Revista de la Asociación Geológica Argentina, 59 (4): 525-538 (2004)

Cenozoic back-arc magmatism of the southern extra-Andean Patagonia (44° 30' - 52° S): A review of geochemical data and geodynamic interpretations

Massimo D'ORAZIO[1,2], Fabrizio INNOCENTI[1,2], Piero MANETTI P[2] y Miguel J. HALLER[3]

[1]*Dipartimento di Scienze della Terra, Università di Pisa, Via S. Maria 53, I-56126 Pisa, Italy.* E-mail: *dorazio@dst.unipi.it*
[2]*Istituto di Geoscienze e Georisorse, C.N.R., Via Moruzzi 1, I-56124 Pisa, Italy*
[3]*Universidad Nacional de la Patagonia San Juan Bosco, CENPAT-CONICET, Puerto Madryn, Argentina.*

RESUMEN. *Magmatismo de retroarco cenozoico de la Patagonia extra-andina austral (44° 30' - 52° S): Una revisión de los datos geoquímicos e interpretaciones geodinámicas*. Durante el Cenozoico erupcionaron persistentemente grandes volúmenes de lava basáltica *s.l.* a lo largo de la margen oriental de la cordillera de los Andes, que dieron lugar a extensos plateaus, centenares de conos de escoria monogenéticos y otras estructuras volcánicas, en un marco geotectónico de retroarco continental. Los productos volcánicos aflorantes en el sector austral de la Patagonia extrandina (44° 30' - 52° S) son de naturaleza principalmente máfica con algunas composiciones ligeramente evolucionadas y escasos productos más diferenciados. Los numerosos análisis químicos publicados de estas rocas indican que las lavas máficas varían desde basanitas fuertemente subsaturadas hasta andesitas basálticas sobresaturadas y, que la mayoría de las lavas tienen características geoquímicas típicas de intraplaca. Sin embargo, algunas lavas provenientes de los sectores centro-occidentales de la Patagonia se caracterizan por una distribución diferente de los elementos incompatibles con relaciones LILE/HFSE y LREE/HFSE altas. La modelización de la distribución de tierras raras sugiere que los magmas alcalinos se generaron a partir de una fusión de bajo grado de una fuente profunda (> 70 km) portadora de granate, mientras que los magmas subalcalinos se originaron por una fusión de mayor grado o por un grado de fusión aún mayor de una fuente enriquecida. Las composiciones isotópicas de Sr, Nd y Pb disponibles muestran una variación geográfica importante: las lavas más australes tienen relaciones $^{87}Sr/^{86}Sr$ más bajas y relaciones $^{143}Nd/^{144}Nd$ y $^{206}Pb/^{204}Pb$ más altas que aquéllas erupcionadas al norte. En su conjunto, las composiciones isotópicas de Sr, Nd y Pb de la Patagonia austral tienen el rango típico de magmas de intraplaca; además, las relaciones isotópicas del Pb tienen el rango de la anomalía isotópica Dupal del Pb del hemisferio Austral. Las variaciones geoquímicas de las lavas de la Patagonia austral son discutidas en términos de sus diferentes componentes: astenósfera subplacada empobrecida y enriquecida, manto continental enriquecido y, materiales subductados y de la corteza continental. El significado geodinámico se interpreta en el marco de una evolución del magmatismo en el espacio y el tiempo y, en el marco más amplio de la historia cenozoica del margen Pacífico de Sudamérica meridional. La interpretación geotectónica para el magmatismo de la Patagonia austral vincula la apertura de ventanas astenosféricas asociadas a la colisión entre dorsales oceánicas en expansión y la fosa de Chile. Sin embargo, la ocurrencia de muchas unidades volcánicas cuya edad y ubicación no son compatibles con el modelo de ventanas astenosféricas, sugiere que en la Patagonia extrandina pudieron actuar durante el Cenozoico otros procesos geodinámicos que provocan fusión del manto.

Palabras clave: *Patagonia, Magmas basálticos, Retroarco, Cenozoico, Ventana astenosférica, Geoquímica, Geodinámica*

ABSTRACT. Huge amounts of basaltic s.l. lavas were persistently erupted along the eastern side of the Andean Cordillera, throughout Cenozoic time, forming extensive plateaus, hundreds of monogenetic scoria cones and other volcanic structures in a continental back-arc setting. The igneous products exposed in the southern sector of the extra-Andean Patagonia (44° 30' - 52° S) are dominantly mafic with minor slightly evolved compositions and rare highly differentiated products. The many published chemical analyses of these rocks, indicate that the mafic lavas range from strongly silica - undersaturated basanites to oversaturated basaltic andesites, and that most of the lavas have a typical within-plate geochemical signature. However, a number of lavas, generally erupted in the western-central sectors of Patagonia, are characterized by different distributions of the incompatible elements with high LILE/HFSE and LREE/HFSE ratios. The REE distribution modelling suggests a low degree of melting of a deep (> 70 km) garnet-bearing source for the alkaline magmas, and a higher degree of melting of the same source, or an even higher degree of melting of an enriched source, for the subalkaline magmas. The available Sr-Nd-Pb isotope compositions clearly attest to a major geographic variation: the southernmost lavas have lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ ratios with respect to those erupted to the north. On the whole, the Sr-Nd-Pb isotope compositions of the southern Patagonia lavas fall within the typical range of within-plate continental magmas; in addition the Pb isotope ratios fall in the range of the Southern Hemisphere Dupal Pb isotope anomaly. The geochemical variations of the southern Patagonia lavas are discussed in terms of different geochemical components: depleted and enriched sub-slab asthenosphere, enriched continental lithospheric mantle, continental crust and subducted materials. The geodynamic significance is interpreted with in the framework of the space-time evolution of the magmatism and in the wider frame of the Cenozoic history of the Pacific margin of southern South America. The slab window openings associated with the collision between oceanic spreading ridges and the Chile Trench are the preferred geodynamic interpretation of the southern Patagonia magmatism. However, the occurrence of many volcanic formations whose age and location are not entirely compatible with the slab window model suggests that other geodynamic processes inducing mantle melting could have been active during Cenozoic time in the extra Andean Patagonia.

Key words: *Patagonia, Basaltic magmas, Back-arc, Cenozoic, Slab window, Geochemistry, Geodynamics*

Introduction

Mafic magmas are erupted on continental areas in a variety of tectonic settings and with highly variable geochemical and isotopic characteristics. Those generated behind active volcanic arcs are particularly interesting as they potentially sample very different physical reservoirs, such as the asthenospheric wedge close and far from the arc, the continental crust (both lower and upper), the sub-slab asthenosphere and the continental lithospheric mantle. In addition, the generation of continental back-arc magmas may be profoundly influenced by the physical parameters controlling slab subduction (e.g. age and temperature of the slab, subduction rate, slab dip, etc.) and by the transfer of chemical components from the slab to the magma sources. Finally, some complex processes associated with subduction, such as ridge-trench collisions and/or slab erosion of the upper plate, may also have a significant role in back-arc magma genesis.

One of the best places for studying continental back-arc magmatism is the extra-Andean Patagonia (Argentina and Chile), where, during Cenozoic time, huge volumes of mainly mafic magmas were produced behind the coeval Andean Arc. In this very wide area, the magmatic evolution can be profitably studied in connection with the relatively well-known Cenozoic history of the interactions between the Pacific oceanic plates and the South American Plate (Cande and Leslie 1986, Tebbens *et al.* 1997).

The magmatism of the southern sector of extra-Andean Patagonia has been studied in much better detail than the northern sector (e.g. Panza and Franchi 2002; Gorring *et al.* 2003, D'Orazio *et al.* 2004 and references therein) and is the object of this paper. The data base of chemical and Sr-Nd-Pb analyses used for this review was built with data taken from Baker *et al.* (1981); Stern *et al.* (1990); Ramos and Kay (1992); Gorring (1997); D'Orazio *et al.* (2000, 2001, 2004); Gorring *et al.* (2003); and the authors' unpublished data set.

Outlines of the geologic and geodynamic setting of southernmost South America

The present geologic structure of southernmost South America can be divided from west to east into four main structural units (Winslow 1982): i) a Paleozoic metamorphic basement, intruded by the Jurassic to Miocene Patagonian Batholith and exposed in the fore-arc region (Hervé *et al.* 1981); ii) the Patagonian Cordillera, made up of deformed silicic volcanic rocks (Late Jurassic, Tobifera or Chon Aike Formation) and ophiolitic/volcaniclastic assemblages that originated in the Early Cretaceous «Rocas Verdes» back-arc basin (Dalziel 1981); iii) the Andean Cordillera foothills, a Late Cretaceous to Late Miocene thin-skinned fold-and-thrust belt built up from (Kraemer, 1998; Coutand *et al.* 1999); iv) the foreland, consisting of two large sedimentary basins (the San Jorge and Magallanes basins) filled by Jurassic to Neogene volcano-sedimentary formations (Biddle *et al.* 1986; Ramos 1989) and separated by the Deseado Massif (e.g. Guido *et al.* 2004) (Fig. 1). Above these sedimentary formations, or interbedded within them, are found the Cenozoic volcanic formations that are the object of this work.

Along the southern sector of the Andean Cordillera, the Quaternary calcalkaline volcanic activity occurs down to the latitude of the Chile Triple Junction (~ 46° 30'S). Between 46° 30' and 49°S, Quaternary volcanoes are totally lacking. Between 49°S and 55°S (the Austral Volcanic Zone of the Andes; Futa and Stern, 1988; Stern and Kilian 1996), volcanic activity resumed in Quaternary time producing some active central volcanoes erupting magmas with adakitic signature.

The Cenozoic geodynamic evolution of southern South America was mainly controlled by the continuous subduction of Pacific oceanic plates under the South American Plate (Fig. 1). In addition, plate reconstruction models (Cande and Leslie 1986) indicate that, two episodes of ridge-trench collision have occurred since Eocene time. The first episode is not well constrained by the available data, but it took place during Eocene time when the oceanic ridge separating the Aluk and Farallon plates collided with the Chile Trench. The resulting triple point migrated southward probably in the time span from 52 to 42 Ma. The more recent episode occurred since 14-15 Ma when the Chile Ridge, separating the Nazca and Antarctic plates, collided with the Chile Trench at the latitudes of the Tierra del Fuego. In this case, due to the different plate boundary configuration, the resulting triple point migrated northward up to its present position close to the Taitao Peninsula (Fig. 1).

Many authors have invoked the middle Miocene to Present subduction of the Chile Ridge under the South American Plate as the dominant cause of several prominent geophysical, structural and magmatic features characterizing southern South America. The most important of these features are the following: 1) the volcanic gap between the Southernmost Southern Volcanic Zone (SSVZ) and the Austral Volcanic Zone (AVZ) of the Andes at the latitudes where the ridge-trench collision occurred recently (Futa and Stern, 1988); 2) the Neogene uplift of the Patagonian Cordillera south of the CTJ and the formation of the Patagonian fold-and-thrust belt (Ramos 1989); 3) the peculiar bimodal (basaltic andesites and dacites) magmatism occurring in the fore-arc region close to the Chile Triple Junctions (Guivel *et al.* 2003); 4) the anomalously low viscosity asthenosphere inferred by the rapid Holocene isostatic rebounds induced by the advances and retreats of the Patagonian icefields (Ivins and James, 1999); and 5) the extensive Cenozoic mafic magmatism occurring in the extra-Andean Patagonia between 46° 30' and 49° 30' S (Ramos and Kay 1992).

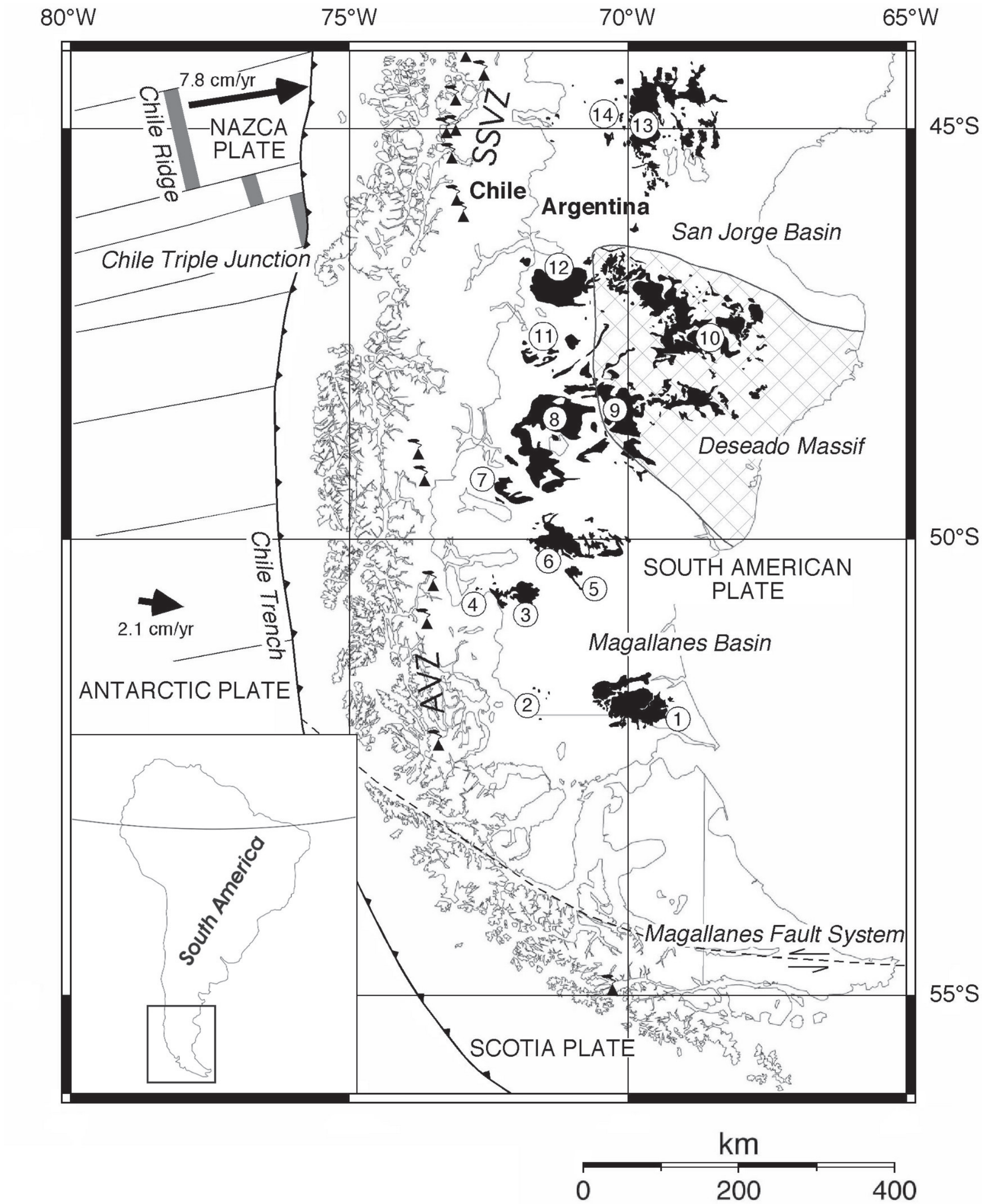

Figure 1: Schematic geodynamic setting of southern South America and adjacent Pacific Ocean. The sketch show the fracture zones of the oceanic Nazca and Antarctic plates (thin continuous lines), the Chile oceanic spreading ridge (grey strips), the Chile trench (heavy continuous line with triangles on the overriding plate), the transcurrent margin between the Scotia and South American plates (dashed line), the Chile Triple Junction, the main active volcanoes of the Southernmost Southern Volcanic Zone (SSVZ) and Austral Volcanic Zone (AVZ) of the Andes (filled smoking triangles), the Cenozoic Patagonian lavas (black areas), and the Deseado Massif (cross-hatched field). Circled numbers are the main Patagonian basalts occurrences cited in the text: 1, Pali Aike Volcanic Field (Late Pliocene-Quaternary); 2, Estancia Glencross Area (Late Miocene); 3, Meseta de las Vizcachas (Middle Miocene-Late Pliocene); 4, Cerro del Fraile (Late Pliocene-Quaternary); 5, Camusú Aike Volcanic Field (Late Pliocene); 6, Mesetas on the north side of Río Santa Cruz valley (Laguna Amenida –Condor Cliff area; Miocene ?-Late Pliocene); 7, Meseta del Viento (Early Pliocene-Late Pliocene); 8, Meseta de la Muerte and Meseta Strobel (Middle Miocene-Early Pliocene); 9, Meseta Central (Late Miocene-Late Pliocene); 10, Mesetas of the Deseado Massif region (Eocene-Late Pliocene); 11, Meseta Belgrano (Late Miocene-Late Pliocene); 12, Meseta del Lago Buenos Aires (Paleocene-Quaternary); 13, Sierra San Bernardo (Oligocene – Quaternary ?); 14, Río Genoa – Senguerr Valley (Pliocene - Quaternary ?). The two large, black arrows are the convergence vectors of the Nazca and Antarctic plates with respect to South America according to the NUVEL-1A model of DeMets *et al.* (1994).

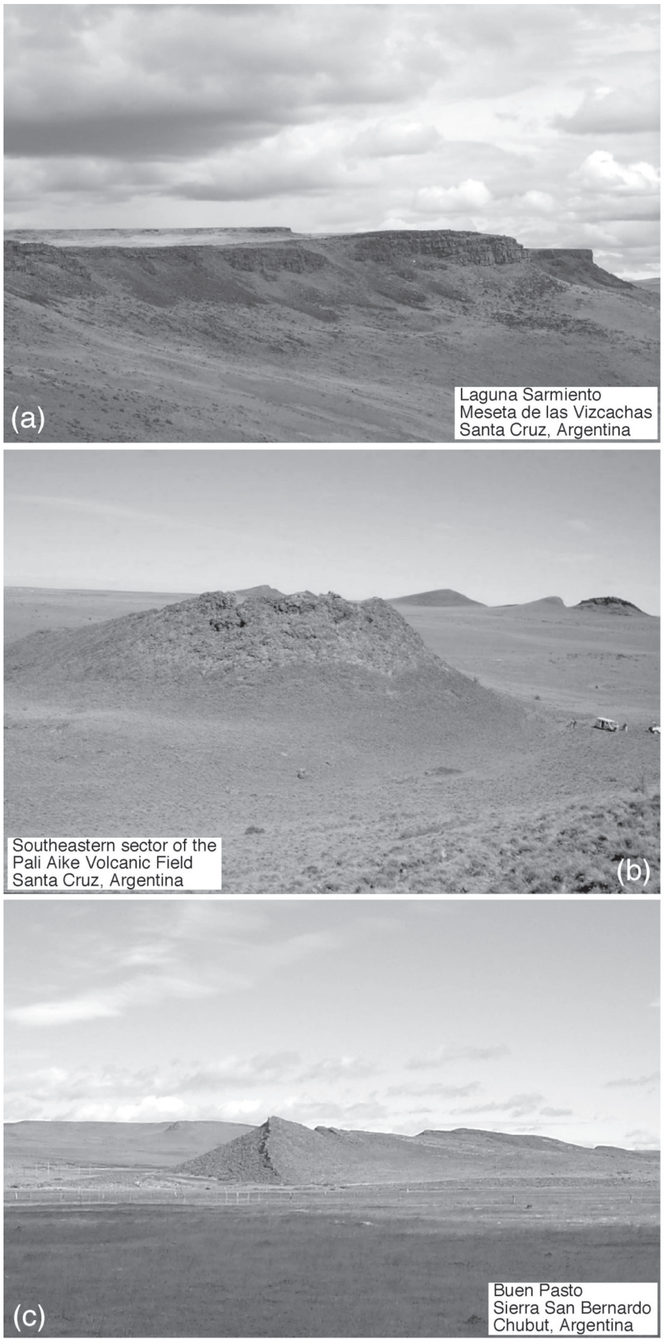

Figure 2: Examples of Cenozoic volcanic structures in southern Patagonia. a) plateau lavas along northern margin of Mesetas de las Vizcachas (Laguna Sarmiento; 50°29.4'S-71°50.6'W); b) monogenetic spatter and scoria cones (southeastern sector of the Pali Aike Volcanic Field; 52°05'S-69°33'W); c) tilted sequence of basalt flows (Buen Pasto; 45°03'S-69°27.7'W).

Main features of the extra-Andean Cenozoic magmatism south of 44° 30' S

Cenozoic mafic magmatism produced a wide discontinuous belt of exposed volcanic (and minor intrusive and sub-intrusive) rocks that covers the entire extra-Andean Patagonia from latitude ~ 38° S to latitude ~ 52° S, a surface area of about 60.000 km^2 (Fig. 1). Due to the extremely variable thicknesses of the volcanic formations, the volume of the exposed rocks has not yet been estimated with sufficient accuracy, but, it is likely between 5.000 and 10.000 km^3. To the south of 44° 30' S, volcanic rocks are found from the easternmost end of the Andean Cordillera up to 700 km east of the Chile Trench. Along the belt, the widest area without volcanic rocks occurs between 51°36'S and 50°54'S.

The most common volcanic structures occurring in this area are wide volcanic plateaux (mesetas) formed by successions of basaltic s.l. lava flows (Fig. 2a). Also common are lava fields erupted from monogenetic scoria and spatter cones (Fig. 2b). Other volcanic structures that could be locally abundant are maars and tuff rings (widespread in the Pali Aike Volcanic Field) and eroded volcanic necks and plugs. Volcanic rocks younger than Oligocene are generally tectonically undeformed, whereas older lavas are commonly gently folded or tilted, having been involved in the last deformative phases of the Andean Foothills (Fig. 2c).

The ages of the volcanic rocks range from Late Cretaceous (Ramos *et al.* 1982) – early Paleocene up to Holocene (Fig. 3). The magma eruption rate was not constant over this time span: indeed, the available data indicate major periods of magma eruption during middle Eocene, late Miocene and late Pliocene – Early Pleistocene periods.

Basaltic s.l. rocks, ranging from nepheline-normative basanites to quartz-normative basaltic andesites, dominate the Cenozoic magmatism of southern Patagonia. Slightly evolved volcanics (trachybasalts and basaltic trachyandesites) were found in several localities, such as the Camusú Aike Volcanic Field (~ 50° S; D'Orazio *et al.* 2004). Acidic volcanic rocks are rare: two notable exceptions are constituted by the Paleocene trachytes from Cerro Rosado (Ramos 2002) and the adakites from Cerro Pampa (Kay *et al.* 1993).

Major-element compositions

The composition of the Cenozoic magmatic rocks from southern Patagonia is reported in the total alkali vs. silica diagram of figure 4 (some selected analyses are presented in Table 1).

The total alkali content and alkali/silica ratios of the basaltic s.l. rocks in the study area are highly variable (Fig. 4). The distribution of the different types of magmatic rocks does not show any significant systematic geographic variation. Some authors (e.g. Ramos and Kay, 1992; Gorring *et al.* 1997) emphasized that, in the region comprised between 46.5 and 49.5°S (the latitudes where the collision between the Chile Ridge and the Chile Trench was younger than 12 Ma) the volcanic activity in each area started with the voluminous effusion of subalkaline or moderately alkaline "main-plateau" lavas and was followed by the less voluminous eruption of more alkaline "post-plateau" lavas. This transition is best

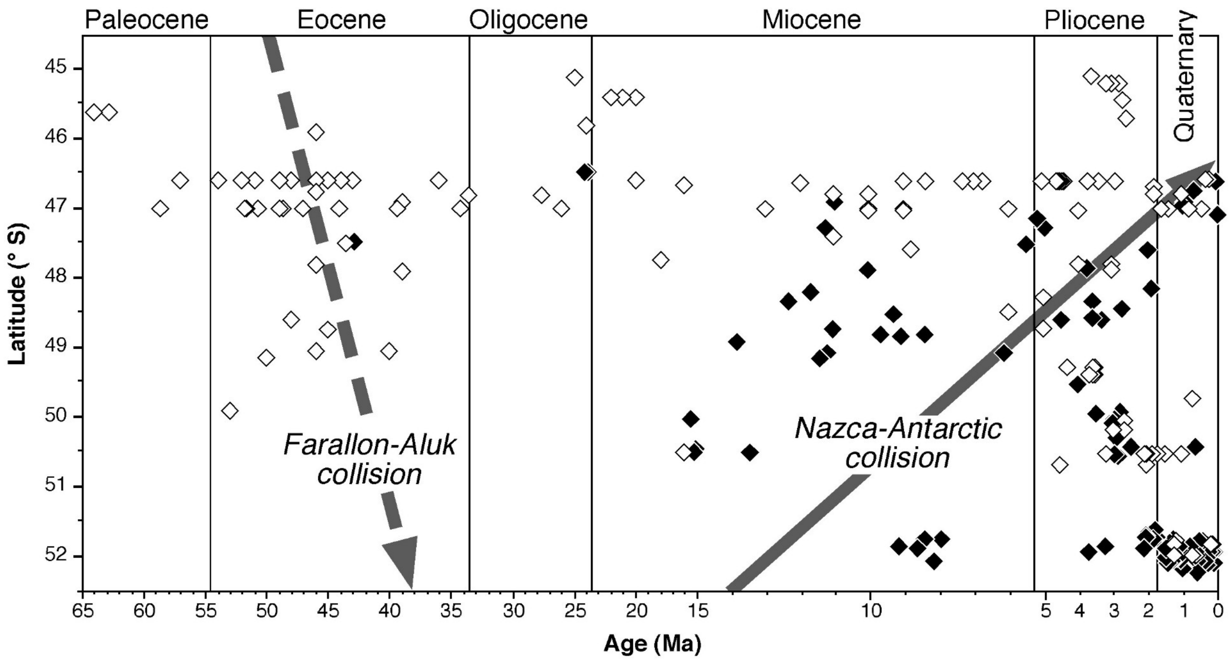

Figure 3: Literature isotopic ages (Ma) of Cenozoic southern Patagonia mafic lavas as a function of their latitude. Empty diamonds, K-Ar data; black diamonds, ^{40}Ar-^{39}Ar data. The grey arrows represent the latitudinal time-migration of the triple points resulting from the collisions between the Farallon-Aluk ridge and the Nazca-Antarctic ridge with the Chile Trench. The coordinates of many dated samples are approximate as the precise locations of these samples were not given in the corresponding original papers. Data mainly from Charrier et al. (1979); Sinito (1980); Baker *et al.* (1981); Mercer and Sutter (1982); Linares and Gonzalez (1990); Meglioli (1992); Gorring *et al.* (1997); Mejia *et al.* (2004) and authors' unpublished data.

developed in the Mesetas de la Muerte, Belgrano and Central (Gorring *et al.* 1997). In the region south of 49° 30' S and north of 46° 30' S, this temporal evolution is much less evident or is not observed at all.

Silica-undersaturated rocks

Basanite lavas with normative nepheline > 10 wt.% are commonly found in three localities: the Pali Aike Volcanic Field (Skewes and Stern 1979; D'Orazio *et al.* 2000), in the post-plateau volcanic sequence of the Meseta del Lago Buenos Aires (Baker *et al.* 1981; Gorring *et al.* 2003) and along the Río Genoa-Senguerr valley (Bruni 2003). The basanites from the latter two localities are very similar in composition whereas those from Pali Aike can be distinguished for their lower contents of $Na_2O + K_2O$ and Al_2O_3. These strongly undersaturated basanite lavas share high TiO_2 (2.2 – 4.1 wt.%) and MgO (6.1 – 12.7 wt.%) concentrations. Some samples from the Pali Aike and Río Genoa-Senguerr valley have extremely high MgO contents (14-16 wt.%) due to the presence of olivine xenocrysts from disrupted mantle peridotite xenoliths.

Strongly undersaturated foid-bearing rocks have been found in the area close to the "Monumento Natural Bosque Petrificado" (~ 47°44' S 68°32' W, Santa Cruz Province; Panza and Franchi 2002).

Moderately silica-undersaturated rocks (normative nepheline from 0.1 to 9.5 wt.%) made up ~ 42% of the samples of the used database. These rocks are commonly found within most of the volcanic formations of southern Patagonia as alkali basalts, basanites, trachybasalts (both hawaiites and potassic trachybasalts) and mugearites (Fig. 4). The geochemical variability of this group of rocks is wider as indicated by the range of concentrations of TiO_2 (1.4 – 3.9 wt.%), MgO (2.2 – 13.9 wt.%), K_2O (0.6 – 4.1 wt.%) and P_2O_5 (0.3 – 1.3 wt.%). In particular, many samples from the Meseta de las Vizcachas and the Meseta Central are characterized by lower contents of TiO_2 (1.4 – 1.8 wt.%) with respect to the other undersaturated samples.

Silica-saturated rocks

Silica-saturated rocks with ol > hy are also common in most of the southern Patagonia volcanic occurrences. They are found as transitional basalts, hawaiites and rare mugearites.

Silica-saturated rocks with hy > ol are subalkaline basalts, transitional basalts, basaltic andesites and rare hawaiites and mugearites (Fig. 4). These lavas form portions of the voluminous "main-plateau" sequence of the volcanic formations occurring between 47.5 and 49° 30' S (e.g. Meseta de la Muerte, Meseta Central, Meseta Belgrano). To the south of 49° 30' S silica-saturated rocks with hy > ol were commonly sampled in the Meseta de las Vizcachas, Camusú Aike, Ea. Glencross Area and in the

Table 1: Selected analyses of Cenozoic southern Patagonia mafic volcanic rocks

Sample	CV-02s	GB-1	PA-222	PA-400	PA-390	MS-13b	PA-224	MP-8	PA-325	MOL-3a	PA-279	VL-1f	MI-5	PA-303	PA-281	RB-4a	PA-265	PA-318	PL-6b	PA-415
Locality	MLBA	MC	PAVF	RGSV	CA	MM	PAVF	MC	TC	MM	MDLV	MV	MD	CAVF	MDLV	MB	EGA	CAVF	MB	SSB
Reference	4	1	2	6	6	1	2	1	6	1	6	1	1	5	6	1	3	5	1	6
Lat. S	46°35.4'	48°34'	52°02.2'	45°11.9'	44°42.6'	49°04'	52°07.8'	48°19'	48°03'	48°54'	50°31.4'	49°32'	47°30'	50°20.8'	50°31.4'	47°50'	51°49.5'	50°23.3'	47°43'	44°42.3'
Long. W	70°40.5'	70°11'	70°01.4'	69°58.4'	70°46.2'	71°32'	69°33.3'	69°54'	67°34.5'	70°39'	71°40.1'	72°20'	68°28'	71°13.3'	71°40.1'	70°49'	71°18.5'	71°02.4'	71°03'	69°36.9'
SiO_2 (wt%)	44,03	44,92	43,84	46,83	46,83	47,90	47,40	50,45	50,32	49,84	48,47	49,01	53,31	48,70	48,84	51,40	51,04	55,24	52,88	53,35
TiO_2	2,77	2,98	3,81	3,06	1,62	2,52	2,84	3,21	1,93	1,67	1,48	1,98	1,78	3,03	1,40	1,43	2,78	1,92	1,77	1,59
Al_2O_3	14,39	13,91	11,44	14,47	13,70	15,50	12,38	15,32	14,73	15,32	14,82	15,20	15,43	15,85	14,26	15,71	13,18	14,42	16,22	15,46
Fe_2O_3 tot	11,29	11,20	13,49	11,27	9,33	11,29	11,75	10,64	11,65	11,13	10,65	11,53	10,67	13,72	10,80	11,02	12,03	10,62	10,99	10,99
MnO	0,21	0,17	0,17	0,14	0,14	0,15	0,16	0,14	0,15	0,16	0,15	0,16	0,12	0,18	0,15	0,11	0,16	0,13	0,18	0,15
MgO	9,58	7,56	10,07	7,76	10,08	7,85	11,29	6,35	7,57	7,21	9,96	9,21	7,03	4,18	10,70	6,24	7,01	6,88	6,04	6,42
CaO	10,92	12,41	11,26	7,51	9,61	8,12	8,97	6,48	8,21	8,50	9,42	8,53	7,97	7,49	8,97	9,53	8,73	8,40	8,31	8,06
Na_2O	3,74	3,33	3,27	4,17	2,21	3,87	3,07	4,53	4,18	3,71	2,48	3,30	4,12	3,59	2,60	3,58	3,18	3,17	3,69	3,40
K_2O	2,32	2,59	1,94	3,09	4,14	2,15	1,26	2,99	0,75	1,05	1,21	1,25	0,51	1,45	1,24	0,50	1,00	0,64	0,95	0,57
P_2O_5	1,11	1,19	0,77	0,88	0,92	0,83	0,58	1,04	0,35	0,32	0,28	0,47	0,21	0,74	0,28	0,19	0,36	0,27	0,37	0,21
LOI			0,57	0,55	0,46		0,69		0,62		3,07			1,00	1,46		1,49	1,14		0,30
Q (wt.%)																	0,3	5,6	0,3	2,7
ne	15,4	13,4	12,3	10,4	8,1	6,7	1,3	4,2												
hy									0,9	3,1	7,6	1,1	18,1	13,0	7,2	16,3	20,0	20,9	21,6	22,4
ol	15,9	9,8	15,1	15,6	18,0	16,3	21,4	14,0	16,4	14,5	15,7	19,8	2,8	5,0	17,6	2,8				
Sc (ppm)	29	11,8	22	16	29	20,9	24	13,4	17	20	24	23,8	17,9	18	24	18,8	20	18	23,7	18
V			250	180	260		220		169		201			167	198		182	154		150
Cr	322	229	312	180	507	249	405	144	223	246	483	353	267	2	513	215	246	214	304	238
Co	47	42	54	40	42	47	57	37	42	45	44	51	42	34	47	45	46	39	42	40
Ni	174	214	176	147	174	172	290	125	162	158	222	201	147	11	257	123	178	140	120	125
Rb			35	57	219		24,2	60	9,8	31,5	18,9	27,5		21,1	26,6		21,6	10,6		9,8
Sr	1097	1279	876	932	858	846	635	1037	545	665	559	592	413	539	476	372	453	373	459	316
Y			27,8	25,8	24,8		25,0	25,4	19,4	22,8	19,1	23,7		44	20,1		25,2	20,4		19,9
Zr			264	379	331		211	457	123	148	112	206		356	107		171	118		87
Nb	78	76	68	74	14,2	53	45	90	28,8	25,1	12,2	28,8	11,1	46	12,2	8,6	26,0	13,6	20,5	12,4
Cs	0,44	0,91	0,56	0,96	7,00	0,90	0,40	0,58	0,04	0,51	0,19	0,74	0,47	0,35	1,46	0,34	0,40	0,44	0,75	0,28
Ba	739	754	599	646	477	516	388	895	271	332	207	283	161	396	252	135	211	163	274	127
La	66	53	44	65	37	47	31,1	57	26,6	27,5	16,1	26,0	9,2	41	17,8	9,0	19,2	13,7	18,2	9,5
Ce	127	111	87	126	94	96	63	115	46	56	33	55	21,0	87	38,0	19,5	41	26,9	40	19
Pr			11,2	14,8	13,8		8,2	12,1	5,4	6,4	4,3			11,6	4,7		5,5	3,8		2,6
Nd	56	51	47	58	59	45	35	57	21,8	25,0	18,2	26,6	11,6	50	20,0	13,4	24,8	17,4	21,8	12,0
Sm	10,1	10,5	9,9	11,1	9,3	8,3	7,8	10,4	5,1	5,2	4,2	5,7	3,4	11,3	4,5	3,6	6,5	4,9	5,3	3,4
Eu	2,96	3,4	3,16	3,26	2,21	2,51	2,54	3,4	1,77	1,60	1,42	1,72	1,35	3,7	1,40	1,16	2,31	1,84	1,63	1,39
Gd			9,1	8,5	6,4		7,4	7,9	4,7	4,6	4,3			10,9	4,5		6,8	5,2		3,7
Tb	1,14	1,20	1,23	1,15	0,86	0,98	1,04	1,13	0,68	0,75	0,60	0,80	0,60	1,59	0,63	0,59	0,99	0,78	0,85	0,62
Dy			6,1	5,7	4,6		5,2	5,5	3,7	4,1	3,8			8,5	3,8		5,1	4,1		3,7
Ho			1,06	0,93	0,88		0,97	0,88	0,66	0,77	0,72			1,60	0,74		0,92	0,74		0,69
Er			2,34	2,10	2,25		2,06	1,90	1,61	2,02	1,81			4,0	1,90		2,21	1,81		1,71
Tm			0,32	0,27	0,32		0,31	0,24	0,23	0,30	0,27			0,56	0,30		0,32	0,25		0,25
Yb	1,99	1,46	1,65	1,45	2,04	2,03	1,66	1,31	1,17	1,70	1,57	1,87	1,25	3,17	1,69	1,49	1,64	1,41	2,04	1,44
Lu	0,27	0,18	0,23	0,17	0,29	0,29	0,24	0,19	0,17	0,25	0,23	0,26	0,16	0,45	0,24	0,22	0,22	0,19	0,30	0,19
Hf	6,7	8,1	6,0	8,3	9,4	7,3	5,0	8,9	2,84	3,4	2,95	4,2	2,29	8,2	2,88	2,28	4,3	2,98	3,5	2,3
Ta	4,76	4,6	3,9	4,7	0,88	3,23	2,71	5,1	1,55	1,44	0,79	1,75	0,68	2,83	0,75	0,53	1,66	0,80	1,26	0,82
Pb	5,4		2,66	5,6	4,7		2,47	5,9	2,78	4,44	3,08	3,4		4,4	6,30		2,95	1,50		1,49
Th	7,8	7,4	5,2	7,7	11,6	5,7	3,4	7,7	3,5	4,2	3,4	3,5	1,22	4,0	5,08	1,12	2,81	1,53	2,62	1,27
U	1,90	2,01	1,52	2,04	3,5	1,66	1,03	1,73	0,38	0,93	0,62	0,99	0,36	1,01	1,26	0,50	0,85	0,44	0,78	0,36

MLBA, Meseta del Lago Buenos Aires; MC, Meseta Central; PAVF, Pali Aike Volcanic Field; RGSV, Río Genoa-Senguerr Valley; CA, Cerro Ante; MM, Meseta de la Muerte; TC, Tres Cerros; MDLV, Meseta de las Vizcachas; MV, Meseta del Viento; MD, Mesetas in the Deseado Massif region ; CAVF, Camusú Aike Volcanic Field; MB, Meseta Belgrano; EGA, Estancia Glencross Area; SSB, Sierra San Bernardo. References: 1, Gorring (1997); 2, D'Orazio et al. (2000); 3, D'Orazio et al. (2001); 4, Gorring et al. (2003); 5, D'Orazio et al. (2004); 6, authors' unpublished data.

wide area surrounding Laguna Amenida. Within this group, the volcanic rocks from Camusú Aike and Ea. Glencross Area can be clearly distinguished for their higher TiO_2 concentration (> 2.6 wt. %).

Silica-oversaturated rocks

Silica-oversaturated rocks are mainly basaltic andesites and rare subalkaline basalts and mugearites (Fig. 4). They occur frequently within the "main-plateau" sequences of the Meseta de la Muerte, in the Laguna Amenida – Condor Cliff area and in the Sierra San Bernardo. Morro Philippi (one of the five "morros" that constitute the late Miocene Estancia Glencross Area volcanics; D'Orazio *et al.* 2001) is entirely built of silica-oversaturated basaltic andesites. This is also the composition of the youngest lavas erupted in the Camusú Aike volcanic field.

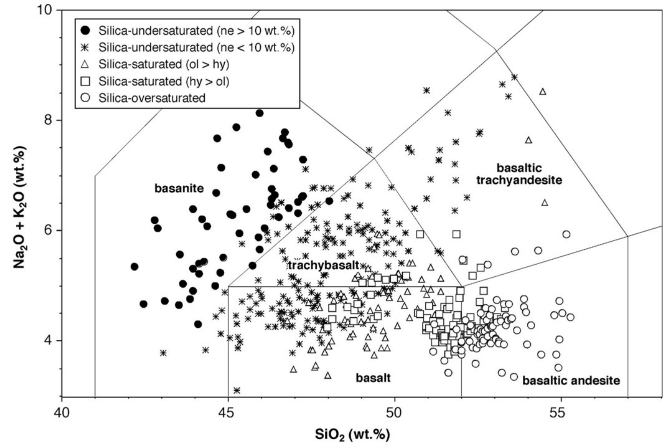

Figure 4: Total alkalis vs. silica diagram for the Cenozoic southern Patagonia mafic volcanics between 44° 30' and 52° S. Samples are subdivided according to the degree of silica saturation. The very rare occurrences of acidic volcanic rocks have been omitted.

Incompatible element distributions

Patagonian volcanics with within-plate basalt signature

The large majority of Patagonian volcanic rocks exposed south of 44° 30' S are characterized by an incompatible element distribution typical of the within-plate basalts. This distribution is marked by an overall enrichment of the most incompatible elements with a maximum enrichment of Nb and Ta (Fig. 5). This kind of distribution of the incompatible elements was found for all lava types, from silica-undersaturated basanites (Fig. 5a) to silica-oversaturated basaltic andesites (Fig. 5b).

Patagonian volcanics with more complex geochemical signature

A large number of samples, mainly from the mesetas de la Muerte, de las Vizcachas, Central and Belgrano, but also from Camusú Aike, Cerro del Fraile, Sierra San Bernardo and the Laguna Amenida – Condor Cliff area, show complex incompatible element distributions (Fig. 5c). In particular, these lavas have high LILE/HFSE and LREE/HFSE ratios (e.g. Ba/Nb > 15 and La/Nb > 1; LILE = large ion lithophile elements, HFSE = high field strength elements, LREE = light rare earth elements). These geochemical imprints were mostly found in subalkaline lavas and in some alkali basalts, but are very rare in the strongly undersaturated basanites. In the diagram of Fig. 6 are plotted the available Nb and Ba concentrations of the southern Patagonia mafic volcanic rocks: the large majority of the samples are characterized by Ba/Nb ratios close to those of within-plate basalts, whereas a small number of samples from the localities cited above have higher Ba/Nb, pointing toward the typical arc values measured for the SSVZ and AVZ of the Andes (e.g. Hickey *et al.* 1986; Stern and Kilian 1996; D'Orazio *et al.* 2003). It is worth noting that all of the volcanic rocks that show these peculiar geochemical features are located in the western or central sectors of the study area.

Rare Earth Element distributions

The shape of the chondrite-normalized REE patterns of most southern Patagonia mafic lavas is LREE –enriched and roughly rectilinear with rare occurrences of slight, positive Eu anomalies (maximum Eu/Eu* = 1.3). The whole range of LREE/HREE ratios is very large, from the highest values shown by the strongly undersaturated basanites ($[La/Yb]_N$ = 13.7 – 36.3) to the lowest values of the Q-normative basaltic andesites ($[La/Yb]_N$ = 2.7 – 10.4). The large variation of the La/Yb ratios is due to the variable enrichment of the LREE more than to the variability of the HREE; indeed, the La_N and Yb_N values of the whole data set vary over a factor of 18 and 9, respectively.

The observed positive correlation between LREE/HREE fractionation and the content of the most incompatible elements may imply for a relation between the degree of melting and the role of residual garnet during mantle melting. The fractionation of olivine or olivine plus clinopyroxene (the main phenocryst phases of primitive lavas from southern Patagonia) induces only negligible variations in the $[Sm/Yb]_N$ ratio, whereas the $[La/Sm]_N$ ratio could be affected by the fractionation of clinopyroxene (Fig. 7). However, unless the fraction of segregated clinopyroxene is very high (> 25 wt%), the variations are within the analytical uncertainty. Hence, we can safely assume that the $[Sm/Yb]_N$ and $[La/Sm]_N$ ratios measured in the primitive southern Patagonia volcanics are very close to those of the primary magmas from which they derived. The high and variable values of both $[Sm/Yb]_N$ and $[La/Sm]_N$ of the ne-normative samples are indicative of low degrees of partial melting in the presence of varying proportions of residual garnet. The very low degree of melting required to reach $[La/Sm]_N$ values > 3.5

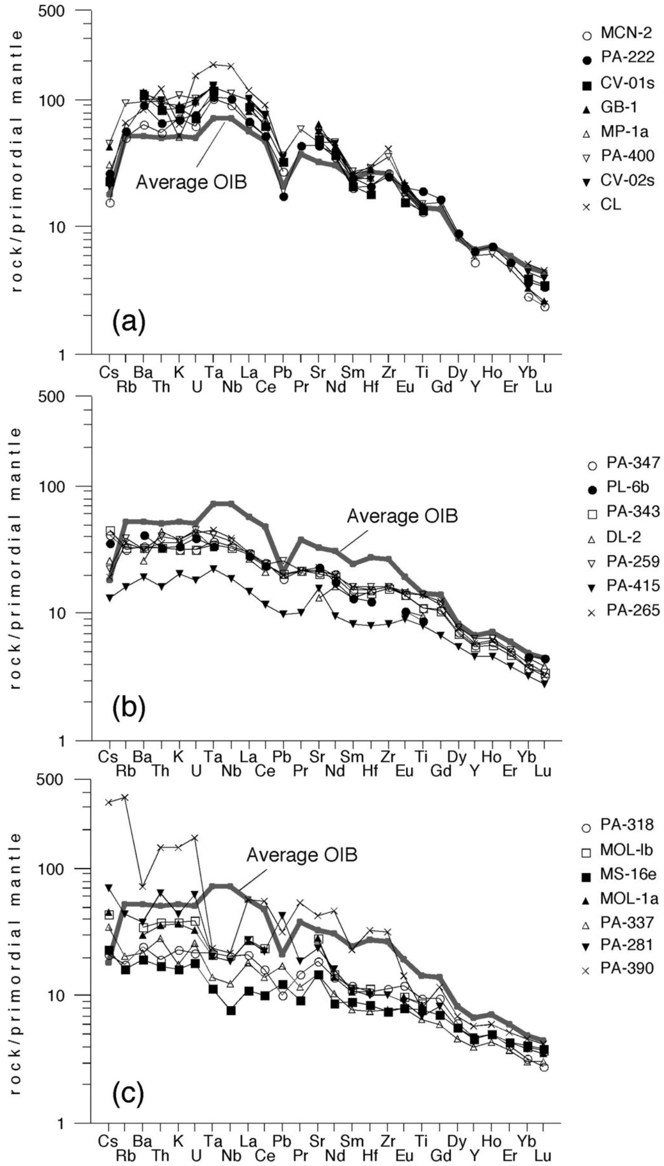

Figure 5: Primordial mantle-normalized incompatible element patterns for selected Cenozoic southern Patagonia mafic volcanic rocks. (a) Basanites with normative nepheline > 10 wt.%; (b) Quartz-normative basaltic andesites, (c) samples with more complex incompatible element distributions. In the diagrams, the average OIB of Sun and McDonough (1989) is also plotted for comparative purposes. Normalizing values after McDonough and Sun (1995). Data sources: Gorring (1997): MOL-1a, MOL-1b, MS-16e (Meseta de la Muerte), GB-1, MP-1a (Meseta Central), MCN-2 (Meseta NE), PL-6b (Meseta Belgrano), DL-2 (Cerro del Fraile); D'Orazio et al. (2000): PA-222 (Pali Aike); D'Orazio et al. (2001): PA-259, PA-265 (Estancia Glencross Area); Gorring et al. (2003): CV-02s (Meseta del Lago Buenos Aires); D'Orazio et al. (2004): PA-318 (Camusú Aike); authors' unpublished data: PA-281 (Meseta de las Vizcachas), PA-337, PA-343, PA-347 (Condor Cliff – Laguna Amenida area), PA-390 (Cerro Ante), PA-415 (Sierra San Bernardo).

by melting a peridotite source with chondritic REE distribution could suggest that the source of these magmas already had a fractionated REE pattern before melting. The lowest observed $[Sm/Yb]_N$ ratios (~ 2.2) were measured on primitive subalkaline lavas, which indicates that either their mantle sources had fractionated REE patterns, or that even these subalkaline magmas originated in equilibrium with residual garnet.

In summary, the available REE data strongly suggest a deep (> 75 km) origin, in the garnet-peridotite stability field, for the alkaline magmas. The REE distributions of the subalkaline lavas suggest either a higher degree of melting of the same source or an even higher degree of melting of a LREE-enriched source. In this case, the source could be in the spinel-peridotite stability field.

Sr-Nd-Pb isotope composition

The range of Sr, Nd and Pb isotope compositions of the southern Patagonia volcanic rocks is wide ($^{87}Sr/^{86}Sr$ = 0.70316 – 0.70555, $^{143}Nd/^{144}Nd$ = 0.51262 - 0.51294, $^{206}Pb/^{204}Pb$ = 18.08 – 19.38, $^{207}Pb/^{204}Pb$ = 15.53 – 15.74, $^{208}Pb/^{204}Pb$ = 38.21 – 39.23), but well within the interval defined by within-plate magmas. The major systematic variations are related to latitude: samples erupted in the southernmost region (substantially in the Pali Aike, Ea. Glencross Area, Meseta de las Vizcachas and Camusú Aike) have lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ values with respect to the majority of Patagonian lavas, erupted north of ~ 50° S (Fig. 8). On a wider regional scale, the volcanic rocks from southernmost Patagonia are isotopically similar to the Neogene post-subduction mafic volcanic rocks of the Antarctic Peninsula, whereas the majority of Patagonian lavas north of 50° S are isotopically more similar to the Quaternary volcanic rocks from the SSVZ of the Andes. In the $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ isotope space (not shown), all the southern Patagonia lavas plot above the Northern Hemisphere Reference Line, falling in the Southern Hemisphere Dupal Pb isotope anomaly (Hart 1984).

Geochemical reservoirs involved in the genesis of the Cenozoic southern Patagonia mafic magmas

Depleted and enriched asthenospheric mantle

The geochemical and Sr-Nd-Pb isotopic features of the magmas erupted in the southernmost end of Patagonia (e.g. Pali Aike, Ea. Glencross Area) are indicative of a deep, relatively depleted mantle source. Likely, this mantle source could be the asthenospheric mantle underlying this sector of the southern South America, possibly extending to the region beneath the Antarctic Peninsula (Hole *et al.* 1993, 1995; D'Orazio *et al.* 1999). Besides the low $^{87}Sr/^{86}Sr$ ratios (< 0.7038) and high $^{143}Nd/^{144}Nd$ ratios (> 0.51285) this mantle is characterized by radiogenic Pb isotope composition ($^{206}Pb/^{204}Pb$ > 18.5, $^{207}Pb/^{204}Pb$ > 15.6, $^{208}Pb/^{204}Pb$ > 38.6), pointing toward a HIMU-like isotopic signature.

An isotopically more enriched asthenospheric domain could be the main source of the magmas erupted north of

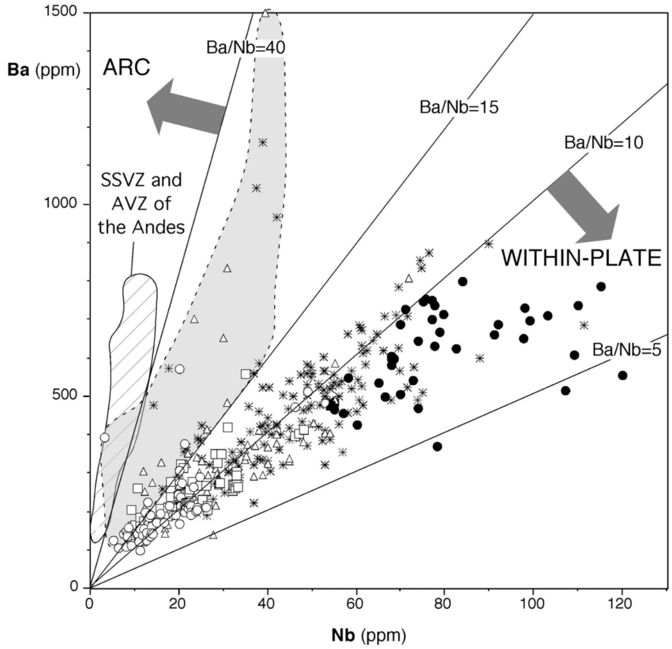

Figure 6: Ba vs. Nb diagram for the Cenozoic southern Patagonia mafic volcanics between 44° 30' and 52° S. Most samples have Ba/Nb ratios < 15, close to the typical values of the within-plate basalts, whereas some samples are characterized by higher values, pointing to the values of arc-related magmas. The field for the volcanic rocks from the Southernmost South Volcanic Zone and the Austral Volcanic Zone of the Andes is plotted for comparative purposes (see the caption of Fig 8 for SSVZ and AVZ data sources). Same symbols as figure 3.

50° S, implying the occurrence of a major discontinuity in the isotopic composition of the asthenosphere of southern Patagonia.

Enriched sub-continental lithospheric mantle

As an alternative to the presence of a large - scale heterogeneity in the asthenosphere under the study area, Gorring and Kay (2001) and Gorring *et al.* (2003) proposed that some of the geochemical signatures of the magmas erupted in the region between 46.5 and 49.5 °S, and not modified by crustal or subduction-related components, were derived from an enriched reservoir located in the sub-continental lithospheric mantle. For the alkaline "post-plateau" lavas from the Meseta del Lago Buenos Aires, Gorring *et al.* (2003) invoked the occurrence of components derived from a heterogeneous sub-continental lithosphere containing both EM2- and EM1-type enriched domains.

Several recent studies of the ultramafic mantle xenoliths hosted in some volcanic rocks indicate that different metasomatizing agents have chemically enriched the Patagonian lithospheric mantle. Kilian and Stern (2002) studied a series of mantle xenoliths from a near back-arc setting (Cerro del Fraile), identifying a slab-melt with adakitic signature as the metasomatizing agent. Gorring and Kay (2000) recognized a relatively recent (< 25 Ma) carbonatite metasomatism for a suite of mantle xenoliths from Meseta Central, whereas Laurora *et al.* (2001) interpreted similar data as evidence of the percolation of aqueous fluids or silicate melts, possibly deriving from a subducted slab, through a depleted mantle lithosphere. More recently, Rivalenti *et al.* (2004) proposed that the incompatible element distribution of bulk rocks and pyroxenes of mantle xenoliths from several localities of central and southern Patagonia were induced by a complex process in which a hydrous component released from the subducting slab (in the near back-arc) or from the garnet-facies asthenosphere (in the far back-arc) triggers melting in the mantle wedge. These melts then rise by reactive porous flow through the overlying mantle lithosphere, enriching it.

The dominant Phanerozoic age of the oldest basement rocks and the evidence for a thin (< 100 km) lithosphere under southern Patagonia (Stern *et al.* 1999) indicate that the lithosphere under this area stabilized in relatively recent time (probably < 500 Ma), so that a highly enriched isotopic composition did not have enough time to develop. Indeed, the isotopic data on these mantle xenoliths (to date available just for the Pali Aike and a single locality of Meseta Central) show depleted compositions (Kempton *et al.* 1999; Stern *et al.* 1999; Gorring and Kay 2000; Fig. 8).

In summary, the available isotopic data do not point to the continental lithospheric mantle as a potential isotopically enriched reservoir for the southern Patagonia magmas erupted north of 50° S; on the contrary, the chemical data indicate that enrichment processes were active in the past. Hence, the occurrence of isotopically and chemically enriched domains in lithospheric mantle under southern Patagonia, but that were not sampled by mantle xenoliths, cannot be excluded. One of the major Phanerozoic tectono-magmatic events that could have been responsible for the creation of an enriched domain in the lithospheric mantle is that related to the Middle Jurassic silicic magmatism of the Chon Aike Province (e.g. Pankhurst *et al.* 1998). This large-volume anatectic magmatism developed during the early stages of Gondwana break-up and was probably associated to the underplating of mafic magmas from a mantle plume at the base of the continental lower crust (Riley *et al.* 2001). Lithospheric mantle domains with Sr and Nd isotope composition matching that of most southern Patagonia lavas north of 50° S can be obtained by veining, in Middle Jurassic time, of an isotopically depleted lithospheric mantle with less than 10 wt.% OIB-type melts.

Magma contamination by crustal materials vs. source contamination by subduction-related components

The southern Patagonia volcanic rocks showing relatively high LILE/HFSE and LREE/HFSE ratios suggest the role of additional components in their genesis. These components could have contaminated magmas during their ascent to the surface and/or could have modified

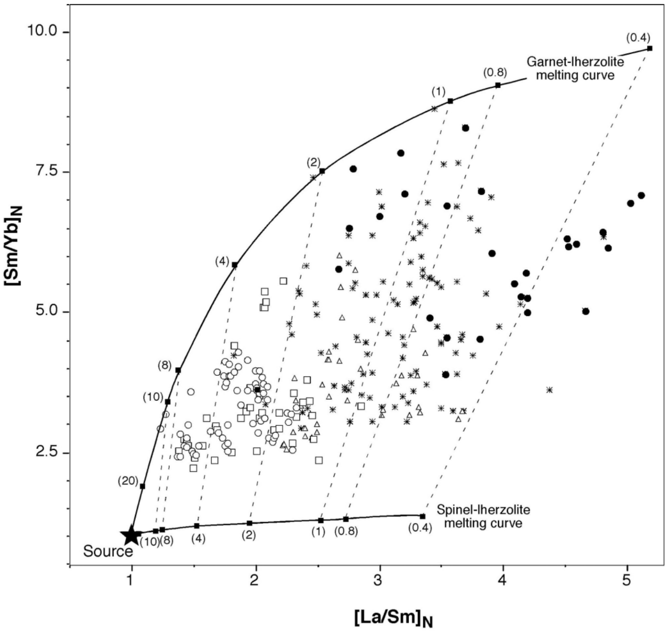

Figure 7: $[Sm/Yb]_N$ vs. $[La/Sm]_N$ diagram for the Cenozoic southern Patagonia mafic volcanics rocks. Only samples with MgO > 6 wt.% are plotted. The non-modal batch equilibrium melting curves of a garnet-lherzolite and a spinel-lherzolite with chondritic REE distribution are also shown. Numbers in parentheses represent the degree of melting (wt.%). Initial mineral modes, melting proportions and REE mineral/melt partition coefficients from McKenzie and O'Nions (1991). Same symbols as in figure 3.

their mantle sources. The materials that may impart such geochemical imprints to magmas are the continental crust and the fluids/melts released from the subducting slabs.

Within the data base used for the preparation of this work, less than 10% of the samples have Mg# values < 50. The magmas these samples represent had enough time to differentiate en route to the surface or, more likely, within crustal ponding levels. Hence, we should have more chances to find the effects of crustal contamination processes by examining the geochemical features of these differentiated samples. However, with the exception of the hawaiite sample PL-9 from Meseta Belgrano, the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of the most differentiated (Mg# < 50) southern Patagonia samples ($^{87}Sr/^{86}Sr$ = 0.70352-0.7423, $^{143}Nd/^{144}Nd$ = 0.51271-0.51291) fall within the range of the most primitive (Mg# > 65) lavas from the same region. These latter, besides their near primary composition, generally have relatively high contents of Sr and Nd, and frequently host mantle xenoliths and xenocrysts, and are thus considered unaffected by crustal contamination. In particular, the hawaiites from the Camusú Aike volcanic field (Mg# = 42 – 49) have Sr-Nd isotope compositions among the most depleted of the whole data set, close to those of the Pali Aike near primary alkaline lavas.

A strong evidence for the occurrence of subduction-related components in the source of some southern Patagonia magmas comes from the peculiar incompatible element distribution of several lavas from the westernmost sectors of the study area. The highly primitive (Mg# = 71 – 72) basanites from the Cerro Ante monogenetic cone (44°42.5' S 70°46' W, Chubut Province) show well marked negative Nb and Ta anomalies, high content of the alkaline elements (Cs, Rb, K) and less marked negative Ti anomalies (Fig. 9). Similar features, but at a lesser extent, characterize the subalkaline, middle Miocene lavas from the Mesetas de las Vizcachas, which also show positive Pb anomalies (Fig. 9). The Sr-Nd isotopic compositions of the Cerro Ante volcanics have not been determined yet, while the available data for the Meseta de las Vizcachas lavas vary within a wide interval ($^{87}Sr/^{86}Sr$ = 0.70350 – 0.70415 and $^{143}Nd/^{144}Nd$ = 0.51276 – 0.51290).

We think that most primitive Patagonian lavas with high LILE/HFSE and LREE/HFSE ratios derive these geochemical features from a contamination of their sources by materials transferred from the oceanic slabs into the asthenospheric wedge or the basal continental lithospheric mantle during the long subduction history of the Pacific margin of South America. Only locally, magma could fractionate at shallow levels assimilating a small fraction of crustal materials.

Geodynamic interpretations

"Sub-slab" models - slab window

The early work of Charrier *et al.* (1979) pointed out that the Triple Junction among the Nazca, Antarctic and South American Plates faces the Meseta del Lago Buenos Aires, describing for the first time the two olivine basaltic units separated by sediments which conform the Meseta. Charrier *et al.* (1979) did not find a direct relationship between the basalts and the Triple Junction. Later, Ramos and Kay (1992) proposed that the basalts of extra-Andean Patagonia between 46 and 49° S originated in close relation to slab window openings under this area, associated with the ridge-trench collisions that occurred along the Chile Trench during Eocene and middle Miocene to Present time. The slab window models for the Neogene magmatism of southern Patagonia were reinforced and refined by new geochemical and geochronological data (Gorring *et al.* 1997, 2003; D'Orazio *et al.* 2000, 2001, 2004; Gorring and Kay 2001). In particular, the data presented by Gorring *et al.* (1997) demonstrated that, in the area between 46° 30' and 49° 30' S, the volcanic activity evolved from the voluminous effusion of subalkaline plateau lavas (the "main-plateau sequence") to the less voluminous effusion of more alkaline lavas, generally from monogenetic cones (the "post-plateau sequence"). This regular evolution of the magmatism is best developed in the Mesetas del Lago Buenos Aires, de la Muerte, Central and in the mesetas overlying the Deseado Massif region. The geochronological data presented in the same paper revealed a rough correlation between the age of the "main-plateau" and "post-plateau" volcanic activity and the eastward movement of the trailing age of the Nazca Plate. In addition, these data

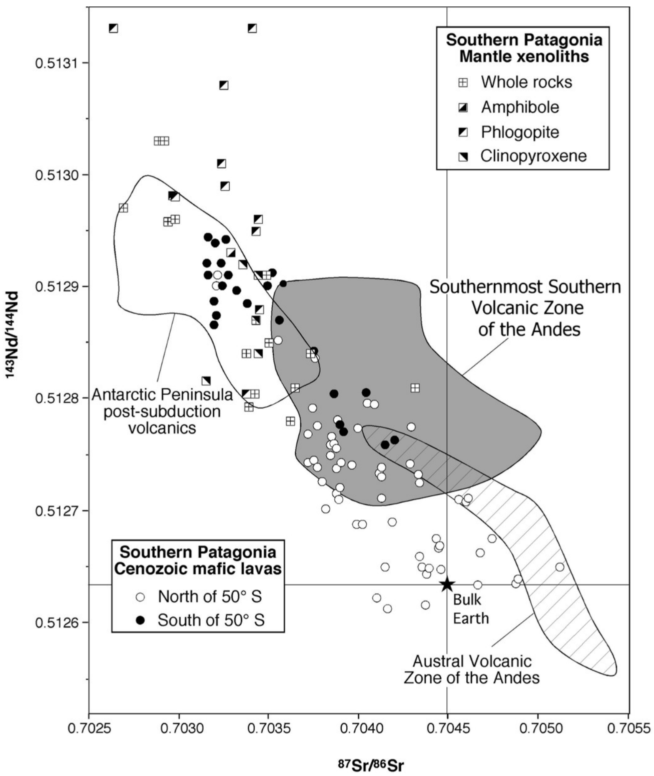

Figure 8: $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ diagram for the southern Patagonia Cenozoic mafic volcanic rocks (Stern et al., 1990; Gorring, 1997; D'Orazio et al., 2000, 2001, 2004; Gorring et al., 2003) and for the southern Patagonia mantle xenoliths (Kempton et al., 1999; Stern et al., 1999; Gorring and Kay, 2000). Also shown are the fields for the Cenozoic post-subduction volcanics from the Antarctic Peninsula (Hole et al., 1993, 1995; D'Orazio et al., 1999), and the Southernmost South Volcanic Zone and Austral Volcanic Zone of the Andes (Hickey-Vargas et al., 1986, 1989; Futa and Stern, 1988; Gerlach et al., 1988; López-Escobar et al., 1993; Stern and Kilian, 1996; D'Orazio et al., 2003, and references therein).

indicate that, in the localities where both the "main-plateau" and "post-plateau" sequences occur, the former predates the latter by 2 to 5 Ma. All the "post-plateau" lavas were erupted after the passage of the trailing edge of the Nazca Plate, and are defined by these authors as "true" slab window lavas, whereas some of the "main-plateau" lavas erupted before the passage of the trailing edge of the Nazca Plate, and a few even before the collision of the Chile Ridge with the Chile Trench. For the magmatism of the region to the south of 49° 30' S, Killian *et al.* (1997) hypothesized on the basis of chemical composition of basalts of Sierra Baguales and the harzburgitic nature of xenoliths of Cerro del Fraile, that an asthenospheric upwelling related to slab window was responsible for the Miocene basalt formation in the area. Following studies (D'Orazio *et al.* 2001) showed eastwards of Cordillera Baguales, at latitudes of about 52° S, a late Miocene subalkaline magmatic activity that predated by 5-7 Ma the alkaline magmatism of the Pali Aike volcanic field, both related to slab window of the Chile Ridge.

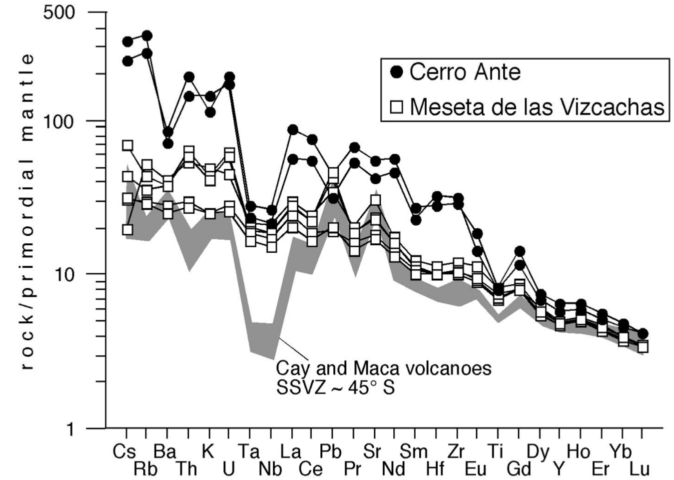

Figure 9: Primordial mantle-normalized incompatible element patterns for the Cenozoic southern Patagonia mafic volcanics showing the most marked subduction-related imprint (authors' unpublished data). In the diagram, the basalts and basaltic andesites from the Cay and Maca volcanoes (~ 45° S, Southernmost South Volcanic Zone of the Andes; D'Orazio et al., 2003) is also plotted for comparative purposes. Normalizing values after McDonough and Sun (1995).

"Supra-slab" models

Stern *et al.* (1990) proposed that the Patagonian alkaline basalts with nearly pure OIB geochemical affinity (called by these authors "cratonic") originated through a two-stage process occurring in the supra-slab asthenosphere and basal continental lithospheric mantle: in the first stage, a plum-pudding-type supra-slab asthenosphere melts at a low degree due to the convection induced by subduction, and these melts intrude the fertile garnet-lherzolite at the base of the lithosphere; in the second stage, this metasomatized basal lithospheric mantle is stretched, thinned, heated and melted to give OIB-type magmas. The same authors recognized a group of basalts (called by these authors "transitional) characterized by higher LILE/HFSE and LREE/HFSE ratios, and lower contents of incompatible elements. These geochemical features were interpreted as due to the addition of slab-derived components to the sources of these magmas. The addition could have occurred at the same time as the basaltic magmatism or during an earlier phase of Cenozoic subduction.

The Oligocene plateau basalts from the huge Meseta de Somuncura (40-43° S) have within-plate geochemical and isotopic signatures, and were erupted well outside of the Cenozoic southern Patagonia slab windows (Kay *et al.* 1993; de Ignacio *et al.* 2001). Thus, their origin is not compatible with slab window models. Kay *et al.* (1993) proposed that the presence of Somuncura Oligocene basalts are related to a thermal anomaly associated to a transient hot-spot related with the coeval rearrangement of Pacific plates. Besides, Ntaflos *et al.* (2003) suggest a plume activity as origin of Somuncura magmatism on the base of garnet and cpx compositions. Otherwise, according to de Ignacio *et al.* (2001) mantle melting under the Somuncura plateau occurred in response to an enhanced corner flow in the mantle wedge. The intake and upwelling of hot asthenosphere would have been favoured by a combination of slab roll-back and concave-up topography of the subducting slab under northern Patagonia during Oligocene time.

Conclusions

To date, the middle Eocene and middle Miocene to Quaternary magmatism of southernmost Patagonia has been most successfully interpreted following the slab window model (e.g. Ramos and Kay 1992; Gorring *et al.* 1997; D'Orazio *et al.* 2000). In particular, the evolution of Neogene slab window magmatism, associated with the collision of the Chile Ridge with the Chile Trench, is constrained by a wealth of geochronological, geochemical, geological and geophysical data. One of the most attractive points of the slab window model is that it could account for the mantle melting mechanism: indeed, according to this model, the sub-slab asthenosphere melts by adiabatic decompression while it rises through the empty space left by the diverging subducting oceanic plates. In addition, the heat supplied by the upwelling sub-slab asthenosphere could induce melting of the asthenospheric wedge and/or the basal lithospheric mantle previously enriched in fluids by transfer of fluids form the subducting slab (Gorring *et al.* 1997).

A significant advance in the understanding of the whole Cenozoic mafic magmatism of extra-Andean Patagonia will be attained by studying in detail the geochemistry and geochronology of the volcanic occurrences not compatible with current models of slab window magmatism. In southern Patagonia, wide exposures of Cenozoic volcanic formations occur that, either because of their locations or their age, cannot be interpreted according to slab window openings. For example, in the sector of southern Patagonia affected by the Eocene and Neogene slab window magmatism, several basaltic formations emplaced during Oligocene, Lower Miocene and, subordinately, Paleocene were found (Panza and Franchi 2002). Moreover, in the areas north and west of Musters and Colhue Huapi lakes (Chubut Province), Pliocene and Quaternary volcanic formations occur (Baker *et al.* 2001; Bruni 2003) that were erupted well outside (to the north) of the Neogene slab window. As shown in this paper, the lavas erupted during Neogene time in the Río Genoa – Senguerr valley and along the Sierra San Bernardo (west of Lago Musters) are very similar to the typical slab window lavas occurring to the south. This suggests similar sources for these magmas, but different processes causing mantle melting. The potential alternatives to mantle melting associated with slab window opening will be evaluated after more geochemical, geochronological and geophysical data are gathered, and could be related to hot-spot or plume related thermal anomalies, mantle upwelling by corner-flow in the asthenospheric wedge, vertical slab tear along subducted fracture zones, or local enhanced lithospheric extension.

Acknowledgements

MIUR-ITALY and the Italian National Antarctic Research Program (PNRA) supported this research.

REFERENCES

Baker, P.E., Rea, W.J., Skarmeta, J., Caminos, R. y Rex, D.C., 1981. Igneous history of the Andean cordillera and Patagonian plateau around latitude 46°S. Philosophical Transactions of the Royal Society of London, A303: 105-149.

Biddle, K.T., Uliana, M.A., Mitchum, R.M., Fitzgerald, M.G. y Wright, R.C., 1986. The stratigraphic and structural evolution of the central and eastern Magallanes basin, southern South America. In: Allen, P.A., Homewood, P. (Eds.), Foreland Basins, International Association of Sedimentologists Special Publication, 8: 41-61.

Bruni, S., 2003. Le rocce ignee della valle del Río Genoa-Senguerr e della catena del Cerro San Bernardo, Chubut, Argentina. Dipartimento di Scienze della Terra, University of Pisa, unpublished thesis, 154 pp.

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

Charrier, R., Linares, E., Niemeyer, H. y Skarmeta, J., 1979. K-Ar ages of basalt flows of the Meseta Buenos Aires in southern Chile and their relation to the southeast Pacific triple junction. Geology, 7: 436-439.

Coutand, I., Diraison, M., Cobbold, P.R., Gapais, D., Rossello, E.A., Miller, M., 1999. Structure and kinematics of a foothills transect, Lago Viedma, southern Andes. Journal of South American Earth Sciences, 12: 1-15.

Dalziel, I.W.D., 1981. Back-arc extension in the southern Andes: a review and critical reappraisal. Philosophical Transactions of the Royal Society of London, 300: 319-335.

de Ignacio, C., López, I., Oyarzun, R. y Márquez, A., 2001. The northern Patagonia Somuncura plateau basalts: a product of slab-induced, shallow asthenospheric upwelling ?. Terra Nova, 13: 117-121.

DeMets, C., Gordon, R.G., Argus, D.F., Stein, S., 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimate of current plate motions. Geophysical Research Letters, 21, 2191-2194.

D'Orazio, M., Gonzalez-Ferrán, O., Innocenti, F., Mazzarini, F., Mazzuoli, R., Tonarini, S. y Adorni-Braccesi, A., 1999. Alkaline basaltic volcanism in the Weddell Sea side of the northernmost Antarctic Peninsula: Sr-Nd isotope and trace-element characteristics. 8th International Symposium on Antarctic Earth Sciences, Wellington, Abstract volume, pp. 92.

D'Orazio M., Agostini S., Mazzarini F., Innocenti F., Manetti P., Haller M. y Lahsen A., 2000. The Pali Aike Volcanic Field, Patagonia: slab-window magmatism near the tip of South America. Tectonophysics, 321: 407-427.

D'Orazio, M., Agostini, S., Innocenti, F., Haller, M.J., Manetti, P. y Mazzarini, F., 2001. Slab window-related magmatism from southernmost South America: the late Miocene mafic volcanics from the Estancia Glencross area (~ 52°S, Argentina-Chile). Lithos, 57: 67-89.

D'Orazio, M., Innocenti, F., Manetti, P., Tamponi, M., Tonarini, S., González-Ferrán, O., Lahsen, A. y Omarini, R., 2003. The Quaternary calc-alkaline volcanism of the Patagonian Andes close to the Chile Triple Junction: geochemistry and petrogenesis of volcanic rocks from the Cay and Maca volcanoes (~ 45°S, Chile). Journal of South American Earth Sciences, 16:219-242.

D'Orazio, M., Innocenti, F., Manetti, P., Haller, M.J., Di Vincenzo, G. y Tonarini, S., 2004. The late Pliocene mafic lavas from the Camusú Aike Volcanic Field (~ 50°S, Argentina): evidences for geochemical variability in slab window magmatism. Journal of South American Earth Sciences, inpress.

Futa, K. y Stern, C.R., 1988. Sr and Nd isotopic and trace element composition of Quaternary volcanic centers of southern Andes. Earth and Planetary Science Letters, 88: 253-263.

Gerlach, D.C., Frey, F.A., Moreno-Roa, H. y López-Escobar, L., 1988. Recent volcanism in the Puyehue-Cordon Caulle region, Southern Andes, Chile (40.5°S): petrogenesis of evolved lavas. Journal of Petrology, 29: 333-382.

Gorring, M.L., 1997. Mantle processes associated with ridge-trench collision: evidence from plateau lavas and xenoliths from Southern Patagonia. Ph.D. Dissertation, Cornell University, NY, U.S.A, Ithaca.

Gorring, M. L. y Kay, S. M., 2000. Carbonatite metasomatized peridotite xenoliths from southern Patagonia: implications for lithospheric processes and Neogene plateau magmatism. Contributions to Mineralogy and Petrology, 140: 55-72.

Gorring, M. L. y Kay, S. M., 2001. Mantle processes and sources of Neogene slab window magmas from southern Patagonia, Argentina. Journal of Petrology, 42: 1067-1094.

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

Gorring, M.L., Singer, B., Gowers, J. y Kay, S.M., 2003. Plio-Pleistocene basalts from the Meseta del Lago Buenos Aires, Argentina: evidence for asthenosphere-lithosphere interactions during slab window magmatism. Chemical Geology, 193: 215-235.

Guido, D.M., Escayola, M.P. y Schalamuk, I.B., 2004. The basement of the Deseado Massif at Bahía Laura, Patagonia, Argentina: a proposal for its evolution. Journal of South American Earth Sciences, 16: 567-577.

Guivel, C., Lagabrielle, Y., Bourgois, J., Martin, H., Arnaud, N., Fourcade, S., Cotten, J. y Maury, R.C., 2003. Very shallow melting of oceanic crust during spreading ridge subduction: origin of near-trench Quaternary volcanism at the Chile Triple Junction. Journal of Geophysical Research, 108, B7, doi:10.1029/2002JB002119.

Hart, S.R., 1984. A large-scale isotope anomaly in the Southern Hemisphere mantle. Nature, 309, 753-757.

Hervé, F., Davidson, J., Mpodozis, E. y Covacevich, E.V., 1981. The late Palaezoic in Chile: Stratigraphy, structure and possible tectonic framework. Annais Acad. Brasil. Ciencias, 53: 361-373.

Hickey, R., Frey, F.A. y Gerlach, D., 1986. Multiple sources for basaltic arc rocks from the Southern Volcanic Zone of the Andes (34°-41°S): trace element and isotopic evidence for contributions from subducted oceanic crust, mantle, and continental crust. Journal of Geophysiscal Research, 91(B6): 5963-5983.

Hickey-Vargas, R., Moreno-Roa, H., López-Escobar, L. y Frey, F.A., 1989. Geochemical variations in Andean basaltic and silicic lavas from the Villarrica-Lanin volcanic chain (39.5° S): an evaluation of source heterogeneity, fractional crystallization and crustal assimilation. Contributions to Mineralogy and Petrology, 103: 361-386.

Hole, M.J., Kempton, P.D. y Millar, I.L., 1993. Trace-element and isotopic characteristics of small-degree melts of the asthenosphere: evidence from the alkalic basalts of the Antarctic Peninsula. Chemical Geology, 109: 51-68.

Hole, M.J., Saunders, A.D., Rogers, G. y Sykes, M.A., 1995. The relationship between alkaline magmatism, lithospheric extension and slab window formation along continental destructive plate margins. In: Smellie, J.L. (Ed.), Volcanism associated with extension at consuming plate margins. Geological Society Special Publications, 81: 265-285.

Ivins, E.R. y James, T.S., 1999. Simple models for late Holocene and present-day Patagonian glacier fluctuations and predictions of a geodetically detectable isostatic response. Geophysical Journal International, 138: 601-624.

Kay, S.M., A. Ardolino, M. Franchi y V. Ramos, 1993. Origen de la Meseta de Somún Curá: distribución y geoquímica de sus rocas volcánicas máficas. XII° Congreso Geológico Argentino y II° Congreso de Exploración de Hidrocarburos, Actas IV: 236-248, Buenos Aires.

Kay, M.S., Ramos, V.A. y Márquez, M., 1993. Evidence in Cerro Pampa volcanic rocks for slab-melting prior to ridge-trench collision in southern South America. Journal of Geology, 101: 703-714.

Kempton, P.D., Hawkesworth, C.J., Lopez-Escobar, L., Pearson, D.G. y Ware, A.J., 1999. Spinel ± garnet lherzolite xenoliths from Pali Aike; Part 2, Trace element and isotopic evidence bearing on the evolution of lithospheric mantle beneath southern Patagonia. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), The J. B. Dawson volume. Proceedings of the International Kimberlite Conference 7, 1: 415-428.

Kilian, R.y Stern, C.R., 2002. Constraints on the interaction between slab melts and the mantle wedge from adakitic glass in peridotite xenoliths. European Journal of Mineralogy, 14: 25-36.

Kilian, R., O. Weigand, y R. Altherr, 1997. Tertiary to Quaternary chemical trends of basalts from the Cordillera Baguales (50°S): constraints on the geotectonic evolution of southernmost Andes. VIII° Congreso Geológico Chileno, Actas 3: 1666-1670.

Kraemer, P.E., 1998. Structure of the Patagonian Andes: regional balanced cross section at 50° S, Argentina. International Geology Review, 40: 896-915.

Laurora, A., Mazzucchelli, M., Rivalenti, G., Vannucci, R., Zanetti, A., Barbieri, M.A. y Cingolani, C.A., 2001. Metasomatism and melting in carbonated peridotite xenoliths from the mantle wedge: the Gobernador Gregores case (Southern Patagonia). Journal of Petrology, 42: 69-87.

Linares, E. y Gonzalez, R., 1990. Catálogo de edades radimétricas de la República Argentina: 1957-1987. Publicaciones Especiales of the Asociación Geológica Argentina, Serie B, (19): 628

López-Escobar, L., Kilian, R., Kempton, P. y Tagiri, M., 1993. Petrography and geochemistry of Quaternary rocks from the Southern Volcanic Zone of the Andes between 41°30' and 46°00'S, Chile. Revista Geológica de Chile, 20: 33-55.

McDonough, W.F. y Sun, S.S., 1995. The composition of the Earth. Chemical Geology, 120: 223-253.

McKenzie, D. y O' Nions, R.K., 1991. Partial melt distributions from inversion of rare earth element concentrations. Journal of Petrology, 32: 1021-1091.

Meglioli, A., 1992. Glacial geology and geochronology of southernmost Patagonia and Tierra del Fuego, Argentina and Chile. Ph.D. Dissertation, Leigh University, Bethlehem.

Mejia, V., Opdyke, N.D., Vilas, J.F., Singer, B.S. y Stoner, J.S., 2004. Plio-Pleistocene time-averaged field in southern Patagonia recorded in lava flows. Geochemistry, Geophysics, Geosystems, 5: 10.1029/2003GC000633.

Mercer, J. y Sutter, J.F., 1982. Late Miocene – Earliest Pliocene glaciation in southern Argentina: implications for global ice-sheet history. Palaeogeography Palaeoclimatology Palaeoecology, 38: 185-206.

Ntaflos, Th., Bjerg E.A., Labudía, C.H. y Thöni, M., 2003. Geochemical evidences for plume activity beneath Patagonian sub-continental mantle. Geophysical Research Abstracts, 5: 09123.

Pankhurst, R.J., Leat, P.T., Sruoga, P., Rapela, C.W., Márquez, M., Storey, B.C. y Riley, T.R., 1998. The Chon Aike province of Patagonia and related rocks in west Antarctica: a silicic large igneous province. Journal of Volcanology and Geothermal Research, 81: 113-136.

Panza, J.L. y Franchi, M.R., 2002. Magmatismo Basáltico Cenozoico Extrandino. In: Haller, M. J. (Ed.), Geología y Recursos Naturales de Santa Cruz. Relatorio del XV Congreso Geológico Argentino. El Calafate, 1 (14): 201-236, Buenos Aires.

Ramos, V.A., 1989. Andean foothills structure in northern Magallanes basin, Argentina. American Association of Petroleum Geologists Bulletin, 73: 887-903.

Ramos, V.A., 2002. El magmatismo Paleógeno de la Cordillera Patagónica. In: Haller, M. J. (Ed.), Geología y Recursos Naturales

de Santa Cruz. Relatorio del XV Congreso Geológico Argentino. El Calafate, 1 (11):165-174, Buenos Aires
Ramos, V.A. y Kay, S.M., 1992. Southern Patagonian plateau basalts and deformation: backarc testimony of ridge collisions. Tectonophysics, 205: 261-282.
Ramos, V.A., H. Niemeyer, J. Skarmeta, y J. Muñoz, 1982. The magmatic evolution of the Austral Patagonian Andes. Earth Science Reviews, 18(3 4): 411 443, Amsterdam.
Riley, T.R., Leat, P.T., Pankhurst, R.J. y Harris, C., 2001. Origins of large volume rhyolitic volcanism in the Antarctic Peninsula and Patagonia by crustal melting. Journal of Petrology, 42: 1043-1065.
Rivalenti, G., Mazzucchelli, M., Laurora, A., Ciuffi, S.I.A., Zanetti, A., Vannucci, R. y Cingolani, C.A., 2004. The backarc mantle lithosphere in Patagonia, South America. Journal of South American Earth Sciences, in press.
Skewes, M.A. y Stern, C.R., 1979. Petrology and geochemistry of alkali basalts and ultramafic inclusions from the Palei-Aike volcanic field in southern Chile and the origin of the Patagonian plateau lavas. Journal of Volcanology and Geothermal Research, 6: 3-25.
Sinito, A.M., 1980. Edades geológicas, radimétricas y magnéticas de algunas vulcanitas cenozoicas de las provincias de Santa Cruz y Chubut. Revista de la Asociación Geológica Argentina, 35: 332-339.
Stern, C.R. y Kilian, R., 1996. Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Andean Austral Volcanic Zone. Contributions to Mineralogy and Petrology, 123: 263-281.
Stern, C.R., Frey, F.A., Futa, K., Zartman, R.E., Peng, Z. y Kyser, T.K., 1990. Trace-element and Sr, Nd, Pb and O isotopic composition of Pliocene and Quaternary alkali basalt of the Patagonian Plateau lavas of southernmost South America. Contributions to Mineralogy and Petrology, 104: 294-308.
Stern, C.R., Kilian, R., Olker, B., Hauri, E.H. y Kyser, T.K., 1999. Evidence from mantle xenoliths for relatively thin (< 100 km) continental lithosphere below the Phanerozoic crust of southernmost South America. Lithos, 48: 217-235.
Sun, S.S. y McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts; implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins. Geological Society Special Publication, 42: 313-345.
Tebbens, S.F., Cande, S.C., Kovacs, L., Parra, J.C., LaBrecque, J.L. y Vergara, H., 1997. The Chile ridge: a tectonic framework. Journal of Geophysical Research, 102: 12035-12059.
Winslow, M.A., 1982. The structural evolution of the Magallanes Basin and neotectonics in the southernmost Andes. In: Craddock, C. (Ed.), Antarctic Geoscience, University of Wisconsin, Madison, 143-154.

Recibido: 6 de junio, 2004
Aceptado: 10 de octubre, 2004