garnet bearing residue derived from a garnetiferous lherzolite melting will selectively retain Y, raising Ti/Y ratios in the resulting melt. Considering that garnet lherzolite is stable at depths below 50 km, Pearce (1996) concludes that the high and distinctive Ti/Y ratios exhibited by intraplate basalts reflect deep melting processes that leave garnet in the residue.

In consequence, and considering that Y chemical behavior is similar to Yb due to their similar ionic potential (Y: $Z/r = 0.033\ pm^{-1}$, Yb: $Z/r = 0.034\ pm^{-1}$), Ti/Yb ratios for Río Frío and Las Máquinas Basalts were compared. They have high Ti/Yb ratios that characterize their intraplate affinity, but Paleocene basalts (Ti/Yb = 6600–7500) show higher values than Lower Miocene ones (Ti/Yb = 4600–4700), which might be reflecting a deeper generation source for Paleocene magmatic melts.

Trace element compositions for both Paleocene and Lower Miocene basaltic magmas show that their melts resulted from partial melting of an E-MORB-type enriched mantle. To confirm this assumption, isotope data from both units were compared in Fig. 12. Isotope ratios for Río Frío and Las Máquinas are virtually the same: the $^{87}Sr/^{86}Sr$ ratio 0.70368, and the εNd 4.6 and 4.5 respectively. These values are taken as evidence that the source of both mafic magmas is similar and corresponds to an isotopically depleted mantle, leading to the conclusion that mantle compositions have not suffered major changes from Paleocene to Lower Miocene.

5. Regional comparison

Regional comparison of Río Frío and Las Máquinas Basalts chemical composition with other mafic magmatism, geographically and/or temporally related, is very useful for precisely defining the Paleocene and Lower Miocene volcanic tectonic setting. Fig. 11 shows Th/Hf vs. Ta/Hf ratios for Río Frío and Las Máquinas Basalts, plus other mafic lava groups such as Cretaceous alkaline intraplate basalts from the Salta and Córdoba provinces (NW and central Argentine), and Recent to post-Miocene retroarc and arc-related mafic lavas from southern Puna (Central Volcanic Zone) and the El Teniente region (34°SL, Chile). The figure shows that typical alkaline intraplate basalts have the highest Ta/Hf ratios (>0.5); while arc-related and MORB lavas have lower values (<0.2). Values for Paleocene and Lower Miocene Río Frío and Las Máquinas Basalts (0.3–0.5) evidence contributions from an incompatible-enriched mantle; however, their enrichment range

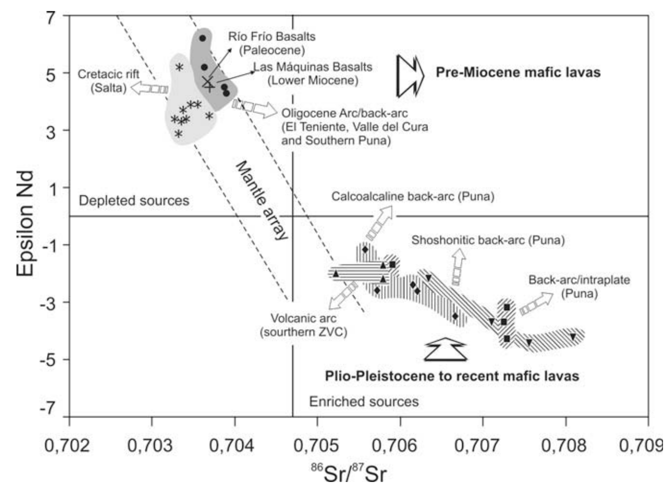

Fig. 12. $^{87}Sr/^{86}Sr$ y εNd ratios for Pre and post-Miocene mafic lavas of Central Andes. Pre-Miocene lavas are isotopically depleted relative to Post-Miocene ones. Río Frío basalts are included within the first depleted group lavas with $^{87}Sr/^{86}Sr$ <0.704 y εNd >+4. Data included correspond to: Cretacic rift from Lucassen et al. (2002) and Kay et al. (1994) and to arc/back-arc from Puna and southern Central Volcanic Zone from Kay et al. (1994, 1999).

is lower compared to alkaline continental rift-related lavas (Fig. 11). This can be explained because of a different degree of melting, or a difference in the original magma composition related to a deeper mantle source, which is typical of continental rift-related lavas.

Similar isotopic behavior is shown by a comparison of Río Frío and Las Máquinas lavas with other mafic, temporally related, volcanic rocks (Fig. 12). Kay et al. (1999) distinguished two groups of mafic lavas for the Central Andes. The first one corresponds to pre-Miocene lavas with isotope ratios of $^{87}Sr/^{86}Sr$ <0.704 and εNd >+4; this group includes: Cretaceous lavas from NW Argentina (Santa Bárbara, 25° SL, Salta) and Upper Oligocene–Lower Miocene arc and back-arc lavas from the Coya Machalí Formation (El Teniente Region, 34° SL), Segerstrom Basalts from southern Puna (24° SL), and Las Máquinas Basalts also discussed herein. Río Frío Basalts from Valle del Cura can be included in this group as well, which corresponds to isotopically depleted mafic lavas. The second group corresponds to younger lavas of Plio–Pleistocene to recent age, and includes lavas from the Puna back-arc in the southern extreme of the Central Volcanic Zone and the shoshonitic back-arc of the Central Puna (Fig. 12). This second group of mafic lavas differs from the first group with respect to their Sr and Nd isotopic ratios; they have $^{87}Sr/^{86}Sr$ >0.705 and εNd <−1.2, which defines them as isotopically enriched lavas.

The difference of the two trends of mafic lavas is the result of different processes related to participation of crust-derived components. Mafic lavas younger than middle Miocene show a Sr isotopic enrichment due to an increased incorporation of crust-derived components that changed the original isotopical composition of primary mafic magmas. Processes that may lead to the observed isotopic signatures include: increase in crustal thickness, crustal material that is incorporated beneath the arc and forearc by subduction erosion, sediment subduction, and the participation of subducted slab-related fluids. All these processes tend to increase original mantle isotope signature towards a more evolved or crustally related one. These processes are related to changes in the subduction angle of the downgoing slab during Tertiary times along the Andean margin, changes that are reflected in the geochemical evolution of the Paleogene and Neogene volcanic-arc mesosilicic rocks along the Central Andes (Hildreth and Moorbath, 1988; Kay and Abbruzzi, 1996; Bissig et al., 2002; Kay and Mpodozis, 2002; Kay et al., 1991, 1999, 2005; Stern, 1991; Stern and Skewes, 1995, 2003; Skewes et al., 2002; Litvak et al., 2007).

6. Mafic magma petrogenesis

Paleocene Río Frío Basalts and Lower Miocene Las Máquinas Basalts share a similar source for their melts: an incompatible-enriched mantle, isotopically depleted. However, they show differences in major and trace elements chemical behavior, reflected also in their petrographical features, which might be the result of three variables: a different degree of mantle melting, a difference in the generation depth of the melts, and/or the tectonic setting that, later, would influence the evolution of the primary magmas. A lesser degree of melting for Río Frío Basalts or a deeper site of melt generation compared to the Las Máquinas Basalts would explain their higher range of incompatible enrichment. Evidence for a deeper generation site of partial melting for Paleocene basalts comes from their higher Ti/Yb ratios with respect to Lower Miocene ones. However, a lesser degree of partial melting may also lead to the observed trace element contents.

The tectonic setting also plays a major role in evaluating the difference between the two volcanic units, because the tectonic regime influences the evolution of primary melts, changing their original chemical composition and controlling the resulting volcanic products. In consequence, alkaline intraplate Río Frío basalts – with no volcanic arc influence – should be associated with an extensional tectonic regime. Magmas generated in this setting correspond to high temperature melts of deep origin, that result from a low degree of melting of an enriched portion of lithospheric mantle (Wilson, 1989). These melts could move easily up towards the surface due to the tensional stresses present. Fast ascent of primary magmas, follow by a vacuum in magmatic chambers, is evidenced by aphiric textures of the basalts and their fine and homogeneous grain size. The interbedded continental red beds in the Río Frío Basalts, which represent inter-eruptive sedimentary episodes (Litvak and Page, 2002), and the normal faulting affecting all the whole sequence, are also evidence of an extensional tectonic regime associated with the genesis and eruptivity of this magmatism. Isotopic composition of Río Frío Basalts volcanics characterize these rocks as primitive melts with negligible crustal contamination, and may be considered representative of Paleocene mantle compositions.

Las Máquinas Basalts have alkaline intraplate chemical compositions similar to the Río Frío Basalts; they are also derived from melting of an enriched portion of a lithospheric mantle. The main difference compared to the older lavas from Río Frío F is shown by Ba/Ta and Ba/La ratios that reflect a magmatic arc influence. Thus, primary Lower Miocene mafic melts originated in a back-arc setting, evolving in a more compressional regime where they remained in an intermediate to shallow magmatic chamber, resulting in porphyric lavas with a high abundance of phenocrysts.

Although trace element behaviors show differences between both units, an isotope depleted trend is the same for both groups of basalts. As mantle composition did not change significantly from Paleocene to Lower Miocene and mafic melts originated during that time kept and reflect their primary chemical composition, differences in their final volcanic products are the consequence of factors such as the tectonic geodynamic stetting in which they evolved, and are not inherited from the mantle source. However, post-Miocene mafic magmas of the Central Andes show enriched isotopic trends that are explained by crustal contamination processes that affected the primary melts. This strong influence in crustal participation reflects major tectonic changes that, in this case, influenced the genesis of primary melts.

7. Tectonic evolution and geodynamical model

The tectonic evolution of the Valle del Cura region and El Indio belt over the Pampean flat-slab was recently well studied by several authors who presented different geodynamical models for the region. Some of them explained Oligocene to Miocene petrogenesis of magmatic rocks and their relationship with mineralized, geomorphic, and/or tectonic events, while other models focused on the petrogenesis of Eocene volcanic rocks (Kay et al., 1991, 1999; Kay and Mpodozis, 2002; Ramos et al., 2002; Bissig et al., 2001, 2002, 2003; Litvak et al., 2007). However, the history of the lowermost Tertiary was generally excluded in previous studies due to the apparent lack in the geological record. The first recognition of the Río Frío Basalts unit complete Paleogene tectonic evolution of this particular section of Central Andes (Fig. 13).

A generalized extensional setting was dominant along the Andean margin during the middle Mesozoic, when subduction between the Farallones and South-American plates began. This subduction was characterized by a negative roll-back velocity and continued until the Middle Cretaceous (Ramos, 1999; Ramos and Aleman, 2000; Haschke et al., 2006). This Cretaceous extensional regime was very conspicuous and is also seen in the Sierras Pampeanas, in the Salta rift (NW Argentine), and in the Cretaceous rift in the Sierra Chica, Córdoba (central Argentine), where alkaline basaltic volcanic and intrusive rock exposures are common (Lucassen et al., 2002; Lagorio, 2001; Ramos et al., 2002; Viramonte et al., 1999).

At the same time, on the Chilean side, this extensional regime is seen by the development of intra-arc basins and inner and external volcanic arc volcanism (Ramos and Aleman, 2000). West of Valle del Cura, in the Coastal Cordillera (Chile, 29°20′–30° S/71° W) volcanic-arc magmatism was basaltic to andesitic, with chemical features that evidence extensional intra-arc basin development with deposition of clastic marine sediments (Morata and y Aguirre, 2003). Evidence of the Cretaceous volcanic arc is also present at the Argentine–Chilean border, in the southern extreme of the Pampean flat-slab segment near 32°S and 70°W (Pagán et al., 2005).

In this context, Río Frío Basalts correspond to volcanic alkaline exposures that indicate the last extensional periods of Upper Cretacieous–Paleocene times, before major changes in the regional tectonic configuration occurred. Because of this tectonic setting, Río Frío primary melts erupted through a thin crust, with no influence of the volcanic arc that was located approximately 200 km to the west (Fig. 13a).

Eocene–Lower Oligocene volcanic-arc magmatism was restricted in the Valle del Cura region and El Indio belt, because the Eocene–Lower Oligocene magmatic arc was not well developed along the central Andean margin due to an oblique convergence direction and a low subduction rate (Pardo Casas and Molnar, 1987). Magmatic rocks of this age include the Bocatoma Intrusive Unit (Nasi et al., 1990 Mpodozis and Cornejo, 1988; Martin et al., 1995, 1997a; Bissig et al., 2001) and similar intrusive bodies of the Copiapó region, where they are related to porphyry copper mineralization (Mpodozis and Kay, 2003; Perello and Mpodozis, 2003). These bodies represent the location of the Eocene–Lower Oligocene magmatic arc for these latitudes, which is closer to the trench than expected for a volcanic arc (Fig. 13b). The location of the Bocatoma arc could reflect subsequent removal of the continental margin by forearc subduction erosion (Litvak et al., 2007).

On the Argentinian Andean slope, Eocene volcanic and volcano-sedimentary rocks are well exposed, including tuffs, conglomerates, volcanic arenites, dacitic ignimbrites, and rhyolitic lava flows of the Valle del Cura Formation (Limarino et al., 1999; Litvak and Poma, 2005). These rocks were interpreted as being emplaced in a retroarc setting related to a broad volcanic arc with a somewhat shallow subducting plate that would allow arc-like magmas to be erupt behind the frontal arc (Fig. 13b) (Litvak et al., 2007). This Eocene–Lower Oligocene retroarc volcanic and volcaniclastic activity was widespread, as shown by similar sequences all along the Valle del Cura region, and to the north in the Macho Muerto area and in the Cordon de la Brea (Limarino et al., 1999; Panteleyev and y Cravero, 2000; Mpodozis and Kay, 2003; Litvak and Poma, 2005).

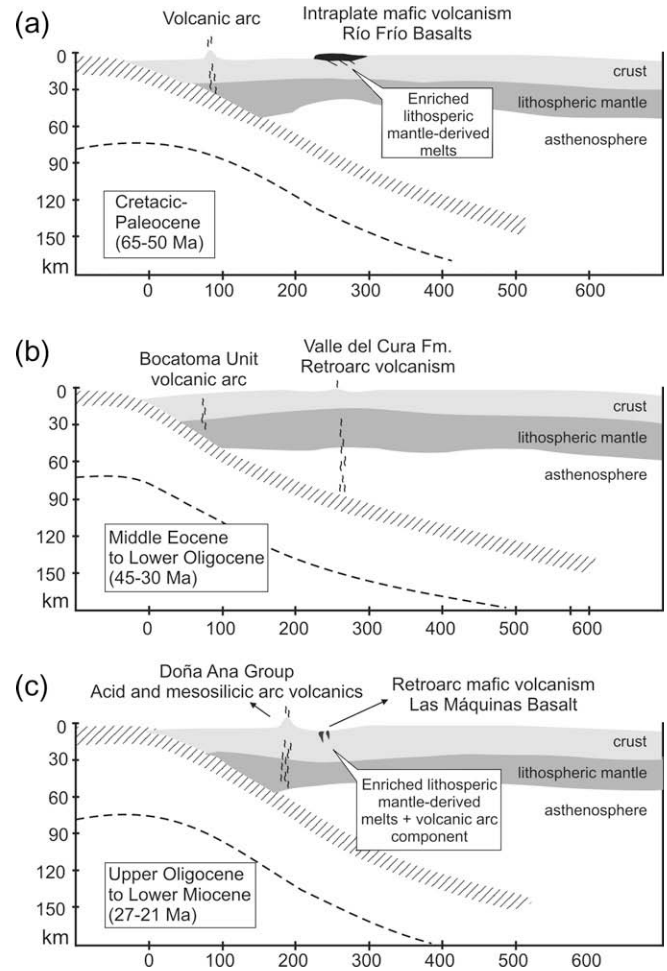

Fig. 13. Geodynamical evolution model for the Lower Tertiary magmatic history of Valle del Cura over the Pampean flat-slab segment, approximately in a 29–30° transect. (a) Paleocene Río Frío Basalt melts erupted through a thin crust, with no influence of the volcanic arc. (b) Eocene–Lower Oligocene volcanic and volcaniclastic activity (Valle del Cura Formation) was developed in a retroarc setting related to a broad volcanic arc. (c) Upper Oligocene to Lower Miocene volcanic arc is represented by the Doña Ana Group volcanic rocks.

Finally, during the Upper Oligocene (~24 Ma) the tectonic configuration of the Andean margin changed due to the break up of the Farellones plate into the Nazca and Cocos plates, resulting in a change to an orthogonal convergence direction at an increased subduction rate (e.g., Pardo Casas and Molnar, 1987). Under these new conditions, an Andean type arc was developed, which is represented by the Doña Ana Group volcanic rocks (Fig. 13c) (Maksaev et al., 1984; Nasi et al., 1990; Martin et al., 1997a). Although there was an increase in convergence velocity, Oligocene Andean subduction had an extensional configuration; in the El Teniente region, normal fault-related depositional basins that are well described by Charrier et al. (2002) were inverted in the latest early Miocene (Kurtz et al., 1997; Godoy et al., 1999). In this context, back-arc volcanism resulted in the eruption of Las Máquinas Basalts. In this case, primary melts had a strong influence of the coeval volcanic arc, which was more active and proximal than during the Paleocene (Fig. 13c).

8. Conclusions

The data presented here provide a more comprehensive geochemical history of the Tertiary volcanics of the Valle del Cura belt, based on new data for the Paleocene volcanics. The Paleocene Río Frío Basalts are the oldest alkaline intraplate-type mafic magmatism represented in the Valle del Cura region over the Pampean flat-slab segment. Together with the alkaline back-arc Las Máquinas Basalts, of Lower Miocene age, they are the more primitive magmas of the area, reflecting Lower Tertiary mantle composition. Although they are melt products derived from geochemically similar enriched lithospheric mantle, a higher degree of incompatible element enrichment in the Río Frío Basalts evidences a deeper generation zone.

The tectonic setting played a major role in the evolution of each mafic melt. The Río Frío magmas are associated with the regional Late Cretaceous–Paleocene extensional tectonic regime affecting the entire South-American plate and the Andean margin, and show no influence of a subducted slab component. The Las Máquinas Basalts evolved in a more compressive regime, in a back-arc setting along the Andean margin since the Upper Oligocene. Despite this difference, they share a similar isotopically depleted signature representing parental magmas. We can conclude that mantle composition did not change significantly during the Early Tertiary Andean Orogenesis until the Lower Miocene. Río Frío Basalts and Las Máquinas Basalts share the isotopic trend of pre-Miocene mafic lavas from the Central Andes that were not affected by crustal contamination processes.

Acknowledgements

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Appendix I

Trace elements and most major analyses were done at Cornell University. All samples were sawed into slabs and fresh unweathered material was chosen for whole-rock analysis. Slabs were broken to 0.25–0.5 cm pieces in a steel mortar; these pieces were pulverized in an aluminum oxide ceramic shatterbox. Major elements analyses were performed on a JEOL-733 Superprobe electron microprobe on glasses made from rock powders; $Li_2B_4O_7$ was used as flux in silicic glasses. Analyses corresponds to averages of 4–6 spots in WDS mode with a 15-kV accelerating voltage, 15 nA beam current, 40 s count time, and 30 mm beam. Data were reduced using a Bence-Albee program. Typical 2σ -precision is ±1–5% at >1 wt.%. Other major elements analyses were done by X-ray fluorescence in Instituto de Geología y Minería, from University of Jujuy, Argentina. They were carried out with a Rigaku FX2000 spectrometer, with Rh tube, operating at 50 kV and 45 mA, under USGS and Japan Geological Survey standards.

Trace elements analyses were carried out by Instrumental Neutron Activation Analysis (INAA) at Cornell University, obtaining results for La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Sr, Ba, Cs, U, Th, Hf, Ta, Sc, Cr, Ni y Co. These analyses were done on ~0.5 g of sample powder that was packed in ultrapure Suprasil® quartz tubing. INAA runs consisted of eleven samples and three internal standards (PAL, WBD, and SIT) that were irradiated in the TRIGA reactor at Ward Laboratory (Cornell University) at a power level of ~400 kW for 3–4 h. Samples and standards were counted for 4–10 h on an Ortec GeLi-detector after 6 and ~40 days following irradiation. INAA precision (2 s) based on replicate analysis of basalt PAL is ±2–7% for most elements and between ±8–16% for U, Sr, Nd, and Ni. The detail of used techniques and standards can be found in Kay et al. (1987).

Sr and Nd isotopes were analyzed at Cornell University on a multi-collector VG Sector 54 thermal ionization mass spectrometer. For lavas, ~250 mg of hand-picked sample chips (<50 mg per chip) were leached in hot 6 N HCl for 30 min and then dissolved in sealed 15 ml Savillex capsules with HF and HNO3 acids. Sr and REE were separated using cation exchange columns with AG50 W-x12 resin and 2.5 N and 6 N HCl as eluants. Nd was eluted using organically-coated PFTE cation exchange resin and 0.16 N HCl. All ratios were measured by thermal ionization mass spectrometry. Sr and Nd ratios were corrected for mass fractionation assuming 86Sr/88Sr = 0.1194 and 146Nd/144Nd = 0.7219. Average measured value for NBS987 Sr standard was 87Sr/86Sr = 0.710235 ± 34 (2σ) based on 67 analyses. The La Jolla Nd standard was 143Nd/144Nd = 0.511864 ± 14 (2σ) from July 1993 to Aug. 1997 based on 10 analyses and 0.511817 ± 12 (2σ) from August–November 1990 based on 15 analyses. Ames Nd standard was 143Nd/144Nd = 0.512138 ± 20 (2σ) based on 10 analyses. εNd values calculated assuming εNd = −15.15 for the La Jolla standard.

References

Bissig, T., Clark, A.H., Lee, J.K.W., Heather, K.B., 2001. The cenozoic history of volcanism and hydrothermal alteration in the Central Andean flat-slab region: new 40Ar–39Ar constrains from the El Indio-Pascua Au(–Ag, Cu) belt, 29°20–30°30″S. International Geology Review 43, 312–340.

Bissig, T., Clark, A.H., Lee, J.K.W., Hodgson, C.J., 2002. Miocene landscape evolution in the Chilean flat-slab transect: uplift history and geomorphologic controls on epithermal processes in the El Indio-Pascu Au (–Ag, Cu) belt. Economic Geology 97, 971–996.

Bissig, T., Clark, A.H., Lee, J.K.W., von Quadt, A., 2003. Petrogenetic and metallogenetic responses to miocene slab flattening: new constrains from the El Indio-Pascua Au–Ag–Cu Belt, Chile/Argentina. Mineralium Deposita 38, 844–862.

Charrier, R., Baeza, O., Elgueta, S., Flynn, J.J., Gans, P., Kay, S.M., Muñoz, N., Wyss, A.R., Zurita, E., 2002. Evidence for Cenozoic extensional basin development and tectonic inversion south of the flat-slab segment, southern Central Andes, Chile (33°–36°S.L.). Journal of South American Earth Sciences 15, 117–139.

Gill, J.B., 1981. Orogenic Andesites and Plate Tectonics. Springer-Verlag, Berlin, Heidelberg, New York. p. 392.

Godoy, E., Yañez, G., Vera, E., 1999. Inversion of an Oligocene volcano-tectonic basin and uplift of its superimposed Mioceno magmatic arc in the Chilean Central Andes: first seismic and gravity evidences. Tectonophysics 306, 217–236.

Groeber, P., 1951. La Alta Cordillera entre las latitudes 34° y 29° 30′. Revista del Instituto Nacional de Investigación de las Ciencias Naturales, Museo Argentino de Ciencias Naturales "Bernardino Rivadavia". Geología 1, 235–352.

Haschke, M., Guenther, A., Melnick, D., Echtler, H., Reutter, K.-J., Scheuber, E., Oncken, O., 2006. Central and southern Andean Tectonic evolution inferred from arc magmatism. In: Oncken, O., Chong, G., Franz, G., Giese, P., Götze, H.-J., Ramos, V., Strecker, M.R., Wigger, P. (Eds.), The Andes, Active Subduction Orogeny: Frontiers in Earth Science. Springer, Berlin, Heidelberg, New York, pp. 337–354.

Hildreth, W., Moorbath, S., 1988. Crustal contributions to arc magmatism in the Andes of Central Chile. Contribution to Mineralogy and Petrology 98, 455–489.

Irvine, T.N., Baragar, W.R.A., 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences 8, 523–548.

Jones, J.P., Martínez, R., y Rossello, E., 1996. La Faja volcánica terciaria del Valle del Cura (San Juan, Argentina): sus alcances y potencial para localizar World Class Deposits. In: XIII Congreso Geológico and III Congreso de Exploración de Hidrocarburos Actas, Buenos Aires, vol. 3, pp. 55–71.

Kay, R.W, 1977. Geochemical constrains on the origin of Aleutian magmas. In: Talwani, M., Pitman III, W.C. (Eds.), Islands Arcs, Deep Sea Trenches and Back-Arcs Basins. AGU Ewing Series, vol. 1, pp. 229–242.

Kay, S.M., 2001. Tertiary to recent magmatism and tectonics of the Neuquén basin between 36.5° and 38° S latitude. Repsol-YPF, Unpublished Report, 77 p.

Kay, S.M., Abbruzzi, J.M., 1996. Magmatic evidence for neogene lithospheric evolution of the Central Andes "flat slab" between 30°S and 32°S. Tectonophysics 259, 15–28.
Kay, S.M., Mpodozis, C., 2002. Magmatism as a probe to Neogene shallowing of the Nazca plate beneath the modern Chilean flat-slab. Journal of South American Earth Science 15, 39–57.
Kay, S.M., Maksaev, V.A., Moscoso, R., Mpodozis, C., Nasi, C., 1987. Probing the evolving Andean lithosphere: mid-late tertiary magmatism in Chile (29°–30°30′S) over the modern zone of subhorizontal subduction. Journal of Geophysical Research 92, 6173–6189.
Kay, S.M., Maksaev, V.A., Moscoso, R., Mpodozis, C., Nasi, C., Gordillo, C.E., 1988. Tertiary Andean Magmatism in Chile and Argentina between 28°S and 33°S: correlation of magmatic chemistry with changing Benioff zone. Journal South American Geology Earth Sciences 1 (1), 21–38.
Kay, S.M., Mpodozis, C., Ramos, V.R., Munizaga, F., 1991. Magma source variations for mid-late tertiary magmatic rocks associated with shallowing zone and thickening crust in the central Andes (28°–33°S). In: Harmon, R.S., Rapela, C.W. (Eds.), Andean Magmatism and Its Tectonin Setting. Geological Society of America Special Paper, vol. 265, pp. 113–137.
Kay, S.M., Coira, B., Viramonte, J.G., 1994. Young mafic back-arc volcanic rocks as indicador of continental lithospheric delamination beneath the Argentine Puna plateau, Central Andes. Journal of Geophysical Research 99, 24323–24339.
Kay, S.M., Mpodozis, C., Coira, B., 1999. Neogene magmatism, tectonism and mineral deposits of the Central Andes (22°–23°S latitude). In: Skinner, B.J. (Ed.), Geology and Ore Deposits of the Central Andes: Society of Economic Geologists Special Publication, vol. 7, pp. 27–59.
Kay, S.M., Godoy, E., Kurtz, A., 2005. Episodic arc migration, crustal thickening, subduction erosion and magmatism in the South-Central Andes. Geological Society of America Bulletin 117, 67–88.
Kurtz, A., Kay, S.M., Charrier, R., Farrar, E., 1997. Geochronology of Miocene plutons and exhumation history of the El Teniente region, Central Chile (34°–35°L.S.). Revista Geológica de Chile 24, 75–90.
Lagorio, S., 2001. Early Cretaceous volcanism of the Sierra de Chica of Córdoba (Argentina): Petrogenesis and geodynamic implications. In: XI Congreso Latinoamericano de Geología y III Congreso Uruguayo de Geología, Abstracts, Proyecto IGCP, Montevideo, vol. 436, 7 p.
Lagorio, S., 2003. El volcaniasmo cretácico alcalino de la Sierra Chica de Córdoba: geoquímica, petrogénesis e implicancias geodinámicas. Ph.D. Tesis, University of Buenos Aires, 399 pp.
Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lameyre, M.J., Le Bas, P.A., Sabine, R., Schmid, H., Sorensen, A., Streckeisen, A.R., Wooley Zanettin, B., 1989. A Classification of Igneous Rocks and Glossary of Terms. Blackwell, Oxford. p. 193.
Limarino, C.O., Gutiérrez, P.R., Malizia, D., Barreda, V., Page, S., Ostera, H., Linares, E., 1999. Edad de las secuencias paleógenas y neógenas de las cordilleras de la Brea y Zancarrón, Valle del Cura, San Juan. Revista de la Asociación Geológica Argentina 54, 177–181.
Litvak, V.D., 2004. Evolución del volcanismo terciario en el Valle del Cura sobre el segmento de subducción horizontal Pampeano, provincia de San Juan. Ph.D. Tesis, University of Buenos Aires, 270 pp.
Litvak, V.D., Page, S., 2002. Nueva evidencia cronológica en el Valle del Cura, provincia de San Juan. Revista de la Asociación Geológica Argentina 57, 483–486.
Litvak, V.D., Poma, S., 2005. Estratigrafía y facies volcánicas y volcaniclásticas de la Formación Valle del Cura: magmatismo paleógeno en la Cordillera Frontal de San Juan. Revista de la Asociación Geológica Argentina 60 (2), 402–416.
Litvak, V.D., Poma, S., Limarino, C.O., 2004. Volcanismo piroclástico de edad eocena media en el Valle del Cura, provincia de San Juan: nuevos datos geológicos y geocronológicos. Revista de la Asociación Geológica Argentina 59, 514–517.
Litvak, V.D., Kay, S.M., Mpodozis, C., 2005. New K/Ar ages on tertiary volcanic rocks in the Valle del Cura, pampean flat slab segment, Argentina. In: XVI Congreso Geológico Argentino, Actas, vol. 2, pp. 159–164.
Litvak, V.D., Poma, S., Suzanne, M., Kay, S.M., 2007. Paleogene and Neogene magmatism in the Valle del Cura region: a new perspective on the evolution of the Pampean flat slab, San Juan province, Argentina. Journal of South American Earth Science 24 (2–4), 117–137.
Lucassen, F.M., Escayola, M.P., Romer, R.L., Viramonte, J.G., Koch, K.Y., Franz, G., 2002. Isotopic composition of Late Mesozoic basic and ultrabasic rocks from the Andes (23°–32°S)-implications for the Andean mantle. Contributions to Mineralogy and Petrology 143, 336–349.
Maksaev, V., Moscoso, R., Mpodozis, C., Nasi, C., 1984. Las unidades volcánicas y plutónicas del Cenozoico superior entre la Alta Cordillera del Norte Chico (29–31°S), Geología, alteración hidrotermal y mineralización. Revista Geológica de Chile 21, 11–51.
Martin, M.W., Clavero, J.R., Mpodozis, C.M., 1995. Estudio geológico regional de la franja del Indio, Cordillera de Coquimbo: Santiago, Chile. Informe registrado II-95-6, Servicio Nacional de Geología y Minería, Chile y Compañía Minera San José, p. 232.
Martin, M.W., Clavero, J.R., Mpodozis, C.M., 1997a. Eocene to late Miocene magmatic development of El Indio belt, 30° S, North-Central Chile. In: VIII Congreso Geológico Chileno, Actas, Antofagasta, vol. 1, pp. 149–153.
Martin, M.W., Clavero, J.R., Mpodozis, C.M., 1997b. Eocene to late Miocene structural development of El Indio belt, 30° S, North-Central Chile. In: VIII Congreso Geológico Chileno, Actas, vol. 1, pp. 144–148.
Morata, D., y Aguirre, L., 2003. Extensional Lower Cretaceous volcanism in the Coastal Range (29°20–30°S), Chile: geochemistry and petrogenesis. Journal of South America Earth Sciences 16, 459–476.
Mpodozis, C., Cornejo, P., 1988. Hoja Pisco Elqui. Servicio Nacional de Geología y Minería, Carta Geológica de Chile N°68, p. 106.
Mpodozis, C., Kay, S., 2003. Neogen tectonics, ages and mineralization along the transition zone between the El Indio and Maricunga mineral belts (Argentine and Chile 28°–29°). In: X Congreso Geológico de Chile, Actas CD, p. 1.
Nasi, C.P., Moscoso, R.D., Maksaev, V.J., 1990. Hoja Guanta, Región de Coquimbo. Servicio de Geología y Minería, Carta Geológica de Chile, N° 67, p. 140.
Nullo, F., 1988. Geología y estructura del área de Guanaco Zonzo y Veladero, oeste de Cordillera de Sancarrón, San Juan. In: III Congreso Nacional de Geología Económica Actas, Olavarría, vol. 2, pp. 501–515.
Otamendi, J., Nullo, F., Godeas, M., Pezzutti, N., 1994. Petrogénesis del volcanismo terciario del Valle del Cura, San Juan, Argentina. In: VII Congreso Geológico Chileno, Actas, vol 2. pp. 1130-1135.
Pagán, F., Pérez, D., Yagupsky, D., 2005. Nuevas evidencias del arco volcánico cretácico, Cordillera Principal (31°58′), Provincia de San Juan, Argentina. In: XVI Congreso Geológico Argentino, Actas, vol. 2, pp. 71–72.
Panteleyev, A., y Cravero, O., 2000. Faja del Potro and Cordón de la Brea Ore Deposits, La Rioja and San Juan, radiometric dating, analytical results and sample documentation. Serie contribuciones Técnicas, Recursos Minerales N° 11. Servicio Geológico Minero Argentino, p. 59.
Pardo Casas, F., Molnar, P., 1987. Relative motion of the Nazca (Farallón) and South America plates since Late Cretaceous time. Tectonics 6, 233–248.
Pearce, J.A., 1983. Role of the sub-continental lithosphere in magma genesis at active continental margins. In: Hawkesworth, C.J., Norry, M.J. (Eds.), Continental Basalts and Mantle Xenoliths. Shiva, Nantwich, pp. 230–249.
Pearce, J.A., 1996. A user's guide to basalt discrimination diagrams. In: Wyman, D.A. (Ed.), Trace Element Geochemistry of Volcanic Rocks: Applications for Massive Sulphide Exploration. Geological Society of Canada, Short Course Notes, vol. 12, pp. 79–113.
Perello, J., Mpodozis, C., 2003. Porphyry copper metallogenesis of the Middle Eocene–Early Oligocene arc of western South America: Relationships with volcanism and arc segmentation. In: X Congreso Geológico de Chile, Actas CD, p. 1.
Pilger, R.H., 1981. Plate reconstructions, aseismic ridges, and low angle subduction beneath the Andes. Geological Society of America Bulletin 92, 448–456.
Pilger, R.H., 1984. Cenozoic plate kinematics, subduction and magmatism: South American Andes. Journal of the Geological Society of London 141, 793–802.
Ramos, V.A., 1999. Plate tectonic setting of the Andean Cordillera. Episodes 22 (3), 183–190.
Ramos, V.A., Aleman, A., 2000. Tectonic evolution of the Andes. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (Eds.), Tectonic Evolution of South America, pp. 635–685.
Ramos, V.A., Page, R., Kay, S.M., Lapido, O. Delpino, D., 1987. Geología de la región del volcán Tórtolas, Valle del Cura, provincia de San Juan. In: X Congreso Geológico Argentino y Simposium Circumpacific Phanerozoic Granites, Tucumán, Actas, vol. 4, pp. 260–263.
Ramos, V.A., Kay, S.M., Page, R., Munizaga, F., 1989. La Ignimbrita Vacas Heladas y el cese del volcanismo en el Valle del Cura, provincia de San Juan. Revista de la Asociación Geológica Argentina 44, 336–352.
Ramos, V.A., Cristallini, E.O., Pérez, D.J., 2002. The Pampean flat-slab of the Central Andes. Journal of South American Earth Science 15, 59–78.
Rollinson, H.R., 1993. Using Geochemical Data: Evaluation, Presentation, Interpretation. Longman Scientific & Technical, Longman Group UK Ltd.. 352 pp.
Skewes, M.A., Arévalo, A., Floody, R., Zuñiga, H., Stern, C.R., 2002. The giant El Teniente breccia deposit: hypogene copper distribution and emplacement. Society of Economic Geologists Special Publication 9, 299–332.
Stern, Ch.R., 1991. Role of subduction erosion in the generation of Andean Magmas. Geology 19, 78–81.
Stern, C.R., Skewes, M.A., 1995. Miocene to present evolution at the northern end of the Andean Southern Volcanic Zone, central Chile. Revista Geológica de Chile 22, 261–272.
Stern, C.R., Skewes, M.A., 2003. Generation of giant Miocene and Pliocene copper deposits in Central Chile: Role of ridge subduction, decreased subduction angle, increased subduction erosion, crustal thickening, and mafic and adakite-like dacitic magma within long-lived, batholith size, open system magma chambers. In: X Congreso Geológico Chileno, Actas CD, Concepción.
Viramonte, J.G., Kay, S.M., Bechio, R., Escayola, M., Novitski, I., 1999. Cretaceous rift related magmatism in central-western South America. Journal of South American Earth Sciences 12, 109–121.
Wilson, M., 1989. Igneous Petrogenesis. Unwin Hyman Inc., London. 466 p.
Wood, D.A., 1980. The application of Th–Hf–Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. Earth and Planetary Science Letters 50, 11–30.
Yañes, G.A., Ranero, C.R., von Huene, R., Díaz, J., 2001. Magnetic anomaly interpretation across the southern central Andes (32°–34°): the role of the Juan Fernández Ridge in the late Tertiary evolution of the margin. Journal of Geophysical Research 106, 6325–6345.