

Trace-element and Sr, Nd, Pb, and O isotopic composition of Pliocene and Quaternary alkali basalts of the Patagonian Plateau lavas of southernmost South America

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Abstract. The Pliocene and Quaternary Patagonian alkali basalts of southernmost South America can be divided into two groups. The “cratonic” basalts erupted in areas of Cenozoic plateau volcanism and continental sedimentation and show considerable variation in $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70316 to 0.70512), $^{143}\text{Nd}/^{144}\text{Nd}$ ($\epsilon_{\text{Nd}}=0$ to +5.5), and $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios (18.26 to 19.38, 15.53 to 15.68, and 38.30 to 39.23, respectively). These isotopic values are within the range of oceanic island basalts, as are the Ba/La, Ba/Nb, La/Nb, K/Rb, and Cs/Rb ratios of the “cratonic” basalts. In contrast, the “transitional” basalts, erupted along the western edge of the outcrop belt of the Pliocene and Quaternary plateau lavas in areas that were the locus of earlier Cenozoic Andean orogenic arc volcanism, have a much more restricted range of isotopic composition which can be approximated by $^{87}\text{Sr}/^{86}\text{Sr}=0.7039\pm 0.0004$, $\epsilon_{\text{Nd}}=+4.0\pm 1.1$, $^{206}\text{Pb}/^{204}\text{Pb}=18.60\pm 0.08$, $^{207}\text{Pb}/^{204}\text{Pb}=15.60\pm 0.01$, and $^{208}\text{Pb}/^{204}\text{Pb}=38.50\pm 0.10$. These isotopic values are similar to those of Andean orogenic arc basalts and, compared to the “cratonic” basalts, are displaced to higher $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$ and to higher $^{207}\text{Pb}/^{204}\text{Pb}$ at a given $^{208}\text{Pb}/^{204}\text{Pb}$. The “transitional” basalts also have Ba/La, Ba/Nb, La/Nb, and Cs/Rb ratios higher than the “cratonic” and oceanic island basalts, although not as high as Andean orogenic arc basalts. In contrast to the radiogenic isotopes, $\delta^{18}\text{O}$ values for both groups of the Patagonian alkali basalts are indistinguishable and are more restricted than the range reported for Andean orogenic arc basalts. Whole rock $\delta^{18}\text{O}$ values calculated from mineral separates for both groups range from 5.3 to 6.5, while measured whole rock $\delta^{18}\text{O}$ values range from 5.1 to 7.8. The trace element and isotopic

data suggest that decreasing degrees of partial melting in association with lessened significance of subducted slab-derived components are fundamental factors in the west to east transition from arc to back-arc volcanism in southern South America. The “cratonic” basalts do not contain the slab-derived components that impart the higher Ba/La, Ba/Nb, La/Nb, Cs/Rb, $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$, $^{207}\text{Pb}/^{204}\text{Pb}$ at a given $^{208}\text{Pb}/^{204}\text{Pb}$, and $\delta^{18}\text{O}$ to Andean orogenic arc basalts. Instead, these basalts are formed by relatively low degrees of partial melting of heterogeneous lower continental lithosphere and/or asthenosphere, probably due to thermal and mechanical perturbation of the mantle in response to subduction of oceanic lithosphere below the western margin of the continent. The “transitional” basalts do contain components added to their source region by either (1) active input of slab-derived components in amounts smaller than the contribution to the mantle below the arc and/or with lower Ba/La, Ba/Nb, La/Nb, and Cs/Rb ratios than below the arc due to progressive downdip dehydration of the subducted slab; or (2) subarc source region contamination processes which affected the mantle source of the “transitional” basalts earlier in the Cenozoic.

Introduction

The Patagonian plateau lavas of southernmost South America (Fig. 1) formed by volcanic activity that began in the late Cretaceous or early Cenozoic and continued episodically into the Holocene (Tyrrell 1932; Skewes and Stern 1979; Baker et al. 1981; Ramos et al. 1982; Rapela et al. 1988). Overlying the largely subalkaline tholeiitic basalts comprising the older, voluminous units of the plateau lavas are Pliocene and Quaternary centers of more restricted

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Fig. 1. Map showing the outcrop of Pliocene and Quaternary (black) and older (lined) units of the Patagonian plateau lavas in southernmost South America and the approximate locations of the samples listed in Table 1. The major plateau regions are *LB*, Laguna Blanca; *MS*, Meseta de Somuncura; *LCH*, Lago Colhue Huapi; *MBA*, Meseta Buenos Aires; *MM*, Meseta de la Muerte; *MV*, Meseta Las Vizcachas; and *PA*, Pali-Aike volcanic field. Also shown are the location of plates and plate boundaries, the Valdivia Fracture zone (*VFZ*), Quaternary orogenic arc lavas (shaded) and volcanic centers (triangles), and the easternmost limit of Cenozoic Andean orogenic arc volcanism (cross-hatched line) which separates the “transitional” (to the west; samples underlined) from the “cratonic” (to the east) Patagonian basalts.

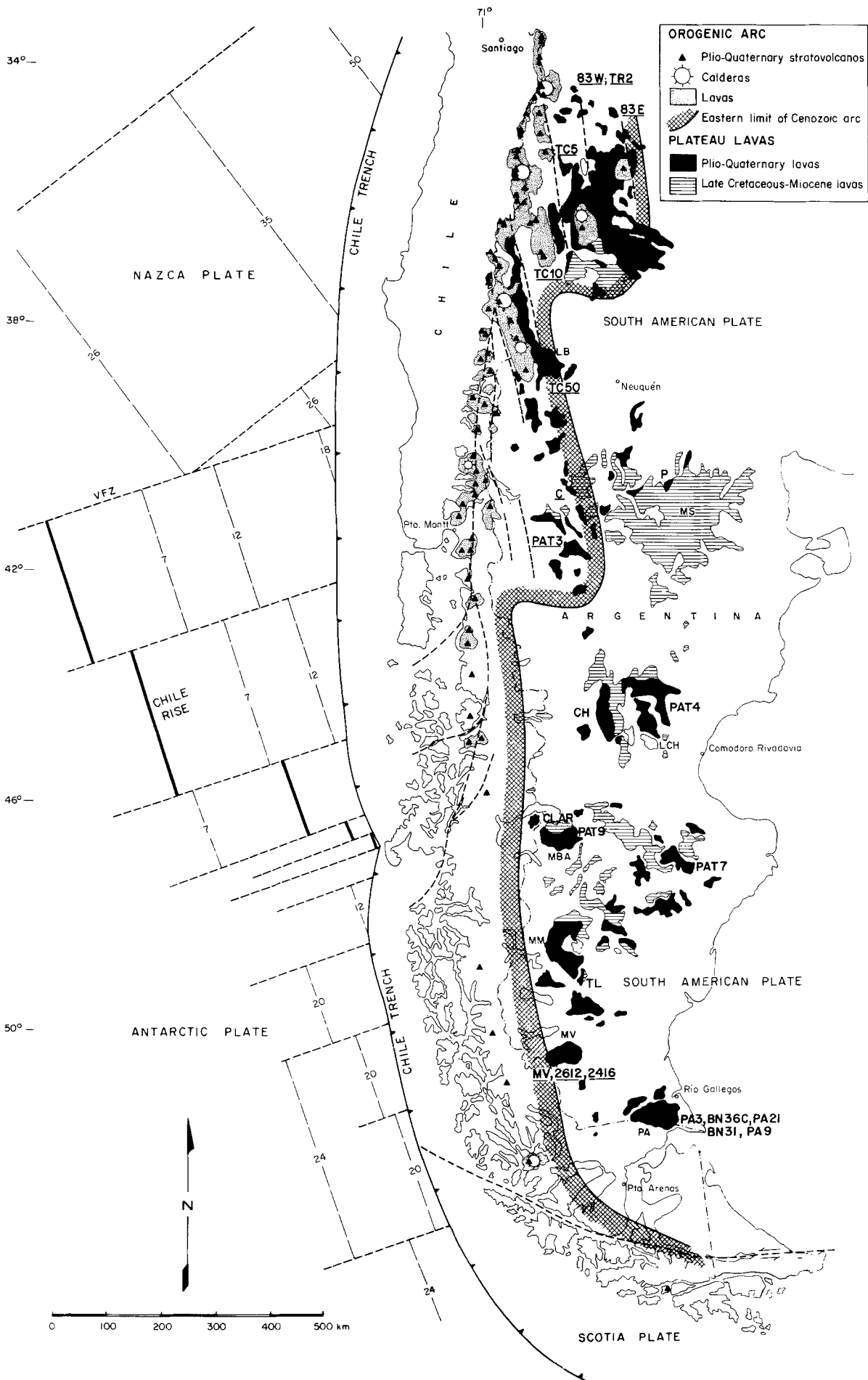


Table 1. Major element composition of Pliocene and Quaternary Patagonian basalts

Group	"Transitional" basalts										
	83W	83E	TR2	TC5	TC10	TC50	C	PAT3	MV	2612	2416
Xenoliths	—	—	—	—	—	—	+	—	+	+	—
SiO ₂	49.81	50.20	45.87	47.56	47.44	48.83	45.51	46.61	48.02	48.40	48.91
TiO ₂	1.62	1.78	1.58	1.88	1.64	1.45	2.12	2.07	1.57	1.60	1.77
Al ₂ O ₃	15.06	16.79	15.00	16.21	15.42	16.72	14.81	15.38	14.41	14.41	14.58
Fe ₂ O ₃	5.41	3.02	3.20	1.76	3.57	3.39	3.42	3.44	3.49	3.63	3.85
FeO	3.14	4.88	6.75	9.11	6.64	5.88	7.26	7.35	6.78	7.21	7.27
MnO	0.15	0.13	0.18	0.17	0.17	0.15	0.18	0.17	0.18	0.18	0.19
MgO	6.14	5.71	10.63	7.78	9.68	8.27	10.23	9.95	10.44	9.64	8.45
CaO	11.20	10.28	10.37	9.63	9.96	8.58	9.44	8.98	8.51	8.60	8.07
Na ₂ O	3.04	4.06	3.63	3.90	3.71	3.24	3.67	3.07	2.92	2.97	3.01
K ₂ O	1.53	1.14	1.21	0.99	1.02	2.42	2.31	1.90	1.35	1.37	1.19
P ₂ O ₅	0.32	0.28	0.54	0.43	0.48	0.76	0.72	0.45	0.36	0.37	0.40
LOI	1.70	0.79	0.81	0.21	0.44	0.39	0.44	0.72	1.20	1.80	1.52
Total	99.12	99.06	99.77	99.63	100.17	100.08	99.48	100.09	99.13	100.18	99.21
Mg#	58	57	68	56	65	64	66	65	68	63	59
Normative nepheline ^b	4	9	16	12	12	8	16	9	0	0	0

Major element compositions determined by wet chemical methods at Skyline Labs. of Denver, Colorado, or by the Servicio Nacional de Geología y Minería, Santiago, Chile

Mg# = 100 Mg/(Mg + Fe²⁺) calculated with Fe²⁺ = 0.85 (total Fe)

^a Location of the "transitional" basalts (underlined in Fig. 1): *83W* from the northernmost unit of the Patagonian plateau lavas on the east side of Rt. 40 2 km south of the Rio Papagayos, Argentina; *83E* from Cerro Negro on the southeast edge of San Rafael, Argentina; *TR2* from a maar west of Rt 40 3 km north of Rio Diamonte, Argentina; *TC5* from the cones of Chihuido on the east side of Rt 40 south of Malargue and west of Laguna Llanecanelo; *TC10* from the cones of Los Volcanes east of Rt 40 and just west of Payun Matru volcano; *TC50* from Laguna Blanca cone southwest of Zapala, Argentina; *C* from xenolith-bearing flow 12 km east of Comallo, Argentina (Gelos and Hayase 1979); *PAT3* from Escorial de Chenquintue 40 km north of Norquingo, Argentina on Rt 40; *MV*, *2612*, and *2416* from Meseta Las Vizcachas east of Estancia Las Cumbres in the Cordillera Bagues, Chile (Munoz 1981)

^b Normative nepheline calculated with Fe²⁺ = 0.85 (total Fe)

volume consisting dominantly, if not exclusively, of alkali basalts. South of 39° S these alkali basalts have erupted east of the stratovolcanos of the contemporaneous Andean orogenic arc, and may be considered to occupy a back-arc tectonic environment (Fig. 1). In the region between 34–39° S, north of the intersection of the Valdivia Fracture Zone (VFZ, Fig. 1) with the Chile Trench, alkali basalts are interspersed with arc stratovolcanos and occupy both an intra-arc as well as a back-arc tectonic environment (Munoz and Stern 1988, 1989; Munoz et al. 1989).

Skewes and Stern (1979) attributed the origin of the Pliocene and Quaternary Patagonian alkali basalts to mechanical and/or thermal perturbation of the subcontinental mantle due to subduction of oceanic lithosphere below the western margin of the continent, rather than to continental rifting or hot spot traces. Yet the Benioff zone of seismic activity associated with the subduction of the Nazca and Antarctic plates does not extend east of the Andean orogenic arc to below the region of the Patagonian basalts (Barazangi and Isacks 1976) and based on their similarity in major element chemistry to alkali basalts from diverse tectonic environments, including intraplate oceanic island basalts (OIB), Skewes and Stern (1979) and Baker et al. (1981) suggested that the Patagonian alkali basalts do not contain components derived from subducted oceanic lithosphere. Hawkesworth et al. (1979) came to a similar conclusion based on the Sr and Nd isotopic composition of the plateau basalts in the region near 46° S. Subsequently, how-

ever, Stern et al. (1983) and Munoz and Stern (1988, 1989) demonstrated that the isotopic composition of some of the westernmost Patagonian alkali basalts is nearly identical to the composition of high-Al basalts erupted from the Andean orogenic stratovolcanos that occur within the same range of latitude. They suggested that variation in the isotopic composition of the subcontinental mantle source of the Patagonian alkali basalts may, in fact, reflect the presence of components derived from subducted oceanic lithosphere in the west and their absence in the east.

As a contribution to the understanding of the origin of these continental back-arc alkali basalts and the nature of the transition from arc to back-arc petrogenetic processes in a continental setting, we present major and trace element and Sr, Nd, Pb, and O isotopic composition of Pliocene and Quaternary alkali basalts from the Patagonian plateau. 10 of the 24 analyzed alkali basalts contain peridotite xenoliths of presumed mantle origin (Skewes and Stern 1979; Stern et al. 1986, 1989). Because peridotite xenoliths are considerably more dense than basaltic liquid, their presence precludes extended evolution in a crustal magma chamber and indicate, in conjunction with the high Mg/Mg + Fe²⁺ and Ni and Cr contents of these Patagonian alkali basalts, that they are relatively primitive (Frey et al. 1978).

The active Andean orogenic arc is much broader north compared to south of 39° S (Fig. 1; Munoz and Stern 1988, 1989; Munoz et al. 1989). Earlier in the Cenozoic the Andean orogenic arc was significantly wider than currently

Table 1 (continued)

"Cratonic" basalts												
P	CH	PAT4	CL	AR	PAT9	PAT7	TL	PA3	BN36C	PA21	BN31	PA9
+	+	-	+	+	-	-	+	+	+	-	-	-
38.73	45.74	46.35	45.07	44.90	49.04	50.02	47.90	45.10	45.09	46.71	45.38	49.61
3.20	2.35	2.77	2.85	3.07	2.60	2.09	2.02	3.94	3.62	2.82	3.14	3.12
14.01	13.20	14.20	14.87	15.21	16.81	14.96	14.45	12.31	10.62	11.10	12.90	13.03
3.02	3.89	2.85	6.02	3.81	2.06	2.41	3.95	3.01	2.82	2.85	3.40	2.21
9.22	7.28	8.34	6.08	8.25	8.34	8.25	7.16	9.31	9.92	7.76	7.70	8.56
0.21	0.17	0.16	0.21	0.21	0.15	0.15	0.15	0.17	0.17	0.17	0.19	0.16
13.30	11.87	9.04	7.61	6.40	5.75	7.43	8.96	9.81	13.50	13.10	8.51	7.04
11.08	6.69	8.51	7.13	7.53	6.69	8.28	7.56	9.01	9.05	9.29	11.36	9.21
4.15	3.85	3.86	4.82	4.70	5.02	3.94	3.54	3.77	2.63	3.34	3.99	3.45
1.10	2.51	2.17	1.78	1.76	2.42	1.19	1.99	1.97	1.36	1.83	1.63	1.91
1.55	0.92	0.79	0.91	0.94	0.71	0.51	0.74	0.92	0.63	0.60	0.61	0.52
0.55	1.62	1.00	2.81	2.68	0.37	0.85	0.55	0.61	0.58	0.61	0.40	0.85
100.53	100.09	100.04	100.16	99.46	100.22	100.08	99.08	99.95	99.99	100.18	99.21	99.67
69	69	60	53	48	50	56	61	60	68	73	59	55
22	12	14	11	14	14	4	6	17	10	14	17	6

^a Location of the "cratonic" basalts (Fig. 1): *P* at Praguaniyue, Argentina (Labudia et al. 1984); *CH* from a cone east of Rt 20 7 km south of La Laurita on the southeast side of the Arroyo Genoa, Argentina; *PAT4* from Pampa Negra on Rt 26 northeast of Sarmiento, Argentina; *CL* from Cerro Lapiz on the northeast edge of western section of Meseta Buenos Aires near Chile Chico, Chile (Baker et al. 1981); *AR* from the northwest edge of the western section of the Meseta Buenos Aires at source of the Arroyo San Alfonso west of Chile Chico, Chile (Niemyer 1978); *PAT9* from southeast edge of the eastern section of Meseta Buenos Aires above Estancia Vizcaina on Rt 40, Argentina; *PAT7* along Rt 501 120 km south of Pico Troncado, Argentina; *TL* from a cone on Rt 40 50 km north of Tres Lagos, Argentina; *PA3*, *BN36C*, *PA21*, *BN31*, and *PA9* from the Pali-Aike volcanic field (Skewes and Stern 1979).

between 39°–42° S (Fig. 1; Rapela et al. 1988) while south of 42° S it extended farther to the east than today (Fig. 1; Halpern 1973; Nullo et al. 1978). Depending on whether they occur within or east of the area of Cenozoic Andean volcanism, the Pliocene and Quaternary Patagonian alkali basalts may be divided into two groups: (1) the "cratonic" basalts from regions of Cenozoic plateau volcanism and continental sedimentation east of the areas of Cenozoic Andean orogenic arc volcanism; and (2) the "transitional" basalts from regions within the areas of earlier Cenozoic Andean orogenic arc volcanism. As discussed below, the "cratonic" basalts have geochemical characteristics similar to intra-plate oceanic island basalts, while the "transitional" basalts have geochemical characteristics intermediate between the "cratonic" and Andean orogenic basalts.

Basalt chemistry

Sample locations, major elements, Ni and Cr contents

Six of the "transitional" basalts (*83W*, *83E*, *TR2*, *TC5*, *TC10*, *TC50*), represented as open circles in subsequent figures, are from the region north of 39° S in which intra-arc alkali basalts are interspersed with central-vent arc stratovolcanos (Fig. 1; Munoz and Stern 1988, 1989; Munoz et al. 1989). No peridotite bearing basalts have been found in this region. The other 5 "transitional" and the 13 "cratonic" basalts are from the region south of 39° in which a clear spatial separation exists between the Pliocene and Quaternary orogenic arc stratovolcano and back-arc plateau lava provinces (Fig. 1). The "transitional" basalts from south of 39° S include samples *C* and *PAT3*, which occur within the outcrop belt of the calc-alkaline Cordilleran Series of the early Cenozoic Patagonian volcanic province (Rapela et al. 1988), and samples *MV*, *2612*, and *2416*, which occur along the eastern edge of a belt of Miocene calc-alkaline volcanics and plutons (Torres del Paine and

Fitz Roy Massif; Halpern 1973; Nullo et al. 1978). Three of these "transitional" basalts (*C*, *MV*, and *2612*) contain peridotite xenoliths. The "cratonic" basalts include samples *CL* and *AR*, which are from some of the westernmost outcrops of the Pliocene and Quaternary plateau lavas, and samples *P*, *CH*, *PAT4*, *PAT9*, *PAT7*, *TL*, *PA3*, *BN36C*, *PA21*, *BN31*, and *PA9*, which occur farther to the east. In the subsequent figures the samples from south of 39° S are represented as either triangles for samples with peridotite xenoliths or squares for those without peridotite xenoliths, and the "transitional" and "cratonic" basalts are distinguished by open and solid symbols, respectively.

The basalts occur as volcanic necks, sills, maars, and spatter cones as well as lava flows. They are all aphanitic or fine grained with less than 10% phenocrysts of olivine, minor clinopyroxene and plagioclase, and, in the case of the sample *P*, nepheline and apatite (Labudia et al. 1984). Only half of the samples had sufficient quantities of phenocrysts to yield mineral separates for O isotopic studies (Table 3).

Table 1 presents the major element composition of the Pliocene and Quaternary Patagonian basalts. None of the samples contain normative quartz, and normative nepheline of the samples varies from absent to greater than 22% in sample *P*, which also contains normative leucite. The basalts all plot in the alkaline and strongly alkaline field on a silica versus total alkalis diagram (Fig. 2A). No highly alkaline or xenolith-bearing basalts have been found north of 39° S (Munoz and Stern 1988, 1989; Munoz et al. 1989) and the "cratonic" group includes a greater proportion of highly alkaline basalts than the "transitional" group.

Some of the basalts have MgO contents greater than 9 wt.% and Mg# ($Mg/(Mg + Fe^{2+})$) greater than 68, similar to primary liquids derived from melting of upper mantle peridotite (Irving and Green 1976; Frey et al. 1978). Ni contents (Table 2) are greater than 110 ppm, and in most cases greater than 200 ppm, for all the xenolith-bearing ba-

Table 2. Trace element composition of Pliocene and Quaternary Patagonian basalts

Sample	"Transitional" basalts										
	83W	83E	TR2	TC5	TC10	TC50	C	PAT3	MV	2612	2416
Ni	112	129	200	115	184	140	211	223	340	369	290
Cr	198	155	500	201	420	290	352	374	703	690	606
V	—	—	260	230	210	220	210	250	210	—	—
Cs	0.8	0.4	1.0	—	0.5	3.9	1.7	1.3	1.4	0.7	1.2
Rb	34	18	26	22	24	92	63	45	29	28	19
Ba	549	294	580	390	370	924	870	435	350	329	303
Sr	920	555	760	580	680	830	1144	698	694	712	643
Nb	15	13	14	16	24	26	44	25	22	16	12
Ta	0.87	0.77	0.63	0.82	1.65	1.85	2.9	2.6	1.6	1.1	1.1
Zr	150	124	147	128	163	272	219	168	132	140	148
Y	19	12	18	21	17	21	26	22	18	16	15
Sc	42.4	34.0	31.4	29.4	27.2	23.7	21.8	26.6	23.1	25.9	31.0
Hf	3.6	3.3	3.2	3.4	3.2	5.4	4.4	3.9	2.8	3.8	4.4
Th ^a	5.3	1.7	3.4	3.0	1.7	3.8	4.3	3.7	3.6	4.5	3.9
U ^a	1.7	0.4	—	—	—	—	—	—	—	1.3	1.4
Pb ^a	10.5	2.5	—	—	—	—	—	—	—	6.0	4.8
La	19.0	10.1	24.4	15.3	18.0	26.6	38.9	19.4	20.7	16.7	11.9
Ce	42.3	22.3	54.1	31.7	41.4	64.4	88.0	47.3	45.0	35.0	26.0
Nd	23.3	12.8	28.2	—	22.9	35.0	46.4	24.9	21.5	18.6	15.8
Sm	5.3	3.4	6.06	4.97	5.48	7.68	9.71	5.79	4.49	4.17	3.95
Eu	1.70	1.42	1.72	1.88	1.69	2.16	2.92	1.83	1.41	1.52	1.59
Tb	0.84	0.65	0.78	0.94	0.63	0.93	0.89	0.61	0.48	0.51	0.54
Yb	1.46	1.20	1.80	2.33	1.69	2.03	1.89	1.93	1.30	1.24	1.49
Lu	0.30	0.24	0.26	0.37	0.26	0.31	0.26	0.31	0.18	0.20	0.22

Ni, Cr, V, and Ba were determined by atomic absorption methods by the Servicio Nacional de Geología y Minería of Chile

Rb, Sr, Nb, Y, and Zr were determined by XRF techniques at U.S.G.S. in Denver

Duplicate analysis of Ni, Cr, V, Ba, Rb, Sr, Nb, Y, and Zr by XRF for seven samples performed at the U. of Mass. indicates that with the exception of Nb, the values reported are accurate to $\pm 10\%$. Nb is accurate to $\pm 20\%$

Cs, Ta, Sc, Hf, Th (when reported without U or Pb), and REE were determined by instrumental neutron activation at M.I.T., except for samples 83W and 83E which were determined at Michigan Technological University. The techniques and precision for the determinations at M.I.T. are given by Ila and Frey (1984)

^a Th, U, and Pb, when reported together, were determined by isotope dilution mass-spectrometry at the U.S.G.S. in Denver (Peng et al. 1986)

salts. Both MgO and Ni contents are higher in the alkali plateau compared to Andean arc high-Al basalts (Fig. 2B). Cr contents (Table 2) are greater than 150 ppm, and generally greater than 300 ppm, for all the xenolith-bearing basalts. Most samples without xenoliths have lower MgO, Mg#, Ni (Fig. 2B), and Cr. Disruption and digestion of olivine-rich xenoliths could increase MgO, Mg#, Ni and possibly Cr in xenolith-bearing basalts, but this process should not significantly affect incompatible element content or isotopic composition of the basalts.

Incompatible elements

Incompatible element concentrations are listed in Table 2. Figure 3 plots the normalized trace element compositions of the "cratonic" xenolith-bearing (Fig. 3A) and other basalts (Fig. 3B), and the "transitional" basalts from north (Fig. 3C) and south of 39° S (Fig. 3D). Shown for comparison are the equivalent data for high-Al basalts erupted from the Llaima stratovolcano along the volcanic front of the Andean orogenic arc at 39° S (Hickey et al. 1986).

The "cratonic" basalts include more high La (Fig. 4A) and high La/Yb (Fig. 4B) basalts than the "transitional" basalts consistent with the greater proportion of highly alkaline basalts in the former group. However, the correlation between alkalinity (normative nepheline) and La among the

Pliocene and Quaternary Patagonian basalts is not well defined (Fig. 4A). All the basalts have more fractionated rare earth elements (REE) than the subalkaline high-Al basalts erupted from stratovolcanos along the volcanic front of the Andean orogenic arc (Figs. 3 and 4B). La contents of the alkali plateau basalts are greater while their Yb contents are generally similar or lower than these Andean orogenic arc basalts. Basalts erupted from subalkaline Andean arc stratovolcanos east of the volcanic front, however, have La and La/Yb within the lower end of the range of the Patagonian alkali basalts (Fig. 4B; Hickey et al. 1986, 1989).

Rb, Ba, Th, Sr, and K are more enriched in the Patagonia alkali compared to the Andean orogenic arc high-Al basalts (Fig. 3). The "cratonic" basalts, however, do have Ba/La lower than Andean arc high-Al basalts and within the range of intraplate OIB because of their relatively higher enrichment of LREE (Fig. 4C). In the case of the "transitional" basalts, Ba/La is within the range of Andean and other convergent plate boundary arc basalts (Fig. 4C) and higher than intraplate OIB. Kay et al. (1988) also reported high Ba/La Pliocene and Quaternary alkali basalts on the western margin of the Meseta Somuncura (MS, Fig. 1).

High field strength elements (HFSE) Ti, Nb, Zr, and Ta are also more enriched, both in total content (Fig. 3) and relative to REE, in the Patagonia alkali basalts com-

Table 2 (continued)

"Cratonic" basalts												
P	CH	PAT4	CL	AR	PAT9	PAT7	TL	PA3	BN36C	PA21	BN31	PA9
460	380	196	185	110	73	165	250	177	400	382	98	126
524	464	273	217	160	103	199	325	162	450	421	178	176
160	150	230	170	180	130	180	170	—	—	—	—	—
0.6	0.9	0.5	0.5	1.1	0.4	0.2	0.6	0.2	0.2	1.6	0.8	0.4
32	56	40	40	31	39	19	34	28	15	23	29	33
740	600	566	555	515	490	400	490	510	320	460	604	372
1590	990	1015	1125	1060	980	691	816	1079	640	781	932	608
172	88	53	120	107	74	42	54	75	53	60	68	49
9.5	6.3	2.9	7.1	6.3	4.5	2.0	4.5	3.7	2.8	3.0	3.6	2.9
496	350	269	435	410	282	171	310	348	222	223	270	229
38	25	28	26	28	22	20	26	24	22	20	22	20
15.9	13.7	17.7	12.5	13.0	13.1	18.3	16.5	18.4	20.8	21.6	22.4	22.9
9.5	7.2	5.8	8.5	8.2	5.9	3.9	6.3	6.3	4.9	5.2	6.3	5.7
14.4	7.7	6.1	9.7	8.7	5.3	4.0	4.8	3.5	2.3	2.9	5.8	3.6
3.8	2.1	1.6	3.1	2.8	—	—	1.3	1.0	—	0.8	1.4	0.9
7.5	5.1	5.1	5.2	5.5	—	—	4.1	1.4	—	2.1	3.5	2.8
113	60.9	54.8	77.6	66.6	44.7	30.3	40.3	41.4	29.6	30.7	36.1	16.0
233	123	112	151	130	91	58.8	86	91.8	66.2	66.9	80.8	37.6
98	52	52.8	58	52	39.4	26.9	37.1	47.3	34.2	33.8	39.7	21.4
16.8	10.2	10.1	10.4	9.94	7.98	5.62	7.53	10.5	7.66	8.15	8.47	5.47
5.27	2.97	2.96	3.22	2.94	2.61	1.97	2.43	3.31	2.42	2.48	2.75	2.12
1.52	0.88	0.87	1.00	0.96	0.79	0.65	0.78	1.10	0.88	0.95	0.94	0.69
2.21	1.66	1.58	2.25	2.05	1.80	1.43	1.45	1.54	1.43	1.66	1.59	1.41
0.30	0.19	0.23	0.31	0.30	0.24	0.21	0.22	0.19	0.20	0.26	0.23	0.20

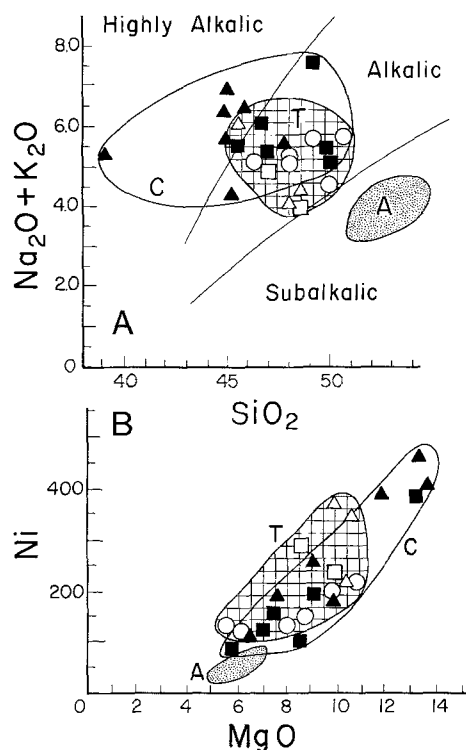


Fig. 2 A, B. Silica versus total alkalis (A) and magnesium versus nickel (B) for the "transitional" (open symbols; cross-hatched field T) and "cratonic" (solid symbols; field C), xenolith-bearing (triangles) and other (circles north of 39° S and squares south of 39° S) Pliocene and Quaternary Patagonian basalts. In A the boundary dividing the subalkalic from the alkalic field is from Irvine and Barager (1971) and the boundary between the alkalic and strongly alkalic field is from Cong et al. (1979). Shaded field A corresponds to Quaternary Andean orogenic arc high-Al basalt erupted between latitudes 36°–42° S (Hickey et al. 1986)

pared to the Andean orogenic arc high-Al basalts. The strong contrast between the characteristic depletion of HFSE relative to REE in Andean arc high-Al basalts compared to their enrichment relative to REE in the Patagonia alkali plateau basalts can be seen in the differing La/Nb ratios of the two associations (Fig. 4D). The Patagonian basalts all fall within the range of intraplate OIB, although the "transitional" basalts have, on the average, slightly higher La/Nb than the "cratonic" basalts.

Cs contents are similar in both Patagonian and arc basalts (Fig. 3). Although Cs and Rb are readily mobilized by low temperature alteration, the "cratonic" basalts generally fall in the range of OIB or MORB with respect to Cs/Rb and K/Rb (Fig. 5). The "transitional" basalts have higher Cs/Rb and lower K/Rb as do Andean orogenic arc and other convergent plate boundary basalts (Morris and Hart 1983; Hickey et al. 1986 and 1989).

Isotopic compositions

The Sr isotopic composition of all the Patagonian alkali basalts range from 0.70316 to 0.70512 (Table 3; Fig. 6; Stern 1989). Hawkesworth et al. (1979) reported that the Sr isotopic composition of seven Pliocene and Quaternary "cratonic" basalts in the region between 45°–46° S ranged from 0.70338 to 0.70512. Munoz et al. (1989) measured the Sr isotope composition of seven "transitional" basalts in the region between 34°–39° S, which ranged from 0.70385 to 0.70445. The samples from Pali-Aike (PA, Fig. 1) have a limited range of ⁸⁷Sr/⁸⁶Sr from 0.70316 to 0.70333, while samples from Meseta Buenos Aires (MBA, Fig. 1) range widely from 0.70321 to 0.70465 (Table 3 and Hawkesworth et al. 1979). Apparently, local as well as regional variations may sometimes be present. The highest values of ⁸⁷Sr/⁸⁶Sr

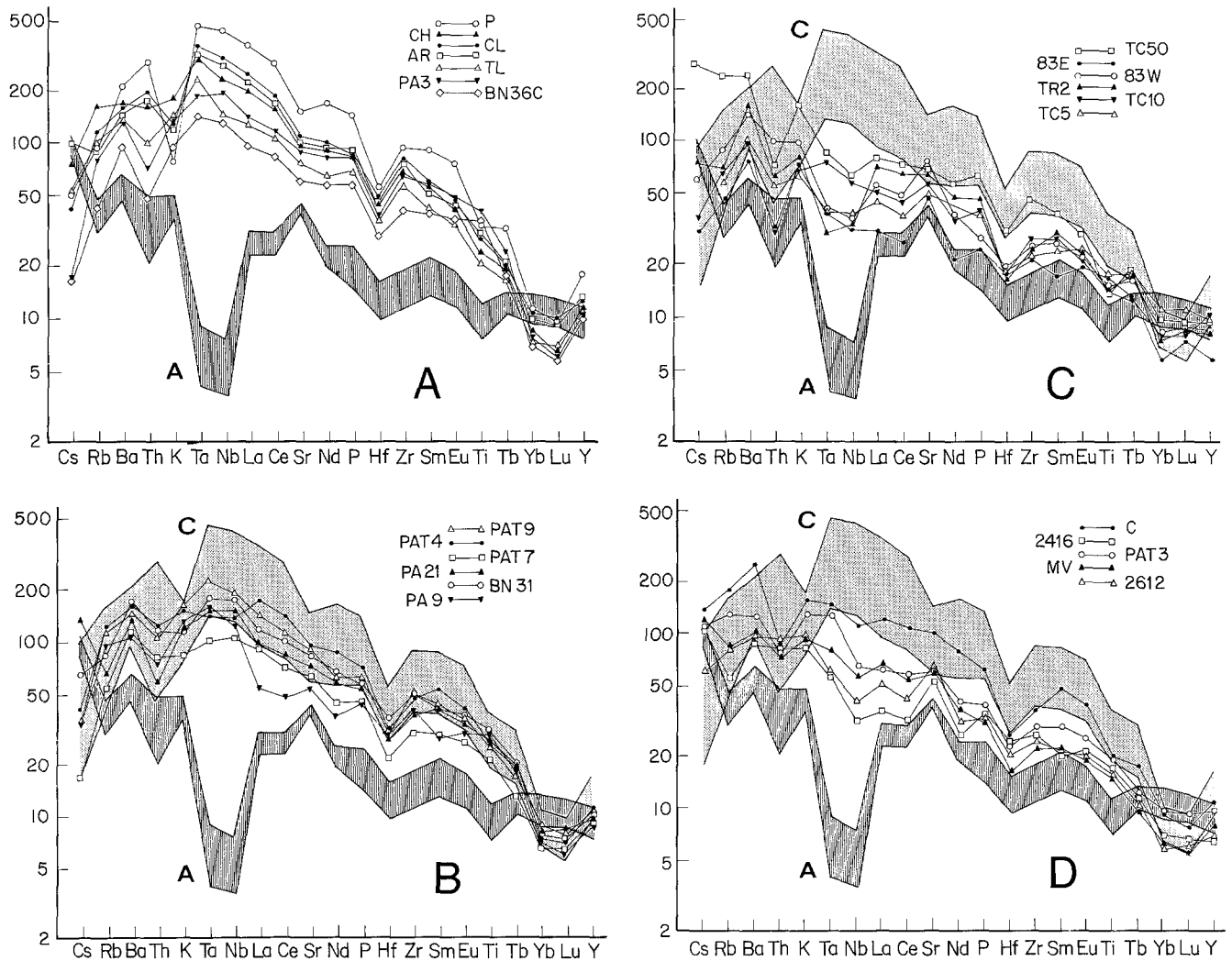


Fig. 3A–D. Normalized trace element compositions of Pliocene and Quaternary Patagonian basalts compared with Quaternary Andean orogenic arc high-Al basalts from the Llama volcano (*shaded field A*; Hickey et al. 1986). **A** plots xenolith-bearing “cratonic” basalts, **B** plots other “cratonic” basalts, **C** plots “transitional” basalts from the region 34°–39° S in which intra-arc alkali basalts occur between orogenic arc centers, and **D** plots both xenolith-bearing and other “transitional” basalts from south of 39° S. *Shaded field C* in **B**, **C**, and **D** is for the “cratonic” xenolith-bearing basalts shown in **A**. Normalization factors (*Cs*, 0.012; *Rb*, 0.35; *Ba*, 3.5; *Th*, 0.05; *K*, 120; *Ta*, 0.02; *Nb*, 0.39; *La*, 0.315; *Ce*, 0.813; *Sr*, 11; *Nd*, 0.597; P_2O_5 , 0.011; *Hf*, 0.18; *Zr*, 5.6; *Sm*, 0.192; *Eu*, 0.072; TiO_2 , 0.103; *Tb*, 0.049; *Yb*, 0.208; *Lu*, 0.032; *Y*, 2.2) are taken from Gerlach et al. (1988)

occur in samples from the area of Lago Colhue Huapi (LCH, Fig. 1).

Figure 6 shows that the range of Sr isotopic composition of the “cratonic” basalts is greater than the range of high-Al basalts erupted from Andean orogenic volcanoes between 36°–46° S. Furthermore, the “cratonic” basalts include values of $^{87}Sr/^{86}Sr$ that are both higher and lower than any arc basalts (Stern 1989). The “transitional” basalts range in $^{87}Sr/^{86}Sr$ from 0.70350 to 0.70445, which is more nearly similar to the range of orogenic arc basalts in the southern Andes.

Generally, $^{87}Sr/^{86}Sr$ does not correlate with the Rb/Sr of the samples. Only in one area east of Meseta Buenos Aires, do Hawkesworth et al. (1979) report such a correlation with a slope corresponding to an “age” of 500 my. Neither does $^{87}Sr/^{86}Sr$ correlate with other trace element ratios, such as Ba/Nb (Fig. 6). This is not unexpected in that the “transitional” and “cratonic” basalts have some

significantly different trace element characteristics but overlapping Sr isotopic compositions.

The Nd isotopic composition of all the analyzed basalts range from $\epsilon_{Nd} = 0$ to +5.5 (Table 3), as do three Pliocene and Quaternary basalts analyzed by Hawkesworth et al. (1979). Nd isotopic composition correlates inversely with Sr isotopic composition (Fig. 7), and plot within the array of oceanic basalts. All the basalts have Sm/Nd less than Bulk Earth, but except for those in the vicinity of Lago Colhue Huapi, the $^{143}Nd/^{144}Nd$ are greater than $^{143}Nd/^{144}Nd$ of Bulk Solid Earth (BSE) or Primitive Upper Mantle (PUM) (Fig. 7), indicating time integrated depletion of Nd relative to Sm for the source regions of these basalts.

The field of $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ of all the Patagonian alkali basalts is larger than and encompasses the field for high-Al basalts erupted from Andean orogenic volcanoes between 37°–46° S (Fig. 7). In detail, the “transitional” basalts define a field very similar to Andean oro-

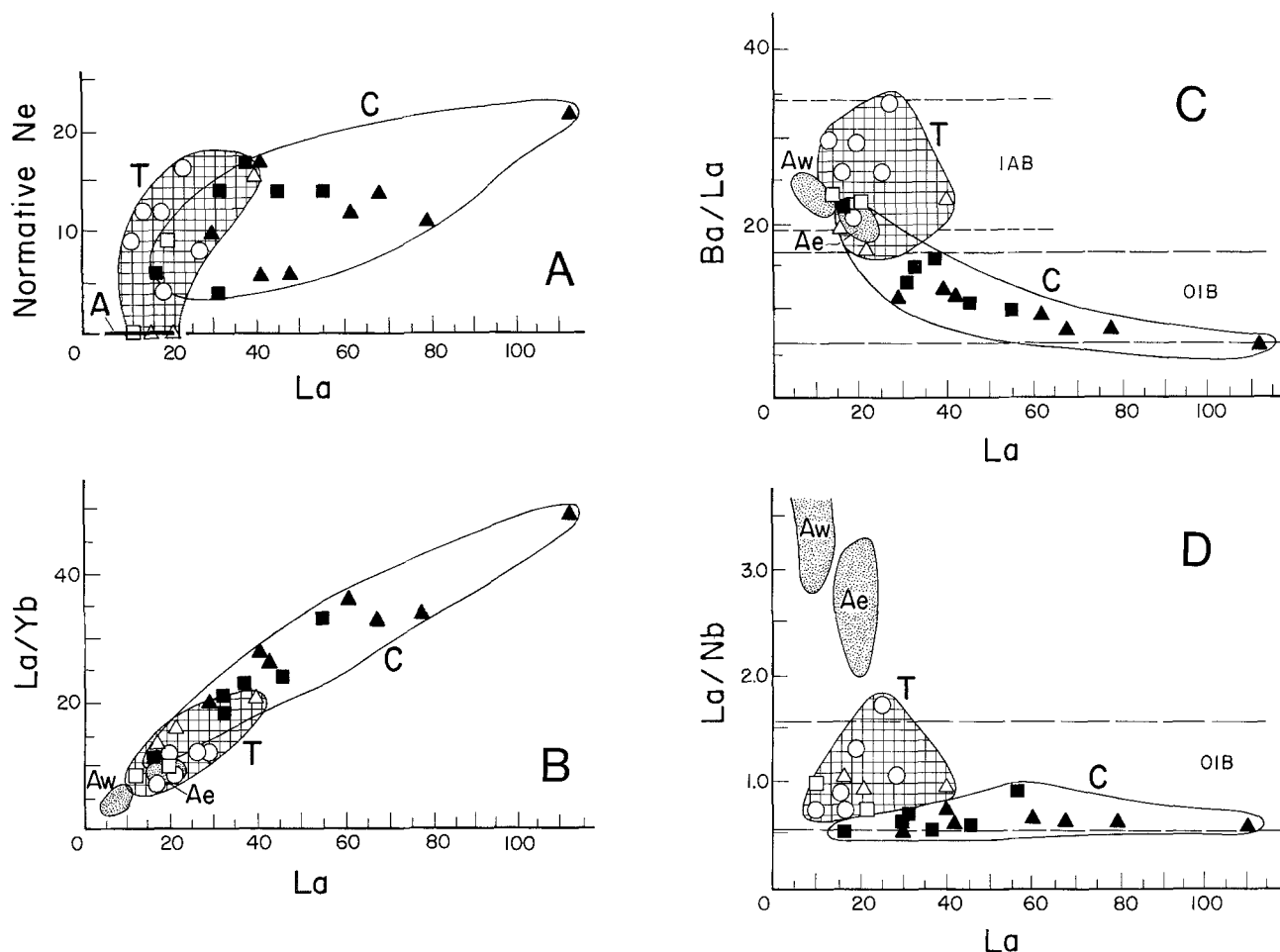


Fig. 4A–D. Normative nepheline versus La (A), La/Yb versus La (B), Ba/La versus La (C), and La/Nb versus La (D) for the “transitional” (open symbols; cross-hatched field T), and “cratonic” (solid symbols; field C) xenolith-bearing (triangles) and other (circles north of 39° S, squares south of 39° S) Pliocene and Quaternary Patagonian alkali basalts. Shaded field Aw corresponds to Quaternary Andean orogenic arc high-Al basalts erupted from stratovolcanos along the volcanic front and shaded field Ae to basalts erupted from Andean arc stratovolcanos east of the volcanic front (Hickey et al. 1986, 1989). The limits of the field of oceanic island basalt (OIB) and island arc basalts (IAB) are taken from Hickey et al. (1986)

genic arc high-Al basalts, and have higher $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$ than the “cratonic” basalts.

The Pb isotopic composition of the Patagonian alkali basalts ranges widely compared to the orogenic high-Al basalts in the southern Andes (Table 3, Figs. 8 and 9). However, the four “transitional” basalts analyzed for Pb isotopes – including two interspersed between arc stratovolcanos north of 39° S and two from south of 39° S along the westernmost outcrop of the plateau basalts in a region of earlier Cenozoic calc-alkaline orogenic arc volcanism – do have Pb isotopic compositions similar to the orogenic arc high-Al basalts. These “transitional” basalts have, in common with the orogenic arc high-Al basalts, higher $^{207}\text{Pb}/^{204}\text{Pb}$ at a given $^{208}\text{Pb}/^{204}\text{Pb}$ compared to both intra-plate oceanic island basalts (Fig. 9), as well as the “cratonic” basalts. The “cratonic” basalts, on the other hand, have $^{208}\text{Pb}/^{204}\text{Pb}$ at a given $^{207}\text{Pb}/^{204}\text{Pb}$ that is generally similar to OIB – one exception being sample BN31, which, like the “transitional” and orogenic arc basalts, has high $^{207}\text{Pb}/^{204}\text{Pb}$ relative to its $^{208}\text{Pb}/^{204}\text{Pb}$. This sample, however, does not fall within the field of the orogenic arc basalts with respect to either $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 8) or Sr and Nd isotopic composition.

When considering the combined Pb, Sr, and Nd isotopic data (Figs. 6–10), the “transitional” basalts resemble orogenic arc high-Al basalts from the southern Andes. Their range of isotopic composition is relatively restricted, and may be approximated as a single component with $^{87}\text{Sr}/^{86}\text{Sr} = 0.7039 \pm 0.0004$, $\epsilon_{\text{Nd}} = +4.0 \pm 1.1$, $^{206}\text{Pb}/^{204}\text{Pb} = 18.6 \pm 0.08$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.60 \pm 0.01$, $^{208}\text{Pb}/^{204}\text{Pb} = 38.50 \pm 0.10$. Although the “transitional” basalts are similar to some oceanic basalts with respect to Sr and Nd isotopic composition, their $^{208}\text{Pb}/^{204}\text{Pb}$ relative to $^{207}\text{Pb}/^{204}\text{Pb}$ are distinctive from oceanic basalts.

The “cratonic” basalts exhibit considerably more isotopic heterogeneity. They can be regarded collectively as a mixture of two end member components with (1) $^{206}\text{Pb}/^{204}\text{Pb} = 18.2$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.52$, $^{208}\text{Pb}/^{204}\text{Pb} = 38.3$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7052$, and $\epsilon_{\text{Nd}} = 0$, and (2) $^{206}\text{Pb}/^{204}\text{Pb} = 19.4$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.65$, $^{208}\text{Pb}/^{204}\text{Pb} = 39.2$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7032$, and $\epsilon_{\text{Nd}} = +5.5$, respectively. Neither of the end member isotopic values of Sr and Nd are similar to mid-ocean ridge basalt (MORB) or the Prevalent Mantle composition (PREMA) defined for oceanic basalts by Zindler and Hart (1986) (Fig. 7). Although the 10 “cratonic” basalts overlap in $^{206}\text{Pb}/^{204}\text{Pb}$ with much of the MORB field,

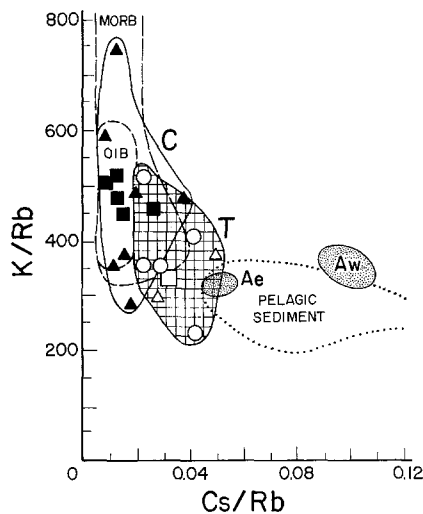


Fig. 5. K/Rb versus Cs/Rb for the “transitional” (open symbols, cross-hatched field T) and “cratonic” (solid symbols, field C) xenolith-bearing (triangles) and other (circles, north of 39° S, and squares south of 39° S) Pliocene and Quaternary Patagonian alkali basalts. Shaded field Aw corresponds to Quaternary Andean orogenic arc high-Al basalts erupted from stratovolcanos along the volcanic front, and shaded field Ae corresponds to basalts erupted from Andean arc stratovolcanos east of the volcanic front (Hickey et al. 1986, 1989). Fields for intra-plate OIB, MORB, and oceanic pelagic sediment from Hickey et al. (1986, 1989).

including basalts of the Nazca plate, they have distinctly higher $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ than MORB for a given $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 8). Also, these basalts show an inverse correlation between Sr and Pb isotopic composition (Fig. 10) and a direct correlation between Nd and Pb isotopic composition, clearly in opposition to the general MORB trend.

The “cratonic” basalts bear more resemblance to some oceanic island basalts than MORB (Figs. 7 and 10). For example, the isotopic composition of one of the end members of the “cratonic” basalts approach the BSE or PUM composition defined for oceanic basalts by Zindler and Hart (1986), while the Sr and Nd isotopic composition of the other end member trends towards their High U/Pb Mantle (HIMU) component. However, this second end member lacks the radiogenic Pb of the HIMU component that has been interpreted to form in an old elevated $^{238}\text{U}/^{204}\text{Pb}$ environments. The Sr and Nd isotopic range of these “cratonic” alkali basalts is also similar to the range exhibited by the Cenozoic continental basalts of eastern China (Peng et al. 1986). However, this comparison breaks down also, because the Patagonian basalts lack the low $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 10) of the Chinese basalts which have been interpreted to derive from an old, low $^{238}\text{U}/^{204}\text{Pb}$ reservoir in the subcontinental mantle lithosphere.

Measured $\delta^{18}\text{O}$ of whole rock samples range from 5.1 to 7.8, but olivine and clinopyroxene mineral separates have

Table 3. Sr, Nd, Pb, and O isotopic composition of Patagonian basalts

Sample	“Transitional” basalts											
	83W	83E	TR2	TC5	TC10	TC50	C	PAT3	MV	2612	2416	
$^{87}\text{Sr}/^{86}\text{Sr}$	0.70404	0.70431	0.70436	0.70412	0.70385	0.70422	0.70423 0.70424	0.70370	0.70354	0.70350	0.70356	
$^{143}\text{Nd}/^{144}\text{Nd}$	0.51279	0.51278	—	—	—	—	0.51287	—	—	0.51290	0.51287	
ϵ_{Nd}	+3.0	+2.8	—	—	—	—	+4.5	—	—	+5.1	+4.5	
$^{206}\text{Pb}/^{204}\text{Pb}$	18.62	18.52	—	—	—	—	—	—	—	18.67	18.65	
$^{207}\text{Pb}/^{204}\text{Pb}$	15.61	15.59	—	—	—	—	—	—	—	15.60	15.58	
$^{208}\text{Pb}/^{204}\text{Pb}$	38.53	38.36	—	—	—	—	—	—	—	38.45	38.60	
$\delta^{18}\text{O}$: WR_M	—	—	—	—	—	—	6.2	6.8	5.1	7.6	7.6	
WR_C	—	—	—	—	—	—	—	—	5.9	5.8	6.2	
OL	—	—	—	—	—	—	—	—	5.6	5.4	6.0	
CPX	—	—	—	—	—	—	—	—	5.7	—	6.0	
“Cratonic” basalts												
P	CH	PAT4	CL	AR	PAT9	PAT7	TL	PA3	BN36C	PA21	BN31	PA9
0.70400	0.70489	0.70512	0.70321	0.70322	0.70406	0.70405	0.70387	0.70316	0.70333	0.70317	0.70328	0.70324
0.70398	0.70499	0.70518	0.70320	0.70325	—	—	0.70392	—	—	—	—	—
0.51274	0.51264	0.51265	0.51290	0.51291	—	—	0.51276	0.51292	—	0.51291	0.51291	0.51292
+2.0	0.0	+0.2	+5.1	+5.3	—	—	+2.4	+5.5	—	+5.3	+5.3	+5.5
18.56	18.26	18.45	19.37	19.38	—	—	18.55	19.14	—	18.96	18.95	19.01
15.62	15.53	15.58	15.60	15.64	—	—	15.58	15.62	—	15.61	15.68	15.62
38.57	38.30	38.51	38.84	39.23	—	—	38.46	38.80	—	38.63	38.75	38.77
7.8	6.7	—	6.2	6.2	6.2	—	7.0	—	5.3	6.8	6.3	6.5
6.5	6.0	—	6.1	—	—	—	5.6	—	—	5.9	5.4	5.3
6.1	5.6	—	5.7	—	—	—	—	—	—	5.5	5.1	—
—	—	—	—	—	—	—	—	—	—	—	5.0	5.0

$\delta^{18}\text{O}$ reported in units per mil; WR_M , measured whole-rock values; WR_C , whole-rock calculated from $\delta^{18}\text{O}$ of clinopyroxene and olivine assuming $\Delta^{18}\text{O}$ (basalt-mineral)=0.2 to 0.4; OL, olivine; CPX, clinopyroxene. All $\delta^{18}\text{O}$ values are precise to ± 0.2

Sr, Nd, and Pb isotopic compositions were determined at the U.S.G.S. in Denver. None of the isotopic data were corrected for age. Techniques, normalization values, and precisions are discussed in Peng et al. (1986). The second value for $^{87}\text{Sr}/^{86}\text{Sr}$ represents a complete duplicate analysis. ϵ_{Nd} was calculated using CHUR , 0.512638

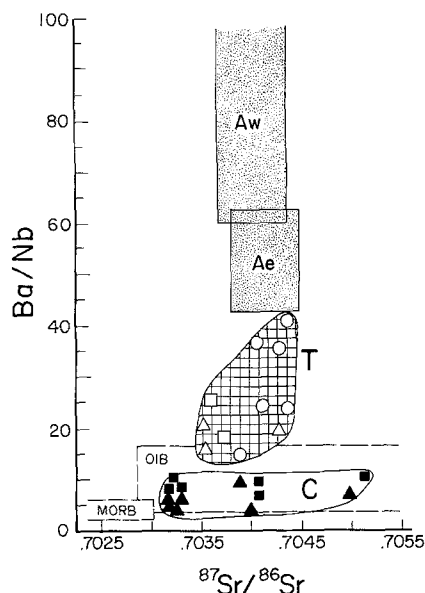


Fig. 6. Ba/Nb versus $^{87}\text{Sr}/^{86}\text{Sr}$ for the “transitional” (open symbols, cross-hatched field T) and “cratonic” (solid symbols, field C) xenolith-bearing (triangles) and other (circles north of 39°S , squares south of 39°S) Pliocene and Quaternary Patagonian alkali basalts. Shaded field Aw corresponds to Quaternary Andean orogenic arc high-Al basalts erupted from stratovolcanos along the volcanic front and shaded field Ae to basalts erupted from Andean arc stratovolcanos east of the volcanic front (Hickey et al. 1986, 1989). Fields for MORB and OIB from Hickey et al. (1986)

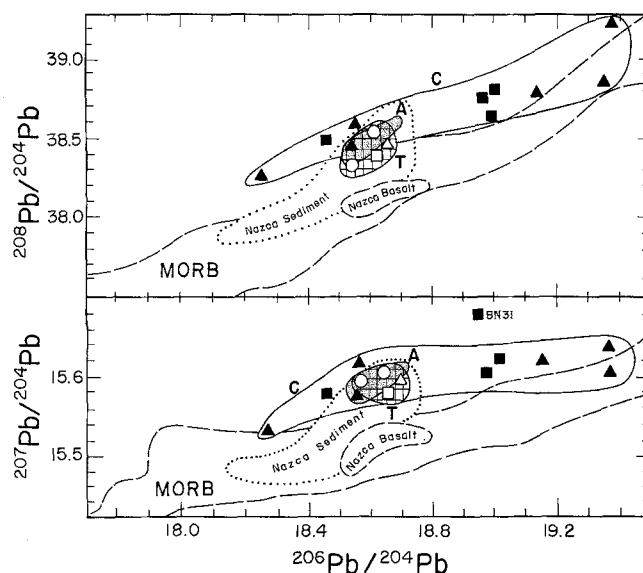


Fig. 8. Plots of $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ of the “transitional” (open symbols, cross-hatched field T) and “cratonic” (solid symbols, field C) xenolith-bearing (triangles) and other (circles north of 39°S , squares south of 39°S) Pliocene and Quaternary Patagonian alkali basalts. Fields for the Southern Volcanic Zone (SVZ) of the Andes, Nazca plate basalts and sediments, and MORB are from Barreiro (1984)

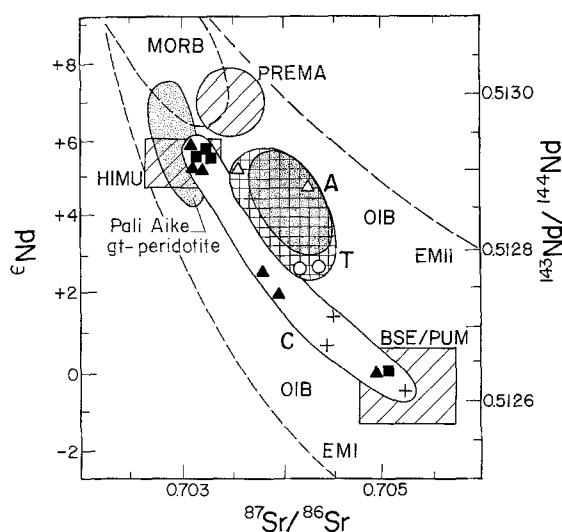


Fig. 7. $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ for “transitional” (open symbols, cross-hatched field T) and “cratonic” (solid symbols, crosses from Hawkesworth et al. 1979, field C) xenolith-bearing (triangles) and other (circles north of 39°S , squares south of 39°S) Pliocene and Quaternary Patagonian alkali basalts. Shaded field A corresponds to Quaternary Andean orogenic arc high-Al basalts (Hickey et al. 1986, 1989; Futa and Stern 1988). Fields of MORB, OIB, PREMA, HIMU, and BSE/PUM and trends towards EMI and EMII are from Zindler and Hart (1986) as defined for oceanic basalts. Also shown are the isotopic compositions of fertile garnet-lherzolite xenoliths from the Pali-Aike volcanic field (Stern et al. 1986 and 1989)

a more restricted range of 5.0 to 6.1 and indicate a range in $\delta^{18}\text{O}$ values of 5.3 to 6.5 for the basalts (Fig. 11). The higher measured values for the whole rock samples are interpreted to result from low temperature alteration by surface waters. There is no correlation between either measured or calculated $\delta^{18}\text{O}$ values and tectonic setting or Sr, Nd, and Pb isotopic composition (Fig. 11). The range of calculated $\delta^{18}\text{O}$ values for the Patagonian plateau basalts is slightly more restricted and generally lower than those of measured whole rock samples of Andean orogenic arc basalts from the southern Andes (Harmon et al. 1984).

Discussion and conclusions

The isotopic and trace element data presented here suggest that the “cratonic” Pliocene and Quaternary Patagonian alkali basalts are similar to some intra-plate oceanic island basalts (OIB) and distinct from the “transitional” basalts. The latter group has some characteristics in common with Andean orogenic high-Al basalts. The two groups of basalts are discussed separately below.

“Cratonic” basalts

The mantle source of the Pliocene and Quaternary “cratonic” Patagonian alkali basalts, those that have erupted in regions of Cenozoic plateau volcanism and continental platform sedimentary rocks, is isotopically heterogeneous. Sr and Nd isotopic composition of these alkali basalts coincide with much of the mantle array defined by oceanic basalts (Fig. 7). The Pb isotopic composition of these samples are also similar to some oceanic basalts (except for sample BN31; Figs. 7–10), as are ratios of incompatible trace elements such as Ba/La, Ba/Nb, La/Nb, Cs/Rb and K/Rb (Figs. 3–5). Such geochemical similarities between oceanic

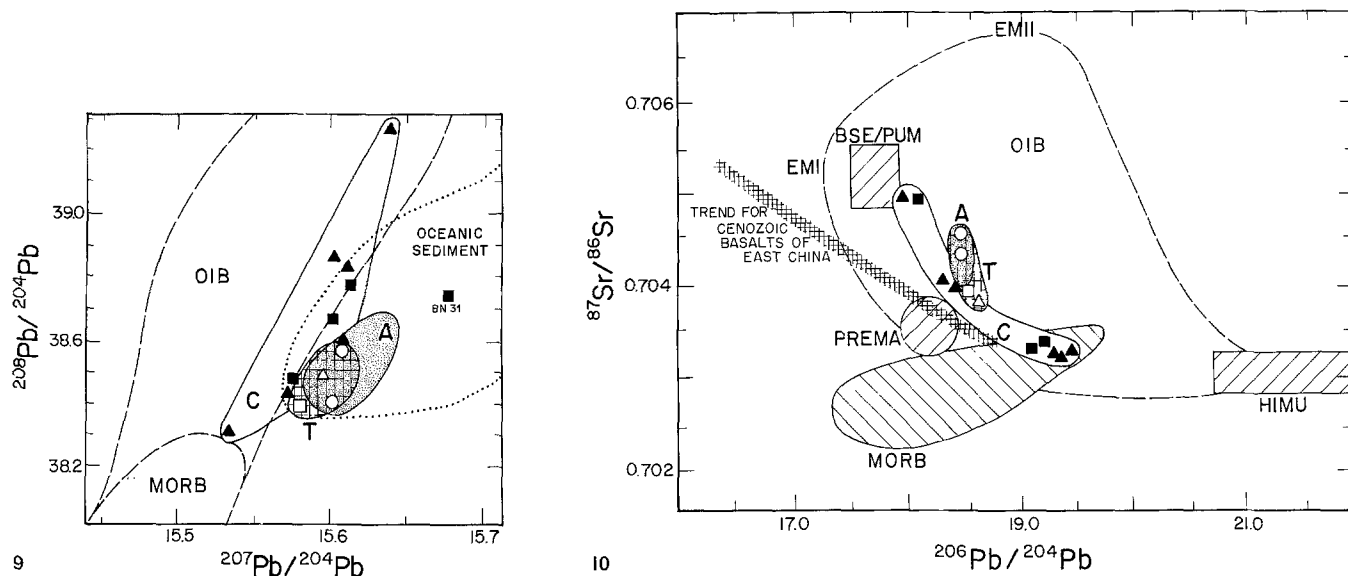


Fig. 9. Plot of $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ for the “transitional” (open symbols, cross-hatched field T) and “cratonic” (solid symbols, field C) xenolith-bearing (triangles) and other (circles north of 39°S , squares south of 39°S) Pliocene and Quaternary Patagonian basalts. Field for MORB, OIB, and Nazca plate pelagic sediments are from Hickey et al. (1986).

Fig. 10. Plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ for the “transitional” (open symbols, cross-hatched field T) and “cratonic” (solid symbols, field C) xenolith-bearing (triangles) and other (circles north of 39°S , circles south of 39°S) Pliocene and Quaternary Patagonian plateau alkali basalts. Field for the Andean SVZ are from Hickey et al. (1986), for Chinese Cenozoic alkali basalts from Peng et al. (1986) and for MORB, OIB and PREMA, BSE/PUM, EMI, EMII, and HIMU from Zindler and Hart (1986)

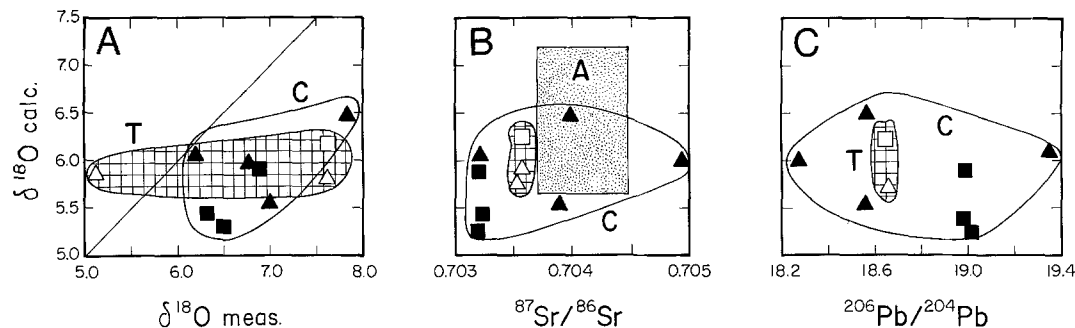


Fig. 11. A Measured whole rock $\delta^{18}\text{O}$ versus whole rock $\delta^{18}\text{O}$ calculated from the oxygen isotopic composition of the phenocryst mineral phases of the Patagonian alkali basalts lavas (Table 3); B calculated whole rock $\delta^{18}\text{O}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ of the Patagonian basalts; and C calculated whole rock $\delta^{18}\text{O}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ of the Patagonian basalts. Symbols are as in Fig. 2. Field A in B is the measured whole rock $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ of basalts from orogenic arc of the southern Andes (Harmon et al. 1984; Stern and Muehlenbacks, unpublished data)

and continental basalts have been noted previously (Allegre et al. 1981). Thus, we conclude that the geochemical similarities between the oceanic island and the “cratonic” Patagonian alkali basalts are consistent with both being derived from compositionally similar sources.

The peridotite xenoliths within the Patagonian alkali basalts equilibrated within the subcontinental lithosphere at depths between 30–80 km (Skewes and Stern 1979; Stern et al. 1986, 1989), implying that the source of these basalts was either in the deepest parts of the sub-continental lithosphere or the asthenosphere. Zindler et al. (1984) have proposed a model in which oceanic seamount basalts, with a range of Sr and Nd isotopic compositions similar to the Patagonian basalts, form by different degrees of partial melting of a relatively uniformly depleted asthenosphere with small scale isotopic heterogeneities. They attribute the heterogeneity to unequilibrated remnants of subducted oce-

anic lithosphere and hot-spot plumes caught up in upper mantle convection. Presumably, such a heterogeneous plum-pudding asthenosphere would be global and should also exist below the South American continental lithosphere. However, if all the observed isotopic variability found within the “cratonic” Patagonian alkali basalts was due to different degrees of melting of asthenosphere, those basalts that formed by greater degrees of partial melting should trend toward either PREMA or MORB end members. In fact, there is no correlation between alkalinity and isotopic composition; basalts of greatly different alkalinity have similar isotopic composition.

Lithospheric isotopic heterogeneities may also have contributed to the spread in isotopic composition of the “cratonic” Patagonian alkali basalts. There is no definitive evidence to identify an evolved subcrustal lithosphere, however, in that the range of isotopic variability of the “cr-

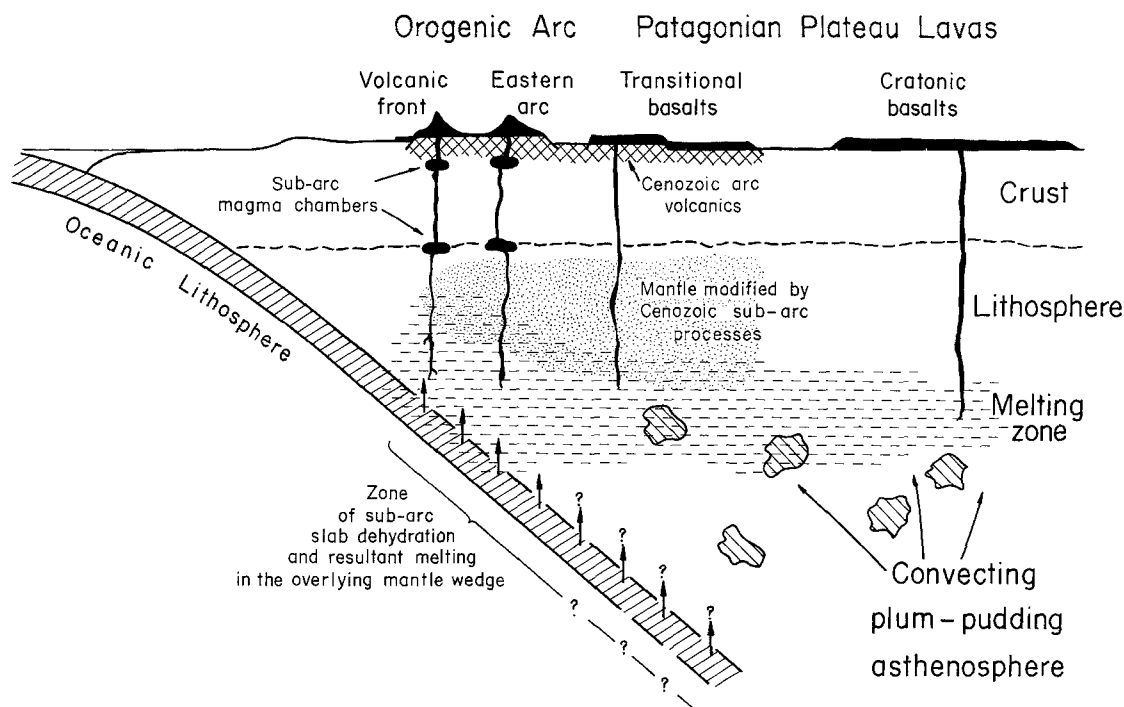


Fig. 12. Schematic cross-section of the southern South American western continental margin (south of 39° S) modified after Stern et al. (1986) and Hickey et al. (1986 and in 1989). Below the Andean orogenic arc relatively large amounts of volatile-rich melts or fluids derived from the subducted oceanic lithosphere cause relatively large degrees of melting of the plum-pudding OIB-source type asthenosphere. Below the “cratonic” lavas to the east, smaller degrees of melting of the asthenosphere are associated with convection in response to slab subduction and asthenosphere derived melts metasomatize the lower lithosphere prior to melting of this so-modified mantle. Either small amounts of fluids added to the asthenosphere, or melting of what had previously been sub-arc lithosphere, imparts an intermediate geochemical character to the “transitional” basalts

tonic” alkali basalts overlap but does not extend beyond that of oceanic basalts (Fig. 7). Nevertheless, involvement of the Patagonian subcrustal lithosphere cannot be excluded on this basis because this lithosphere may be relatively young. The oldest reported ages of crustal rocks in the region of southernmost South America through which the Patagonian plateau lavas have erupted are early Paleozoic. This region has been widely interpreted as accretionary continental lithosphere, possibly including some allochthonous blocks, formed during the Phanerozoic by arc and arc-trench gap magmatic and tectonic processes along the western margin of Gondwanaland (deWit 1977; Stern et al. 1986; Ramos 1988; Dalziel 1988). Therefore, it is unlikely to possess distinctive radiogenic isotopic compositions resulting from the ancient enrichment and depletion events inferred from studies of Archean cratonic lithosphere (Cohen et al. 1984). In fact, the Sr and Nd isotopic composition of the Pali-Aike alkali basalts (PA, Fig. 1) is within the field of the whole-rock isotopic composition of the fertile garnet-lherzolite xenoliths (Fig. 7) derived from the underlying continental lithosphere (Stern et al. 1986, 1989). The 500 My pseudo-isochron observed by Hawkesworth et al. (1979) for the plateau basalts near 46° S, which approximates the inferred Phanerozoic age of the Patagonian lithosphere, also suggests an important contribution from this lithosphere in the generation of the basalts.

Studies of other continental as well as ocean island basalts have also concluded that the subcrustal mantle lithosphere may play an important role in producing isotopic heterogeneities observed in basalts. We envision a model (Fig. 12) similar to that proposed by Chen and Frey (1985), McDonough et al. (1985) Peng et al. (1986) and Perry et al.

(1987) in which the “cratonic” Patagonian alkali basalts result from mixing of melts from both asthenosphere and lower lithosphere. The young lithosphere beneath Patagonia – itself probably constructed only a few hundred million years earlier largely out of asthenospheric material (Stern et al. 1986, 1989) – may have a similar range in isotopic composition as the present underlying asthenosphere and thus impart no distinctive isotopic signature to the Patagonian plateau alkali basalts.

The alkaline character and high incompatible trace element concentrations of the “cratonic” Patagonian alkali basalts (Figs. 2 and 3) suggest that they are formed by variable but low degrees of partial melting of these mantle sources. Their large enrichment of LREE relative to HREE (Figs. 3 and 4B) and high $^{143}\text{Nd}/^{144}\text{Nd}$ (Fig. 9), which are greater than BSE/PUM for all the samples except those from near Lago Colhue Huapi, could result from very small degrees of partial melting of depleted sources (Frey et al. 1978). However, we suggest that the generation of the “cratonic” basalts involves a two-stage process that begins by variable but generally low degrees of partial melting of a plum-pudding asthenosphere caused by convection in response to subduction of oceanic lithosphere below the western margin of the continent (Fig. 12). The resulting melts, with high LREE/HREE and isotopic compositions similar to oceanic basalts, intrude the fertile garnet-lherzolite at the base of the lithosphere. Subsequent melting of the so modified and metasomatized lower continental lithosphere as it is heated, thinned and converted to mantle with asthenospheric physical properties, yields incompatible element enriched alkali basalts with isotopic composition little changed from that of oceanic basalts. This physical model

is similar to that proposed for basalt generation below the western U.S. by Perry et al. (1987) although the amount of extension related to the generation of the Pliocene and Quaternary Patagonian alkali basalts is smaller. The mineralogy, mineral chemistry and textures of peridotite xenoliths indicate that below the Pali-Aike volcanic field the lithosphere has, in fact, been recently metasomatized, heated and thinned to approximately 80 km (Stern et al. 1986, 1989; Douglas et al. 1987).

Implications for Andean arc magmatism

Mixing, differentiation, and contamination in sub-arc magma chambers is likely to have modified the composition of Andean orogenic magmas, making it difficult to characterize their mantle source regions. Data from the Patagonian alkali basalts provide an alternative approach for evaluating lithospheric and asthenospheric mantle contributions to Andean magmas. We suggest, on the basis of the OIB petrochemical characteristics of the "cratonic" Patagonian basalts that below the southern Andes both the asthenosphere and lithosphere may possess OIB source type characteristics. Hickey et al. (1986) also suggested that sub-arc mantle with OIB source characteristics may be an important source component in the generation of arc basalts in the southern Andes, particularly in producing cross-arc west to east variations in incompatible element concentrations and ratios.

A significant feature of Andean arc high-Al basalts is their relatively restricted range of Sr, Nd and Pb isotopic composition compared to both the mantle array defined by oceanic basalts and the "cratonic" Patagonian alkali basalts (Figs. 7–11). This restricted range of isotopic composition may be the result of relatively greater degrees of partial melting of sub-arc mantle sources as implied by the hypersthene normative compositions and lower La contents (Fig. 4A) of the Andean arc basalts. Greater degrees of partial melting should tend to eliminate small scale mantle isotopic heterogeneities within asthenosphere or lithosphere, which are preserved by the relatively low degrees of partial melting responsible for the "cratonic" alkali basalts. Magma mixing in sub-arc magma chambers may be another important factor in homogenizing the isotopic composition of Andean arc basalts (Fig. 12; Gerlach et al. 1988).

Of equal if not greater significance is the fact that the Andean orogenic basalts are isotopically distinct from the array defined by the "cratonic" Patagonian alkali basalts, being displaced to higher $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$, higher $^{207}\text{Pb}/^{204}\text{Pb}$ at a given $^{208}\text{Pb}/^{204}\text{Pb}$, and higher average $\delta^{18}\text{O}$ (Figs. 7–11). These regional cross-arc isotopic differences strongly support the previously published conclusions of Hickey et al. (1986, 1989) and Futa and Stern (1988) that the sub-arc source region has been contaminated by H_2O -rich silicate melts or silica-rich fluids derived from subducted oceanic lithosphere including pelagic sediment and sea-water altered basalt (Fig. 12). The presence of ^{10}Be in some of the Andean orogenic basalts further implies that their source region contains components derived from subducted oceanic sediment (Morris et al. 1985).

The association of higher Ba/La, Ba/Nb, La/Nb, and Rb/Cs with higher $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$, higher $^{207}\text{Pb}/^{204}\text{Pb}$ at a given $^{208}\text{Pb}/^{204}\text{Pb}$, and higher $\delta^{18}\text{O}$ in the Andean orogenic arc compared to the "cratonic" Patagonian

alkali basalts suggests that the typical arc-like trace element ratios of the Andean orogenic arc basalts are also related to source region contamination processes rather than preferential retention of REE and HFSE in residual mantle phases. Also, the presence of such residual phases below the arc, but not below the Patagonian plateau, is not consistent with the greater degrees of partial mantle melting inferred to occur below the arc. The differences in the trace element ratios of the arc and "cratonic" basalts (Figs. 3–6) imply that the slab-derived melts or fluids responsible for the sub-arc source region contamination processes were rich in not only in Cs, Rb, Ba, and Sr relative to LREE and HFSE, but LREE relative to HFSE as well.

"Transitional" basalts

The "transitional" Patagonian alkali basalts have erupted in regions that either currently, as between 34–39° S, or earlier in the Cenozoic, were the locus of Andean orogenic arc volcanism. These alkali basalts have Ba/La that overlaps with Andean and other convergent plate boundary basalts (Fig. 4C), and Ba/Nb, La/Nb, Rb/Cs, and K/Rb that are intermediate between Andean orogenic arc basalts and the "cratonic" alkali basalts (Figs. 4–6). Isotopically, the "transitional" alkali basalts encompass and have only a slightly greater range of Sr, Nd, and Pb isotopic composition than Andean orogenic arc basalts but they also do include compositions that are intermediate between the "cratonic" and arc basalts (Figs. 7–10). Like the Andean orogenic arc basalts, the "transitional" alkali basalts are displaced to higher $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$ and higher $^{207}\text{Pb}/^{204}\text{Pb}$ at a given $^{208}\text{Pb}/^{204}\text{Pb}$ than the "cratonic" basalts, although generally not as greatly as the arc basalts (Figs. 7 and 9). The isotopic similarities of the "transitional" basalts with Andean orogenic basalts – particularly their high $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$ and high $^{207}\text{Pb}/^{204}\text{Pb}$ at a given $^{208}\text{Pb}/^{204}\text{Pb}$ compared to the "cratonic" basalts – as well as their relatively high Ba/La, Ba/Nb, La/Nb and Cs/Rb suggest that sub-arc type enrichment processes also affected the mantle source of the "transitional" basalts. The low $\delta^{18}\text{O}$ values of these basalts necessitates, however, that the mass of the melt or fluid from the slab must have been small relative to the mass of the mantle source of the basalts.

The high-Al basalts erupted along the volcanic front of the southern Andean orogenic arc, the subalkaline basalts erupted from stratovolcanos within the Andean cordillera east of the volcanic front, and the "transitional" and "cratonic" alkali basalts define coherent trends of increasing alkalinity, incompatible element concentrations, and La/Yb (Figs. 2–4) and decreasing La/Nb, Ba/Nb, and Cs/Rb (Figs. 4 and 5). Increasing alkalinity, incompatible element concentrations, and La/Yb eastward of the volcanic front may result from decreasing degrees or partial melting (Hickey et al. 1986, 1989; Futa and Stern 1988; Munoz and Stern 1988, 1989). Decreasing La/Nb, Ba/Nb, and Cs/Rb suggest (1) decreasing input, consistent with the lower $\delta^{18}\text{O}$ of the plateau compared to the arc basalts (Fig. 11), of high La/Nb, Ba/Nb, and Cs/Rb slab derived components into relatively low La/Nb, Ba/Nb, and Cs/Rb mantle such as the asthenosphere and lower continental lithosphere sources of the "cratonic" basalts, and/or (2) decreasing La/Nb, Ba/Nb, and Cs/Rb of the slab derived components eastward of the volcanic front due to progressive down

dip melting or dehydration reactions (Futa and Stern 1988). Hickey et al. (1986, 1989) have shown that eastwardly decreasing input into the sub-arc mantle of slab derived components, either of constant or variable composition, coupled with eastwardly decreasing degrees of partial melting of this mantle as the input of these components decreases, is capable of explaining the cross-arc variations in incompatible trace element concentrations and ratios in the southern Andes. This model was extended to the "transitional" intra-arc basalts between 34°–39° S by Munoz and Stern (1988, 1989) and may also be extended to the "transitional" back-arc basalts south of 39° S as implied by the coherent variations observed between the arc and these back-arc basalts (Fig. 12).

Because there exist neither seismic evidence for a subducting slab east of the volcanic front of the Andean orogenic arc in the region below the plateau basalts, nor ^{10}Be data, we do not know whether the arc-like enrichment processes in the mantle source regions of the "transitional" basalts are occurring currently or occurred during earlier Cenozoic arc volcanism. Munoz and Stern (1989), for example, suggested that Quaternary alkali basalts erupted along the Pino Hachado precordilleran uplift between 38°–39° S have high Ba/La and Ba/Nb similar to Andean arc basalts because their mantle source region inherited these characteristics during the Pliocene when this uplift was the locus of the volcanic front of the Andean arc. Because the subcrustal lithosphere is not likely to be involved in upper mantle convection, it is capable of preserving the effects of previous localized igneous episodes. Therefore, we conclude that the arc-like petrochemical characteristics of the "transitional" basalts may reflect incorporation of components from subcrustal lithosphere modified by sub-arc type enrichment processes which occurred earlier in the Cenozoic (Fig. 12). A more refined determination of the timing and mechanism by which slab-derived components are incorporated in the mantle source regions of the "transitional" Patagonian basalts awaits more detailed information on the temporal and spatial distribution of both these type of basalts and Andean orogenic arc magmatism.

Summary

In summary, we envision decreasing degrees of partial melting in the asthenosphere wedge eastward away from the Andean orogenic arc to be a fundamental factor in the transition from arc to back-arc magmatism in southernmost South America (Fig. 12). Directly below the arc, mantle melting is associated with the input of volatile-rich melts or fluids derived from the subducted oceanic lithosphere, and the eastward decrease in melting across the arc itself may be related to decreased input of these slab-derived components. Further to the east the degree of melting may be more dependent on convection in the asthenosphere and no evidence of slab-derived components is observed in the "cratonic" Patagonian alkali basalts. The intermediate geochemical character of the "transitional" alkali basalts may result from either a decrease in the quantity and/or a change in the composition of the components being derived from the subducted slab, or from previously established arc-like geochemical characteristics within the continental lithosphere.

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