HAL open science

A uniform isotopic and chemical signature of dust exported from Patagonia: Rock sources and occurrence in southern environments

Diego M. Gaiero, Frédéric Brunet, Jean-Luc Probst, Pedro J. Depetris

To cite this version:

Diego M. Gaiero, Frédéric Brunet, Jean-Luc Probst, Pedro J. Depetris. A uniform isotopic and chemical signature of dust exported from Patagonia: Rock sources and occurrence in southern environments. Chemical Geology, 2007, 238 (1-2), pp.107-120. 10.1016/j.chemgeo.2006.11.003 . hal-03592061

HAL Id: hal-03592061

https://hal.science/hal-03592061v1

Submitted on 1 Mar 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

This is an author-deposited version published in: http://oatao.univ-toulouse.fr/
Eprints ID: 2524

To cite this document: Gaiero, Diego M. and Brunet, Frédéric and Probst, Jean-Luc and Depetris, Pedro J. (2007) *A uniform isotopic and chemical signature of dust exported from Patagonia: Rock sources and occurrence in southern environments.* Chemical Geology, 238 (1-2). pp. 107-120. ISSN 0009-2541

Any correspondence concerning this service should be sent to the repository administrator: staff-oatao@inp-toulouse.fr

doi:10.1016/j.chemgeo.2006.11.003

A uniform isotopic and chemical signature of dust exported from Patagonia: Rock sources and occurrence in southern environments

Diego M. Gaiero [a,*], Frederic Brunet [b,1], Jean-Luc Probst [b,2], Pedro J. Depetris [a]

[a] *CIGeS, FCEFyN, Universidad Nacional de Córdoba, Argentina, Avda. Vélez Sarsfield 1611, X5016GCA, Córdoba, Argentina*
[b] *Laboratoire des Mécanismes de Transfert en Géologie, UMR CNRS/Université Paul Sabatier n° 5563, 14 avenue Edouard Belin, 31400 Toulouse, France*

Abstract

Patagonia is considered to be the most important source of dust from South America that is deposited in surrounding areas, and we present here a systematic Sr and Nd isotopic study of sediment currently being exported. Eolian and suspended riverine sediments from Patagonia have a homogeneous chemical and isotopic composition that results from the mixing of by-products from explosive Andean volcanism, derived from the extensive Jurassic silicic Province of Chon Aike and pyroclastic materials from the basic to intermediate southern Andean Quaternary arc, which are easily denudated and dispersed. The main Andean uplift and the glaciations that began in the Late Tertiary account for the extensive distribution of these sediments in the extra-Andean region. The present geochemical signature of Patagonian sediments was produced during the Pleistocene, along with the onset of the southern Andean explosive arc volcanism. Previously published compositions of sediments from other southern South American source regions, assumed to be representative of Patagonia, are distinct from our data. Considering the alleged importance of Patagonia as a dust source for different depositional environments in southern latitudes, it is surprising to verify that the chemical and isotopic signatures of Patagonian-sourced sediments are different from those of sediments from the Southern Ocean, the Pampean Region or the Antarctic ice. Sediments from these areas have a crustal-like geochemical signature reflecting a mixed origin with sediment from other southern South American sources, whereas Patagonian sediments likely represent the basic to intermediate end-member composition.

Keywords: Patagonia; Radiogenic isotopes; Major and trace elements; Dust source

* Corresponding author. Tel.: +54 351 4344983; fax: +54 351 4334139.
E-mail address: dgaiero@efn.uncor.edu (D.M. Gaiero).
[1] Present address: Department of Earth Sciences, University of Ottawa, 140 Louis Pasteur, Ottawa, ON, Canada, K1N 6N5.
[2] Present address: AEE Laboratory, ENSAT-Institut National Polytechnique, avenue de l'Agrobiopole, BP 32607, Auzeville Tolosane, 31326 Castanet Tolosan Cedex, France.

1. Introduction

Wind-transported dust is a tracer of atmospheric circulation and also supplies worthy information on the climatic conditions prevailing in source areas. The analysis of dust provenance in different depositional environments (e.g., continents, ocean, polar ice sheet), is of vital importance to improve our understanding on the variability of dust concentration and composition, and to constrain models of atmospheric circulation and dust transport. Thus, the accuracy of atmospheric dust model simulation depends largely on the correct determination of continental source areas (Grousset and Biscaye, 2005).

Prospero et al. (2002) showed that in South America there are three persistent dust sources: Patagonia (39°–52°S), central-western Argentina (26°–33°S), and the Puna–Altiplano plateau (19°–26°S), and suggested that these sites were probably much more active during the LGM (Last Glacial Maximum). Apart from different latitudinal positions, these areas also have different source signatures that assist in tracing the path of exported sediments and, moreover, in establishing the latitudinal displacements of westerlies or the role played by other wind-systems during the Late Quaternary.

From the three areas mentioned above, Patagonia is the most important dust supplier in southern South America (Prospero et al., 2002) and it is the only continental landmass south of 39°S, where the atmospheric circulation is totally governed by westerly wind dynamics. Thus, a marked precipitation deficit recorded in the main Patagonian plateau and strong westerlies that sweep this region turn the atmospheric pathway into the main transport agent representing about 90% (35 g m^{-2} y^{-1}) of the particle mass delivered to the SW Atlantic (Gaiero et al., 2003). Moreover, atmospheric circulation models estimate that wind strength was much higher during the LGM (Lunt and Valdes, 2001). In consequence, materials derived from this area were extensively used to explain loess deposition in the Pampas (Zárate, 2003 and cites therein) and to reconstruct paleo-atmospheric (Grousset et al., 1992; Basile et al., 1997; Smith et al., 2003; Delmonte et al., 2004a) and -oceanic circulation (Diekmann et al., 2000; Walter et al., 2000) in different southern environments (e.g. Argentinean Pampean Region, Southern Ocean, Antarctica). In most cases, however, researchers working in the reconstruction of paleo-environments in the southern hemisphere have employed sparse geochemical and isotopic data from southern South American materials (Grousset et al., 1992; Basile et al., 1997; Walter et al., 2000; Delmonte et al., 2004a) and, further, there are no regional and systematic studies that define their signatures based on the study of likely sources.

It is clear then, that a key aspect to improve atmospheric circulation models (AGCMs) in the region is to understand primarily the characteristics of South American dust sources. In this work we move in this direction, determining isotopes and trace elements in the most abundant Patagonian rocks, and we seek to establish the extent to which they contribute to the chemical and isotopic signature of the Recent sediments exported from this region.

In a companion paper, Gaiero et al. (2004) started defining the signature of materials exported from Patagonia, showing that REEs patterns in both, river- and wind-borne material exported from Patagonia match well with Recent tephra from the Hudson volcano located in the southern Andes. Now, new Sr and Nd isotopic data measured in top soils, eolian dust, and river bed sediments, along with the composition of major and trace elements others than REEs, allow us to dig deeper into the geochemical "fingerprint" of Recent Patagonian sediments. Hence, one of the main goals in our study is to produce a well-defined geochemical signature for the sources that supply the pool of particles that have contributed to the long range atmospheric dust transport in the region.

2. Study area

The main features of the Patagonian region were summarized by Gaiero et al. (2003, 2004 and references therein). Briefly, climate is controlled by the westerlies that, after the Andean uplift (Late Tertiary), discharge most of their moisture on the Andes and continue as dry winds to the east. This situation determines that only a narrow strip along the Andes, with steep slopes and significant rainfall, is the active supplier of most of the weathered material that is currently being exported. Thus, a comprehensive geochemical study of the sediments exported by one of the Patagonian rivers (Chubut), indicates a preeminence of physical denudation that is not restricted to present times but also occurred during repeated cycles recorded in the geological past. By virtue of a similar geological history, this scenario could be shared by other Patagonian rivers draining the eastern slope of the Andes (Pasquini et al., 2005).

During glacial–interglacial periods, southern Andean glaciers delivered huge volumes of rock-flour and coarse debris. Hence, unconsolidated alluvial deposits of the last cold Pleistocene period were spread over the whole region, which were later capped by a 5 to 10 cm-thick Holocene sandy layer of fluvial origin (e.g., Clapperton, 1993).

2.1. Patagonian geology

The geology of Patagonia is dominated by volcanic rocks erupted since Jurassic times. Basement outcrops are restricted to areas within the Patagonia Massif and in the Andean Cordillera, exhibiting a wide variety of crystalline and sedimentary sequences (Pankhurst et al., 1999). The Mesozoic–Cenozoic Patagonian Batholith runs the length of the western (Chile) Andean cordillera and only occurs north-east of the Andes forming two belts; the Sub-cordilleran batholith, and the batholith of Central Patagonia that extends as far as the Deseado Massif, near the Atlantic coast (Pankhurst and Rapela, 1995; Pankhurst et al., 1998) (Fig. 1). Jurassic volcanic rocks are predominantly rhyolitic ignimbrites that constitute one of the world's most voluminous silicic provinces, extending as far south as the Antarctic Peninsula. They comprise several formations in Patagonia grouped

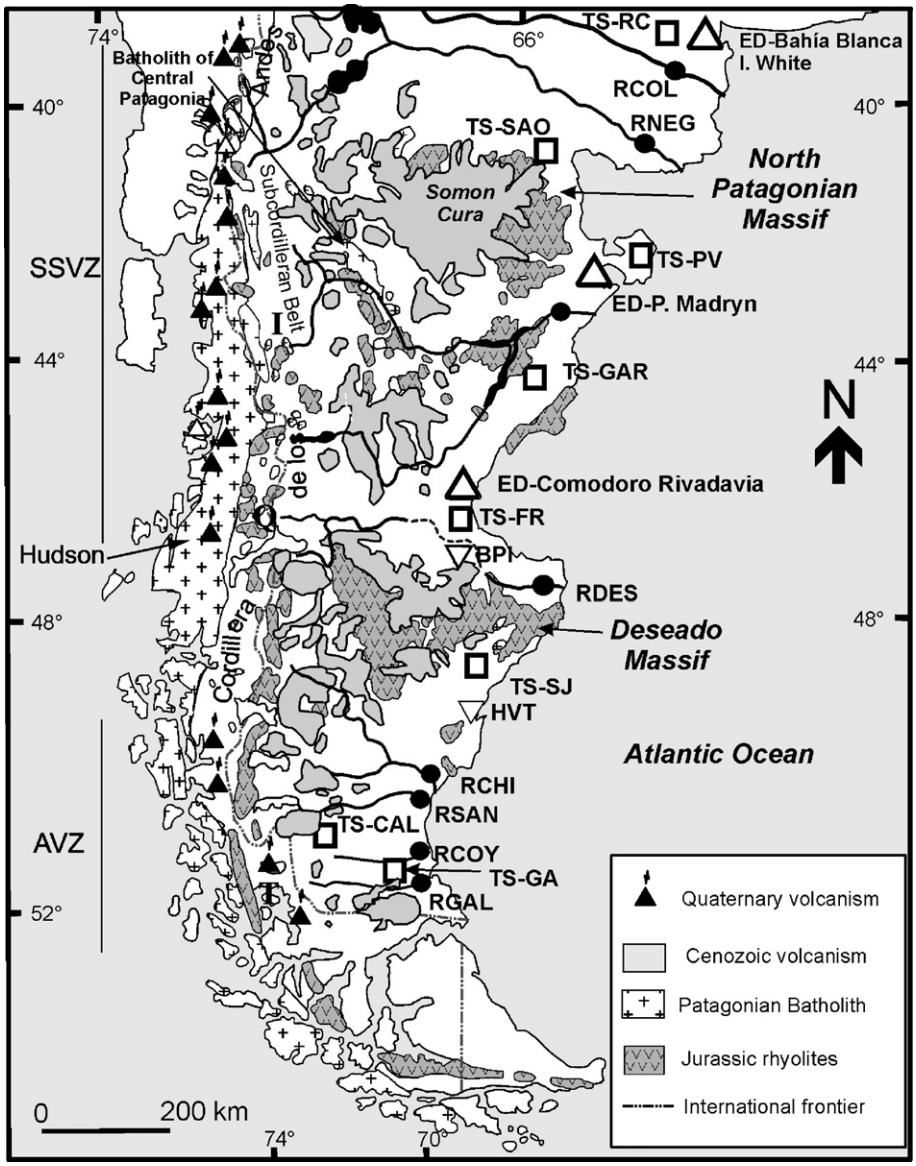

Fig. 1. Map of Patagonia showing the main rock outcrops and sampling points (see references in Table 1). The Jurassic volcanic province (Chon Aike) and their Andean formations (I; Ibañez, Q; El Quemado, T; Tobífera), together with the Patagonian Batholith distributions are based on Rapela et al. (2005). Cenozoic volcanism and the Quaternary volcanism distribution are based in the work of D'Orazio et al. (2000) and Futa and Stern (1988). Dots indicate suspended particulate matter (SPM) and bedload samples (BS) locations. Squares denote topsoil (TS) sampling locations and triangles denote eolian dust (ED) sampling stations. The geographic coordinates of the samples are shown in Table 1.

Table 1
Major, trace elements[a] and isotopic composition of Recent Patagonian materials (RPM)

Reference as in Fig. 1		SiO_2	Al_2O_3	MgO	CaO	Fe_2O_3	MnO	TiO_2	Na_2O	K_2O	Sr	Ba	Sc	Y	Rb	Cs	U	Hf	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	εNd(0)
Top soils <63 μm size fraction (TS)																					
TS-CAL	El Calafate (50° 20′S–71° 30′W)	66.3	13.9	1.23	3.29	4.70	0.15	0.89	3.21	1.48	349	413	12.0	24.5	39.4	1.33	1.78		0.705198	0.512610	−0.5
TS-SJ	San Julián (49° 20′S–67° 45′W)	61.5	14.5	1.67	4.31	6.05	0.11	0.97	2.47	1.78	298	414	16.5	27.5	56.0	3.02	2.47		0.705922	0.512661	0.5
TS-GAR	Garrayalde (RN 3) (44° 4′S–66° 40′W)	62.4	15.0	1.23	3.94	5.65	0.12	1.28	3.06	1.53	392	464	14.0	28.0	38.4	1.66	1.72		0.704971	0.512669	0.6
TS-SAO	San Antonio Oeste (40° 44′S–64° 56′W)	53.8	15.3	2.94	6.35	7.55	0.13	0.99	1.95	1.90	270	453	19.0	25.5	57.1	4.32	1.88		0.70572	0.512651	0.3
TS-FR	Fitz Roy (RN 3) (47° 00′S–67° 15′W)	45.3	11.0	2.42	16.1	5.45	0.80	0.87	1.94	1.40	264	540	12.5	22.5	41.9	2.94	1.65		0.706321	0.512622	−0.3
TS-RC	Rio Colorado (38° 59′S–64°S 04′W)	53.1	14.7	2.34	8.50	7.05	0.13	0.93	2.55	1.89	322	456	16.5	26.5	59.8	4.33	2.00		0.706431	0.512593	−0.8
TS-PV	Peninsula de Valdéz (42° 30′S–64° 02′W)	58.8	15.1	2.53	4.67	7.00	0.12	1.00	2.61	1.93	287	460	17.0	26.0	52.2	3.37	1.81		0.705439	0.512645	0.2
TS-GA	Güer Aike (51° 38′S–69° 37′W)	51.7	10.8	3.11	11.3	4.60	0.11	0.84	2.29	1.38	443	317	11.5	21.5	28.9	0.94	1.16		0.705383	0.512622	−0.3
Bed sediment <63 μm size fraction																					
RCOL	Colorado R. (Rio Colorado)	59.5	14.8	2.00	6.83	6.15	0.10	0.94	3.32	1.96	399	647	13.5	25.1	66.8	3.95			0.705929	0.51252	−2.3
RNEG	Negro R. (Gral. Conesa)	60.5	16.4	2.11	3.83	7.50	0.14	1.03	2.85	1.87	353	499	18.3	32.2	77.1	10.2			0.705698	0.512575	−1.2
RCHU	Chubut R. (Trelew)	62.2	15.7	1.70	4.58	5.45	0.10	1.03	0.14	2.98	367	487	12.8	26.2	54.8	na	1.24				
RDES	Deseado R. (Jaramillo)	65.2	13.4	1.75	3.22	4.65	0.10	0.77	1.70	1.67	282	755	13.0	34.6	60.0	4.49					
RCHI	Chico R. (Rio Chico)	66.3	14.7	1.66	2.83	5.20	0.09	0.79	2.75	2.05	327	552	14.1	26.8	68.8	4.96					
RSAN	Santa Cruz R. (Cte. Piedrabuena)	65.2	15.0	1.75	2.50	5.90	0.10	0.90	2.34	1.82	257	462	15.2	28.8	72.0	3.43			0.706732	0.512501	−2.6
RGAL	Gallego R. (Guer Aike)	63.7	14.7	1.81	3.11	5.40	0.18	0.74	2.91	1.43	338	430	15.5	23.8	48.7	1.96					
Suspended particulate matter																					
RCOL	Colorado R. (R. Colorado–Apr. 1998)	60.2	13.6	1.53	5.08	3.70	0.11	0.51	3.13	0.24	369	547	9.6	16.2	71.6	3.59	1.99				
RNEG	Negro R. (Gral. Conesa–Dec. 1997)	56.6	14.7	1.99	3.35	5.80	0.22	0.71	2.53	1.88	319	499	14.4	23.5	74.7	8.67	2.48				

RCHU	Chubut R. (Trelew–Apr. 1998)	57.3	13.5	1.89	3.06	5.00	0.16	0.65	1.59	1.64	254	359	13.6	30.8	59.8	4.26	1.92				
RDES	Deseado R. (Jaramillo–Dec. 1997)	61.2	16.0	2.38	3.12	5.70	0.09	0.72	0.46	1.41	177	278	16.8	33.1	70.8	6.25	1.88				
RCHI	Chico R. (Rio Chico–Apr. 1998)	56.2	17.8	2.43	2.08	6.90	0.09	0.58	0.95	2.83	167	437	21.5	28.0	140	15.3	2.32				
RSAN	Santa Cruz R. (Cte. Piedrabuena–Apr. 1998)	60.2	15.8	1.88	1.79	5.70	0.13	0.66	1.70	2.42	195	613	16.5	23.5	102	7.15	2.26				
RCOY	Coyle R. (Rio Coyle–Dec. 1997)	57.3	16.9	2.41	2.04	7.50	0.11	0.74	0.96	2.24	175	429	21.4	29.8	104	8.57	2.19				
Eolian dust (ED)																					
ED-BB	Bahía Blanca–Aug'97 to Mar'98 (38° 44′S–62° 16′W)	55.3	13.5	1.61	3.79	6.60	0.08	0.77	2.13	1.85	313	699	13.0	21.0	64.9	4.52	2.39	4.38			
ED-BB	Bahía Blanca–Mar to Oct'98	57.2	14.2	1.59	3.73	5.70	0.08	0.73	2.49	1.73	302	489	12.0	20.0	63.9	3.64	1.68	4.87			
ED-BB	Bahía Blanca–Set to Nov'98	60.1	15.5	1.53	3.13	5.80	0.08	0.76	2.62	2.07	302	475	14.0	23.0	73.6	4.63	1.79	5.10	0.70592	0.512615	−0.4
ED-BB	Bahía Blanca–Dec98 to Feb'99	61.3	16.0	1.90	3.05	6.60	0.10	0.84	2.30	2.15	285	493	17.0	29.0	73.9	5.14	2.04	4.74			
ED-BB	Bahía Blanca–Set'99	47.8	12.6	1.48	2.86	4.80	0.09	0.64	1.91	1.90	272	433	12.0	23.0	69.3	4.63	2.21	3.74			
ED-IW	lng, White–Set'97 to Jul'98 (38° 47′S–62° 16′W)	58.2	14.7	1.58	3.38	6.10	0.07	0.74	2.98	2.07	319	508	12.7	19.3	76.5	4.42	2.01	4.54	0.706785	0.512543	−1.8
ED-IW	lng, White–Jul to Dec'98	55.3	14.5	2.57	8.18	6.00	0.10	0.74	2.56	1.87	376	515	13.2	24.9	74.3	4.61	2.26	4.80	0.706562	0.512578	−1.1
ED-PM	Puerto Madryn–May to Nov'98 (42° 47′S–65° 02′W)	57.3	13.3	1.98	7.85	4.50	0.08	0.73	2.58	1.91	283	452	11.4	21.8	63.1	3.30	2.44	5.32	0.706375	0.512653	0.3
ED-PM	Puerto Madryn–Jan to Feb'99	54.2	13.0	2.17	5.17	5.00	0.08	0.96	1.97	1.73	228	384	12.2	21.4	58.6	3.30	2.48	4.39			
ED-PM	Puerto Madryn–Feb to Mar'99	49.7	15.6	2.48	3.34	5.30	0.09	1.77	1.99	1.85	185	364	14.0	21.0	60.4	3.68	2.55	5.28	0.706269	0.512643	0.14
ED-PM	Puerto Madryn–May'99	60.1	13.7	2.20	5.61	4.40	0.07	1.16	2.12	1.83	232	429	11.0	20.0	64.2	2.97	2.56	5.72			
ED-PM	Puerto Madryn–Jun to Jul'99	59.7	17.8	1.85	4.10	4.20	0.07	0.98	2.33	1.82	251	406	11.0	20.0	63.2	2.90	2.10	4.49	0.706089	0.512624	−0.2
ED-PM	Puerto Madryn–Set to Oct'99	56.9	13.6	2.59	5.64	4.80	0.08	1.55	2.10	1.74	222	404	12.0	21.0	64.6	3.41	2.80	5.39			
ED-CR	C. Rivadavia–Apr to Jul'99 (45° 52′S–67° 30′W)	50.0	12.7	1.98	4.17	5.50	0.09	3.63	1.84	1.70	241	455	13.0	21.0	55.2	2.74	1.47	3.68	0.705992	0.512677	0.8
Volcanic materials																					
BPI	Bosque Petrificado Ignimbrite	63.8	13.56	1.37	2.22	2.79	0.13	0.36	1.22	2.27	60	368	8.0	21.0	114	6.40	2.83	4.37	0.717528	0.512420	−4.2
HVT	Hudson volcanic tephra	60.9	16.6	1.77	4.17	6.17	0.17	1.27	5.92	2.37	387	734	16	47	58	1.58	1.41	7.0	0.704313	0.512779	2.8

[a]Major elements (wt.%) and trace elements (ppm).

within the Chon Aike Province (Pankhurst et al., 1998) (Fig. 1). Rocks outcropping to the east contrast with those in the Andean Cordillera (El Quemado, Ibañez and Tobífera Formations), as they are locally deformed, tilted and thrusted as a consequence of Andean (Cretaceous–Tertiary) deformation, and strongly affected by hydrothermal alteration (Pankhurst et al., 1998). Outcrops of these rocks extend from 40°S down to 54°S and their lithological type is similar to that of the eastern Chon Aike Formation; i.e., dominantly rhyolitic ignimbrites.

The geomorphologic features of extra-Andean Patagonia are mostly delineated by one of the largest Cenozoic retroarc continental basaltic provinces (Rapela et al., 1988), where mafic plateau volcanism has occurred throughout Tertiary to Recent time. This volcanic province includes two main series: the Cordilleran Series to the west, which is restricted to a narrow area in the Andes (between 40°S and 43°S) with rhyolitic ignimbrite facies and widespread andesitic composition, and the Basaltic Plateau Series to the east, outcropping all along the Patagonian territories showing a typical basaltic composition (D'Orazio et al., 2000) (Fig. 1).

During the Quaternary, frequent volcanic eruptions occurred in the Andean region having a dominantly basaltic and basaltic–andesitic composition (e.g., Stern, 2004). The southern volcanic zone (SVZ) of the Andean Cordillera is mainly composed of high Al_2O_3 basalts and basaltic andesites, whereas the austral volcanic zone (AVZ) is dominated by magmas with an adakitic signature (Sigmarsson et al., 1998). A further division of the SVZ was introduced by Futa and Stern (1988) into the northern SVZ (NSVZ)(north of 37°S, not shown in Fig. 1) and the southern SVZ (SSVZ) (Fig. 1).

3. Samples location and analytical methods

Since 1995 and during eight different expeditions we collected river bed and suspended sediment samples in the eight main Patagonian rivers. Likewise, we collected top soil samples all along the Patagonian tableland and eolian dust samples down the coast (at three stations). All sampling locations are indicated in Fig. 1. The detailed sampling procedure was published elsewhere (Gaiero et al., 2003, 2004).

Chemical analyses were performed at the EOST-Centre de Géochimie de la Surface, CNRS-UMR 7517, Strasbourg, France. Major, trace element and isotopic composition of the above mentioned materials are shown in Table 1. Sediments were digested by means of the alkaline fusion method ($Li_2B_4O_7$, 1050 °C, with HNO_3 digestion) and chemically analyzed for major (ICP-AES), minor and trace components (ICP-MS). Standard curves of each element were constructed using international standards (BE–N–basalt, GS–N–granite, AN–G–anorthite, FK–N–feldspar) from the CRPG, Nancy, France. Following this methodology the precision based on five determinations was 2% for major and 5% for trace elements. This technique was checked using the geostandard OU-4 (Penmaenmawr microdiorite) and the results obtained for the determined elements are reported in Table 2. REE composition was already published in Gaiero et al. (2004).

Strontium and Nd isotopic compositions were determined at the Université Paul Sabatier (Toulouse), using a Finnigan MAT 261 multicollector mass-spectrometer. For isotopic measurements sediments were dissolved into Savillex beakers in a ($HF+HClO_4+HNO_3$) mixture and Sr and Nd were chemically separated through ionic chromatographic columns following techniques reported elsewhere (Richard et al., 1976; Pin et al., 1994). The measured $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ were corrected for mass fractionation by normalizing to $^{146}Nd/^{144}Nd=0.7219$ and $^{86}Sr/^{88}Sr=0.1194$. Measured blanks are considered to be negligible in all cases. Analysis of the Sr-standard NBS SRM 987 (certified value of 0.710250) yielded a $^{87}Sr/^{86}Sr$ ratio of 0.710239±10 (2 s, $n=6$). Analysis of Nd-standard Rennes (certified value of 0.511962) yielded a $^{143}Nd/^{144}Nd$ ratio of 0.511969±6 (2 s, $n=4$). For convenience, Nd isotopes data are reported in units of $\varepsilon_{Nd}(0)$ ($\varepsilon_{Nd}(0)=[[^{143}Nd/^{144}Nd$ (meas.)/$^{143}Nd/^{144}Nd$ (CHUR)]−1]*10^4). The CHUR (Chondritic

Table 2
Analysis of international geostandard OU-4 (Penmaenmawr microdiorite, from the IAG) (see http://geoanlyst.org; http://georem.mpch-mainz.gwdg.de) and comparison with certified values

	Certified value	Laboratory analysis
SiO_2	63.34±0.06	61.8
Al_2O_3	14.83±0.02	15.5
MgO	2.3±0.008	2.47
CaO	4.48±0.013	4.8
Fe_2O_3	5.82±0.014	6.2
MnO	0.140±0.001	0.141
TiO_2	0.77±0.002	0.78
Na_2O	3.61±0.011	3.63
K_2O	2.70±0.009	2.7
Sr	99.9±1	95
Ba	360.8±2.7	380
Sc	19.1±0.26	19.8
Y	47.1±0.5	45
Rb	98.5±0.8	94.6
Cs	2.07±0.03	1.93
U	2.19±0.07	1.9
Hf	5.54±0.08	4.89

Trace elements are in ppm; oxides in wt.%.

Uniform Reservoir) value is 0.512638 (Jacobsen and Wasserburg, 1980).

The Sr and Nd isotopic measurements as well as major and trace element analyses were carried out on bulk samples (eolian dust and suspended matter) and on a specific grain-size fraction (<63 μm, for bed load and top soil samples). Sedigraph's analyses of eolian dust samples from the three sampling stations indicate that a mean of 86±4% of the mass corresponds to particles with equivalent spherical diameters <10 μm (Gaiero et al., 2003).

The Sr concentration in carbonates is very high and could produce in sediments a distinct Sr isotopic composition. Dissolved $^{87}Sr/^{86}Sr$ composition determined in the eight Patagonian rivers draining the whole region indicate a minor contribution from marine carbonates and evaporites (Brunet et al., 2005). In addition, carbonates in the suspended and bed load of these rivers are low (Gaiero et al., 2002, 2004). In the case of top soils, X-ray diffraction indicate the presence of calcite in some samples (e.g., Fitz Roy, Rio Colorado, Güer Aike) while in others it was a trace content or was not detected (Gaiero et al., 2004). Nevertheless, data from Table 1 indicate that there is no relationship between Sr concentration and Sr isotopic composition for different Patagonian sediment samples and, hence, minor variations in $^{87}Sr/^{86}Sr$ ratios may not be attributable to the presence of carbonates.

4. Results and discussion

4.1. A uniform isotopic signature for a vast region

Similarly to REE patterns and mineralogy (Gaiero et al., 2004), Fig. 2 indicates that Patagonian top soils (TS) show a homogeneous Sr and Nd isotopic composition (mean $^{87}Sr/^{86}Sr = 0.705673 \pm 0.000523 / \varepsilon_{Nd}(0) = -0.04 \pm 0.52$). Bearing in mind that the TS sampling design covered a north–south span of about 1500 km (Fig. 1), the uniform chemical and isotopic composition can only be explained by the occurrence of geological processes operating at a regional scale that homogenized the uppermost sediment layer.

Analyses of matrix material in glacial deposits have been used to estimate the average continental composition (Goldschmidt, 1933), and the southern Andes were repeatedly glaciated since the late Miocene, from 38°44′S to 55°59′S (Rabassa and Clapperton, 1990). It follows then that late Cenozoic deposits from extra-Andean Patagonia are directly associated with the interaction between glaciations and the Andean orogeny. During different glacial–interglacial cycles the Patagonian fluvial systems transported enormous amount of sediments glaciated from the southern Andes which were spread over about 600,000 km^2 of extra-Andean Patagonia (Lapido and Pereyra, 1999).

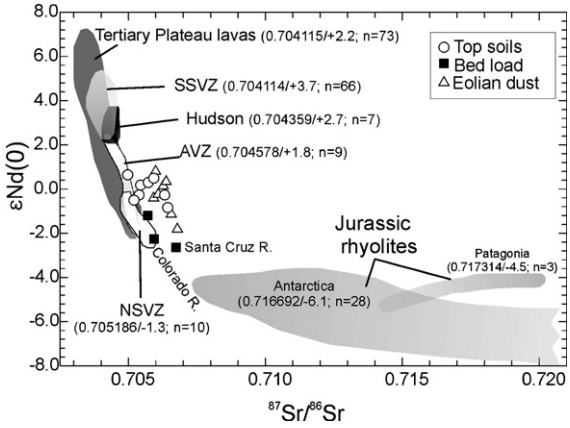

Fig. 2. Isotopic composition of Recent sediments exported from Patagonia (RPM): top soils (<63 μm grain-size), eolian dust and river bedload (<63 μm) (Table 1). Shadowed areas represent the isotopic composition of the most representative Patagonian rocks (see Fig. 1). Numbers in brackets correspond to mean Sr and Nd isotopic composition of each rock type. Data were taken from: Quaternary volcanism (GEOROC database available at http://georoc.mpch-mainz.gwdg.de and this work), Tertiary Plateau lavas (Hawkesworth et al., 1979; Kay et al., 1993; Gorring and Kay, 2001; Gorring et al., 2003; D'Orazio et al., 2003), Jurassic rhyolites (Parada et al., 2001; Riley et al., 2001 and this work). Within the shadowed area representing Andean Jurassic rhyolites we also included a tuff sample from the Bosque Petrificado (Fig. 1 and Table 1).

Wind and rivers employ independent means to sample the Earth's surface. Compared to rivers, Patagonian westerly winds sample large geographical areas and therefore, latitudinal eolian dust samples (ED) also depict a chemical (Gaiero et al., 2004) and isotopic composition which is similar to TS (mean ED $^{87}Sr/^{86}Sr = 0.706285 \pm 0.000314 / \varepsilon_{Nd}(0) = -0.33 \pm 0.89$) (Fig. 2). The latter shows the difference of a slightly more radiogenic Sr composition for ED, most likely as a consequence of transport-induced sorting (Fig. 2). Moreover, contrasting with Sr isotopes, Nd isotopes are not significantly affected by a grain-size differentiation (e.g., Walter et al., 2000; Smith et al., 2003). Only the isotopic composition of the northernmost Patagonian TS sample (Rio Colorado, Fig. 1) seems to be influenced by sedimentary material derived from the Colorado River drainage basin (see explanation below in this section). The slightly more unradiogenic $\varepsilon_{Nd}(0)$ in dust can be explained by the contribution of samples like the ones from Ingeniero White (near Bahia Blanca, see Fig. 1 and Table 1) that suggest that at the northern border of Patagonia, dust particles could derive from the

Colorado River floodplain (Zárate, 2003) or from another source (north, northwest?).

Although the isotopic composition of bed sediments (BS) from the three most important Patagonian rivers (Negro, Santa Cruz, and Colorado) exhibit Sr isotopic composition similar to TS and ED (mean $^{87}Sr/^{86}Sr = 0.706120 \pm 0.000543$), a more negative mean $\varepsilon_{Nd}(0)$ for BS (-2.03 ± 0.75) reflects the contrasting lithology of each drainage basin. For example, the isotopic signature of the Santa Cruz River bed sediments seems to be biased by the only Andean Patagonian outcrop of metasedimentary basement on the eastern slope (mean $^{87}Sr/^{86}Sr = 0.72184/\varepsilon_{Nd}(0) = -7.6$)(Kilian and Behrmann, 2003). On the other hand, volcanoes in the NSVZ are located along the continental divide, on the Chile–Argentina border and the Colorado River drains this area. This feature would explain the isotopic signature of bed sediments from the Colorado (Fig. 2, see also Section 4.3).

4.2. Rock sources defining the Recent Patagonian sediments signature

By virtue of the atmospheric circulation and discrepancies in the chemical composition (Gaiero et al., 2004), we have to assume the lack of significance of other areas as likely sources supplying sediment to the Patagonian plateau. Hence, to study the origin of sediments currently being exported from this region, we probed into the chemical and isotopic composition of the main outcropping rocks.

Considering a possible grain-size fractionation of Sr and the conservative behavior of Nd, isotope compositions of Recent Patagonian Materials (RPM: top soils, eolian dust and bed sediments) appear to match well with materials derived from AVZ, NSVZ and the more evolved basaltic rock from the Tertiary Plateau lavas (Fig. 2). However, some arguments — as those presented below — indicate that a single or a mixed source for the RPM, made up with basic rocks, is discarded. Most likely, the RPM signature seems to contain an old continental component that could explain better its offset position from the average composition of the main mantle-derived material.

The best candidates to explain the old crustal signatures observed on RPM are the extended Jurassic silicic volcanism, the Late Triassic–Late Cenozoic plutonic rocks (Patagonian Batholith) and the Paleozoic–Early Mesozoic metasedimentary basement. The plutonic rocks of the Patagonian Batholith contain a typical mantle-derived isotopic signature (mean $^{87}Sr/^{86}Sr = 0.70542/\varepsilon_{Nd}(0) = 0.04$)(Pankhurst et al., 1999; Kilian and Behrmann, 2003) and, together with the metasedimentary basement, their presence is confined to a restricted area on the eastern slope of the Andes, with scarce regional importance (Fig. 1). Consequently, and based on both, their lithological type (dominant poorly welded ignimbrites) and their extended geographic distribution, the most prominent crustal-like rocks that could explain part of the RPM isotopic composition seem to be those supplied by Jurassic volcanism. Evidences indicate that the Ibañez and El Quemado Formations are close geochemical correlatives with rocks from the Antarctic Peninsula (Pankhurst et al., 1998). Therefore and due to the scarcity of data for Andean rhyolites, we employed with confidence the data from Antarctic rhyolites in our interpretation (Figs. 2 and 3d).

If we assume the above as a truthful scenario then the question is, which of the basic to intermediate volcanic rocks (Tertiary or Quaternary volcanism) are the main sources of RPM? Alike the isotopic composition, RPM depict a homogeneous chemical signature (Fig. 3a). The mixed origin hypothesis leads to higher incompatible element concentrations than Tertiary and, to a lesser extent Quaternary volcanism, but similar to the more evolved Jurassic rhyolites (Fig. 3a–d). Geochemical as well as geographical aspects help to discard Tertiary volcanic rocks as the main basic to intermediate rock contributor to the RPM signature. Their magmas derive from the subslab mantle, and depict a typical intra-plate geochemical signature (Gorring et al., 2003; D'Orazio et al., 2003), with low incompatible and high compatible element concentrations, and REE patterns almost rectilinear showing LREE-enrichment and high LREE/HREE ratios (Fig. 3c). Moreover, they occupy the eastern and relatively flat foreland of Patagonia (Fig. 1), where glacial activity was absent and arid conditions prevailed since the Miocene, thus producing a reduced sediment mass.

Consequently, the mantle-derived end-member found in RPM must be explained by the contribution of the extended explosive arc volcanism of the Patagonian Andes. Within the southern Andes, the extreme geographical position of the AVZ (south of 49°S) and NSVZ (north of 37°S) (Fig. 1) and the dominant atmospheric circulation (westerly winds), preclude a regional influence on the chemical and isotopic composition of RPM. From a geochemical point of view, these volcanic zones erupted lavas with high and variable La/Yb ratios (insert Fig. 3b). In the case of the AVZ, high La/Yb ratios are due to the partial melting of the young and heterogeneous subducted Antarctica plate (Sigmarsson et al., 1998) and, in the case of the NSVZ, due to the likely presence of garnet in the magma source (e.g. Stern, 2004).Thus,

mean REEs patterns found on these volcanic zones are different to the pattern exhibited by the SSVZ, which is very similar to the ones characterizing RPM (Fig. 3a and b). Then, within the southern Andes, the most solid candidates to explain the RPM basic to intermediate composition are the materials derived from the SSVZ (37°S to 48°S).

This hypothesis is further supported by the isotopic mixing model shown in Fig. 4, which indicates that SSVZ materials together with Jurassic rhyolites are good end-members in a mixing hyperbola explaining the RPM isotopic composition (Fig. 4a). The insert in Fig. 4a shows the mixing hyperbola that includes samples from Jurassic Antarctic volcanism. An improved fit of the hyperbola to the RPM isotopic composition is achieved when only Patagonian Jurassic rhyolites are considered (Fig. 4a), indicating that about 60% of the RPM signature is made up with materials erupted from the SSVZ and 40% with the silicic Jurassic rocks. Then, Fig. 4b indicates that to make-up the typical RPM geochemical signature, the evolved Jurassic rock should supply a high proportion of the most incompatible elements, while SSVZ should contribute with the most compatible ones. Elements located between the two end-members (incompatible/compatible) seem to be supplied in equivalent proportions by the two rock types. The mixing contribution of both rock types also help to explain the typical REEs patterns that characterize RPM, where evolved Jurassic volcanism contributes with a high proportion of LREEs (the most incompatibles REEs), while HREEs concentrations are supplied in a similar amount by both rock types (insert Fig. 4b). Mixing proportions obtained from Fig. 4a allow the reconstruction of the mean composition of RPM (Fig. 4c).

4.3. The Hudson contribution to the Recent Patagonian material signature

The eruptive history of the Hudson volcano is traced back to 1.0 Ma (Orihashi et al., 2004). Many previous investigations indicate the significance of the Hudson volcano (the southernmost volcano in the SSVZ, see Fig. 1) as an important particle supplier to the Patagonian surface (Scasso et al., 1994; Smellie, 1999;

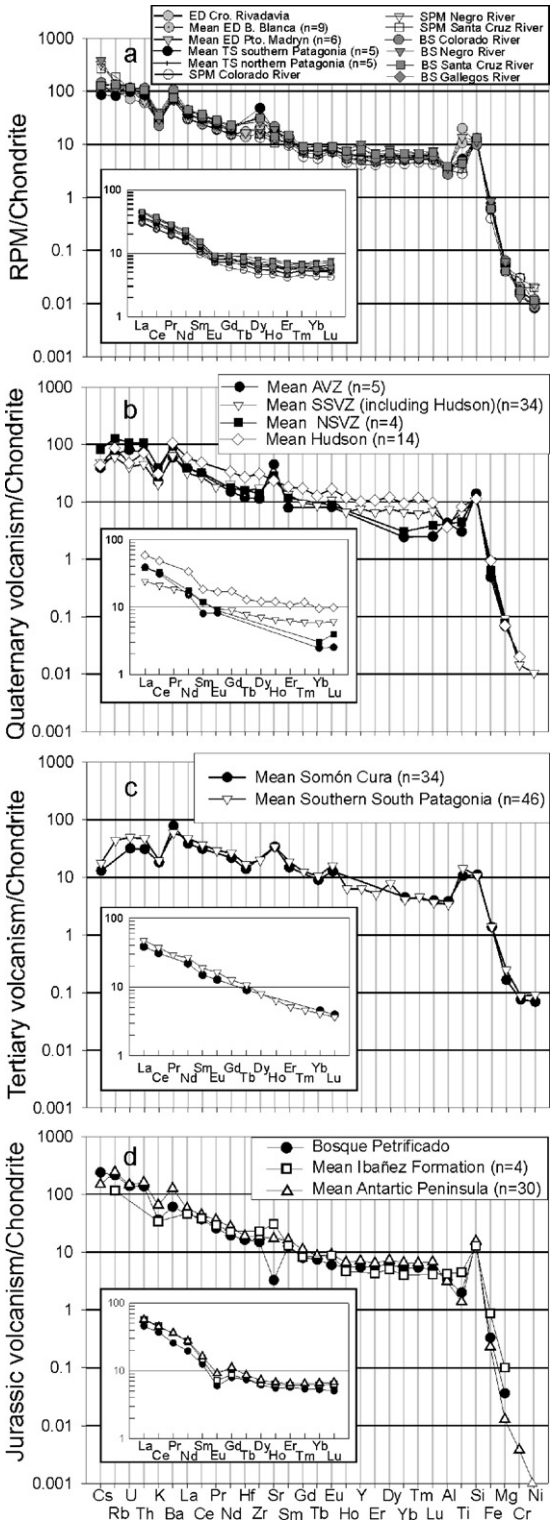

Fig. 3. Extended diagrams showing chemical composition of Recent Patagonian Materials (RPM) and mean composition of Patagonian rocks normalized to chondrite. Major and trace element data are shown in Table 1. Aluminium oxides, Fe_2O_3, Zr, Ti, Ni, Cr and REEs data as in the work of Gaiero et al. (2003, 2004). Data were taken from: Quaternary volcanism (GEOROC database available at http://georoc.mpch-mainz.gwdg.de, López-Escobar et al., 1993; Déruelle and Bourgois, 1993; Naranjo and Stern, 1998; D'Orazio et al., 2003 and this work), Tertiary Plateau (Hawkesworth et al., 1979; Kay et al., 1993; Gorring and Kay, 2001; Gorring et al., 2003), Jurassic rhyolites (Parada et al., 2001; Riley et al., 2001 and this work).

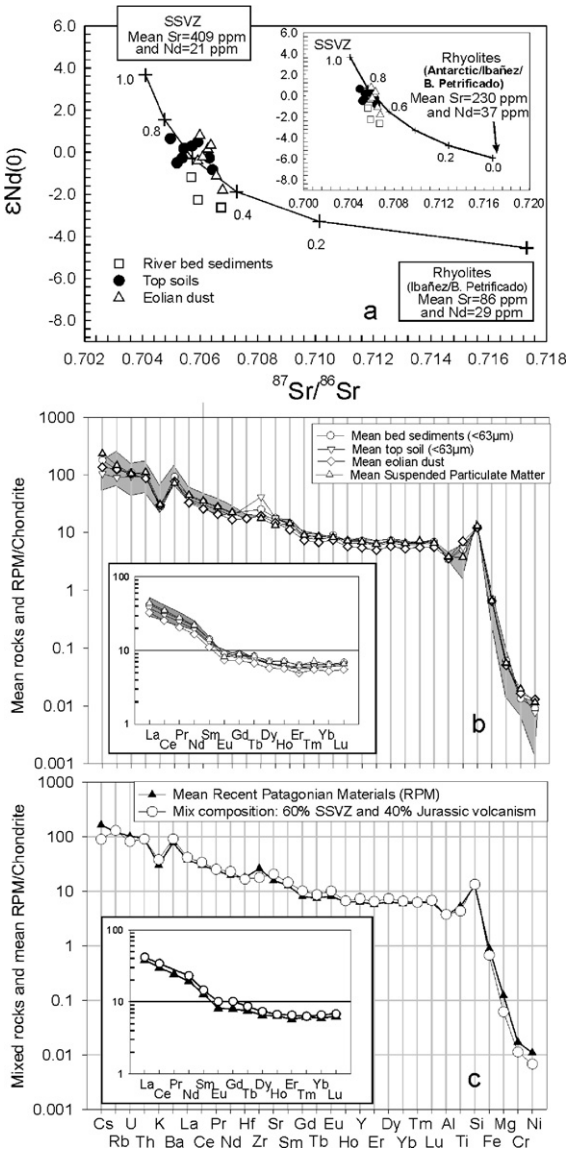

Fig. 4. (a) Two end-members (Southern South Volcanic Zone/SSVZ and Jurassic volcanism) mixing model explaining the homogeneous composition of Recent Patagonian materials (RPM). This is also stressed by the extended diagram that indicates that the mean chondrite-normalized elemental concentration for bed and suspended sediments, top soils and eolian dust fits well within the shadow area shaped by the mean concentrations of the SSVZ and Jurassic volcanism (b). Furthermore, using the mixing proportions from (a) it is possible to accurately reproduce the mean composition representing RPM (c).

Gaiero et al., 2003, 2004; Stern, 2004). Tephrochronological studies indicate that around 6700 BP the Hudson volcano produced the largest Holocene eruption in the southern Andes (>18 km^3 of tephra)(Naranjo and Stern, 1998). Additionally, in 1991 this volcano erupted 4–7 km^3 of tephra distributed over 150,000 km^2 in Chile and Argentina, thus producing the second largest eruption during the 20th century (Scasso et al., 1994). To what extent the materials erupted from this volcano explain the mantle-derived signature of Recent Patagonian materials?

The Hudson volcano shows a chemical (notably REE patterns) and isotopic composition that is very close to that of other volcanoes included in the SSVZ making it difficult to discriminate its influence on RPM (Figs. 2 and 3b). However, unlike the typical calc-alkaline arc magma signature that characterizes SSVZ, the Hudson depicts a within-plate basaltic characteristic, with a significant decrease in the LILE/HFSE ratios (Ramos and Kay, 1992), mostly explained by remarkably high Nb and Zr concentrations (D'Orazio et al., 2003). Independent of sorting mechanisms (Gaiero et al., 2004), RPM (particularly important on TS and ED) depict high Zr concentrations (Fig. 3a). Fig. 5 then indicates that La/Yb vs. Sr/Zr (LILE/HFSE) ratios found in RPM plot within the compositional area corresponding to materials erupted from the Hudson and highlights the significance of this volcano in supplying particles to the southern tip of South America.

Consistent with Fig. 2, Fig. 5 also highlights the influence of NSVZ materials (notably the Maipo volcano) in the chemical signature of bed sediment of the northernmost Patagonian river (Colorado).

Finally, the above suggested rock mixing contribution that build-up the typical RPM fingerprint is also confirmed using LILE/HFSE ratios (Fig. 5), which also leads to discard a significant contribution from other basic to intermediate rocks.

4.4. Patagonian dust signature in different high latitude environments

We now have a systematic study on the geochemical signature of sediments covering the surface of the extra-Andean sector of Patagonia which are eventually exported to other surrounding high-latitude environments.

An important feature of dust deposited during last glacial periods in Antarctic ice cores is that they depict an isotopic signature which shows a clear offset position when compared to bulk sediment samples from different southern environments (e.g. Patagonia, Patagonian shelf, Argentinean loess, North Scotia Sea and South Atlantic core sediments) (Fig. 6). This offset position could be interpreted as the effect of grain-size fractionation that affects the isotopic composition of very fine grain-size materials as that found in Antarctic ice cores (grain-size fraction around 2 μm)(e.g. Delmonte et al., 2004b). As observed above, many authors have previously

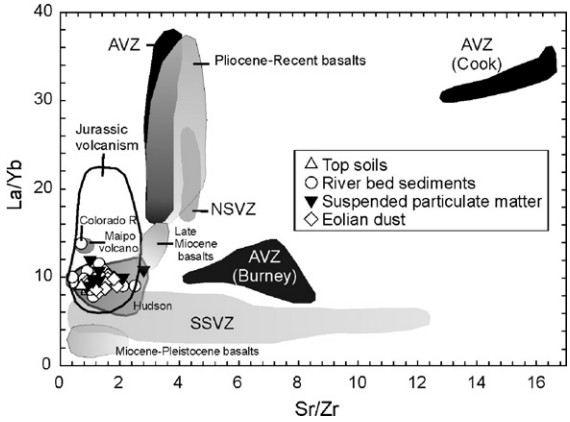

Fig. 5. La/Yb (LILE) vs Sr/Zr (HFSE) ratios for Recent Patagonian materials and Patagonian volcanic rocks. Except for the Colorado River bedload (see Section 4.3), all samples match exactly with the shadowed area representing the Hudson materials and point to the importance of this volcano in supplying particles to the whole Patagonian surface. Data were taken from: Quaternary volcanism (GEOROC database, http://georoc.mpch-mainz.gwdg.de, López-Escobar et al., 1993; Déruelle and Bourgois, 1993; Naranjo and Stern, 1998; D'Orazio et al., 2003 and this work); Tertiary Plateau lavas (Gorring and Kay, 2001; Gorring et al., 2003; D'Orazio et al., 2004); Jurassic rhyolites (Parada et al., 2001; Riley et al., 2001 and this work).

demonstrated that grain-size fractionation affects mainly Sr isotopic composition contrasting with Nd isotopes (Walter et al., 2000; Smith et al., 2003 and cites there in). This is illustrated in Fig. 6, where the isotopic composition of similar loess samples used by Delmonte et al. (2004a) to characterize dust sources in South America (grain-size < 5 μm), are compared to those employed by Smith et al. (2003) to study the Argentine loess origin (bulk sediments). Noticeably, for a similar $\varepsilon_{Nd}(0)$ composition, the fine grain-size fraction of similar loess samples shows a clear offset position to more radiogenic Sr values, thus matching very well with different dust samples found in Antarctic ice cores (Fig. 6). Similarly, the isotopic composition analyzed in a single Patagonian top soil (<5 μm grain-size fraction, Delmonte et al., 2004a) shows higher $^{87}Sr/^{86}Sr$ ratio and similar $\varepsilon_{Nd}(0)$ values when compared to Patagonian dust (~10 μm) and to <63 μm top soil samples (Fig. 6). This could imply that samples with similar $\varepsilon_{Nd}(0)$ values may have a related origin or can represent comparable mechanisms of eolian sediment transport and deposition for materials derived from southern South America.

Having in mind the above, it is clear that the uniform Patagonian "fingerprint" contrasts with the wide range of isotopic signatures previously employed to invoke a Patagonian origin for the terrigenous particles found in Antarctic ice cores (Grousset et al., 1992; Basile et al., 1997; Delmonte et al., 2004a) (Fig. 6). However, the differences between these data could be mainly attributed to the reduced number of samples belonging to the extra-Andean part of Patagonia, and also taking into account that most of these samples represent other southern South American environments (e.g., Pampa Plains, Chilean Patagonia, Tierra del Fuego), with contrasting environmental conditions during glacial times (Zárate, 2003; Gaiero et al., 2004). When the new isotopic signature defining the Patagonian region is plotted together with that of continental sediments found at higher latitudes (e.g., Pampean loess, Argentinean shelf sediments, Atlantic Ocean sediment cores and Antarctic dust cores) (Fig. 6), it becomes clear that none of them contain a pure Patagonian signature. If the conservative character of Nd isotopes and the grain-size fractionation dependence of Sr isotopes is confirmed, then Fig. 6 would indicate a similar origin for sediments found in different depositional southern environments, where Patagonian dust could represents the more basic to intermediate end-member composition.

Delmonte et al. (2004a) concluded that dust trapped in Antarctic ice during glacial times was provided almost exclusively from southern South America. Also, Gaiero et al. (2004) based on REEs composition of Recent sedimentary materials from different areas of southern South America proposed that, similarly to Pampean loess (considered as a proximal facies), most

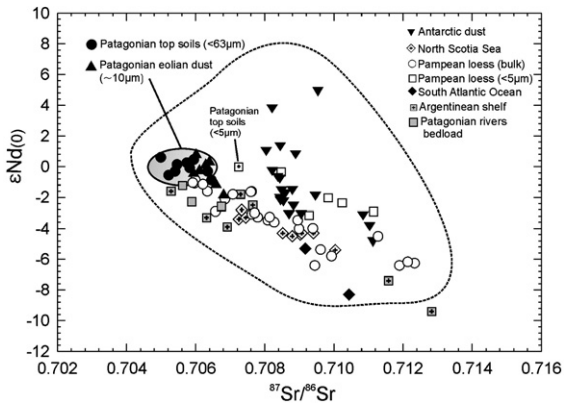

Fig. 6. Strontium and Nd isotopic composition of sediments from different high latitude depositional environments (data from Grousset et al., 1992; Basile et al., 1997; Gallet et al., 1998; Walter et al., 2000; Smith et al., 2003; Delmonte et al., 2004a), compared to the new data set obtained for top soils and eolian dust from Patagonia. The broken line represents the area used by Delmonte et al. (2004a) to represent the isotopic composition of sediments (<5 μm) from South America, which could explain the composition of dust found in Antarctic ice cores (data from Delmonte et al., 2004a,b). Also, Pampean loess and Patagonian top soil (<5 μm) data were taken from Delmonte et al. (2004a).

sediment cores of the North Scotia Sea and Antarctica could reflect a distal transport of dust with an admixed composition from areas with an undifferentiated geochemical signature (Patagonia, the closest landmass) and a proportion from source areas with sediments containing an upper crustal signature (Central-Western Argentina?/Puna–Altiplano Plateau?).

5. Concluding remarks

Recent Patagonian sediments appear to show a uniform chemical and isotopic signature explained by the presence of a regional availability of particles derived mainly from explosive volcanism that facilitates both, physical erosion, aerial, subaerial, or fluvial regional dispersion of the pyroclastic material.

After the main Andean uplift, increased denudation of Jurassic ignimbrites and of the sedimentary rocks derived from them, resulted in the accumulation of synorogenic sediments on the eastern slope of the Andes. As the southern Andes were repeatedly glaciated since the Late Miocene, the sediments were distributed on the extra-Andean region by inputs from glacial meltwater and by fluvial erosion of volcaniclastic deposits. Moreover, due to a predominant lava flow rock-type and because the Andean uplift caused a drastic orographic rain shadow (Blisniuk et al., 2005), the Tertiary Plateau volcanism, which occupied most of the eastern arid flat foreland, contributed little to build up the Patagonian geochemical signature.

Geochemical data indicate that the present Patagonian signature was achieved during the Pleistocene, along with the onset of the southern Andean arc explosive volcanism. The volcanic front in the SSVZ occurred in Chile, west to the continental divide. Particles derived from this area gradually contaminated extra-Andean surface sediments by dispersing tephra by means of dominant westerlies. Furthermore, during different glacial–interglacial cycles, fluvial systems transported enormous amount of sediment from the Andes that were then distributed over the entire Patagonian surface. In spite of the recent ash contribution from the Hudson volcano, contamination with materials supplied by this volcano does not modify the typical SSVZ and thus, the REEs distribution and isotopic composition of the Recent Patagonian materials was not significantly altered.

The uniform signature depicted by the Patagonian dust has strong implications for paleoclimatic studies in the region. Sediments deflated from the Patagonian surface result in easy-to-trace end-members in adjoining depositional environments, thus granting the opportunity to gain insight into present and paleo-circulation dynamics in the southern hemisphere. Further studies should elucidate the origin of the crustal-like fraction composition observed in Antarctic dust, South Atlantic sediments, Argentinean shelf and Pampean loess. This will allow the advancement of our knowledge on paleo-atmospheric circulation during glacial times in order to contribute to the improvement of AGCMs models.

Acknowledgements

This work was supported by the EC Project PARAT (Contract CI1*-T94-0030). We acknowledge the aid of the ECOS/SECyT program that promotes the scientific cooperation between France and Argentina. Funding was also supplied by Argentina's FONCYT (PICT 07-08524) and CONICET (PEI/6112). We are grateful to S. Bidart, M. Haller, C. Meister, and D. Puebla for their assistance with eolian traps. Our thanks to R. Rouault and J. Samuel of the Centre de Géochimie de la Surface (CNRS) at Strasbourg for major and trace element analyses and to P. Brunet of the LMTG (CNRS) at Toulouse for Nd and Sr isotopic measurements. Constructive comments of B. Delmonte and an anonymous reviewer are highly appreciated. D.M.G. and P.J.D. are members of the CICyT in Argentina's CONICET.

References

Basile, I., Grousset, F.E., Revel, M., Petit, J.R., Biscaye, P.E., Barkov, N.I., 1997. Patagonian origin of glacial dust deposited in East Antantica (Vostok and Dome C) during glacial stages 2, 4 and 6. Earth Planet. Sci. Lett. 146, 573–589.

Blisniuk, P.M., Stern, L.A, Chamberlain, C.P., Idleman, B., Zeitler, P.K., 2005. Climatic and ecologic changes during Miocene surface uplift in the Southern Patagonian Andes. Earth Planet. Sci. Lett. 230 (30), 125–142.

Brunet, F., Gaiero, D.M., Probst, J.-L., Depetris, P.J., Gauthier-Lafaye, F., Stille, P., 2005. ^{13}C tracing of dissolved inorganic carbon sources in the Patagonian rivers (Argentina). Hydrol. Process. 19, 3321–3344.

Clapperton, C., 1993. Quaternary geology and geomorphology of South America. Elsevier, Amsterdam, p. 780.

Delmonte, B., Basile-Doelsch, I., Petit, J.R., Maggi, V., Revel-Rolland, M., Michard, A., Jagoutz, E., Grousset, F., 2004a. Comparing the Epica and Vostok dust records during the last 220,000 years: stratigraphical correlation and provenance in glacial periods. Earth-Sci. Rev. 66 (1–2), 63–87.

Delmonte, B., Petit, J.R., Andersen, K.K., Basile-Doelsch, I., Maggi, V., Ya Lipenkov, V., 2004b. Dust size evidence for opposite regional atmospheric circulation changes over east Antarctica during the last climatic transition. Clim. Dyn. 23 (3–4), 427–438.

Déruelle, B., Bourgois, J., 1993. Sur la dernière eruption du volcan Hudson (sud Chili, août 1991). C.R. Acad. Sci. Paris 316 (2), 1399–1405.

Diekmann, B., Kuhn, B.G., Rachold, V., Abelmann, A., Brathauer, U., Fütterer, D.K., Gersonde, R., Grobe, H., 2000. Terrigenous sediment

supply in the Scotia Sea (Southern Ocean): response to Late Quaternary ice dynamics in Patagonia and the Antarctic Peninsula. Palaeogeogr. Palaeoclimatol. Palaeoecol. 162, 357–387.

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

D'Orazio, M., Innocenti, F., Manetti, P., Tamponi, M., Tonarini, S., González-Ferrán, O., Lahsen, A., Omarini, R., 2003. The Quaternary calc-alkaline volcanism of the Patagonian Andes close to the Chile triple junction: geochemistry and petrogénesis of volcanic rocks from Cay and Maca volcanoes (45°S, Chile). J. South Am. Earth Sci. 16, 219–242.

D'Orazio, M., Agostini, S., Innocenti, F., Haller, M.J., Manetti, P., Mazzarini, F., 2004. Slab window-related magmatism from southernmost South America: the Late Miocene mafic volcanics from the Estancia Glencross Area (~52°S, Argentina–Chile). Lithos 57 (2–3), 67–89.

Futa, K., Stern, C.R., 1988. Sr and Nd isotopic and trace element compositions of Quaternary volcanic centers of the southern Andes. Earth Planet. Sci. Lett. 88, 253–262.

Gaiero, D.M., Probst, J.L., Depetris, P.J., Leleyter, L., Kempe, S., 2002. Riverine transfer of heavy metals from Patagonia to the Southwesten Atlantic Ocean. Reg. Environ. Change 3, 51–64.

Gaiero, D.M., Probst, J.-L., Depetris, P.J., Bidart, S.M., Leleyter, L., 2003. Iron and other transition metals in Patagonian riverborne and windborne materials: geochemical control and transport to the southern South Atlantic Ocean. Geochim. Cosmochim. Acta 67 (19), 3603–3623.

Gaiero, D.M., Depetris, P.J., Probst, J.-L., Bidart, S.M., Leleyter, L., 2004. The signature of river-and wind-borne materials exported from Patagonia to the southern latitudes: a view from REEs and implications for paleoclimatic interpretations. Earth Planet. Sci. Lett. 219 (3–4), 357–376.

Gallet, S., Jahn, B., Van Vliet Lanoë, B., Dia, A., Rossello, E., 1998. Loess geochemistry and its implications for particle origin and composition of the upper continental crust. Earth Planet. Sci. Lett. 156, 157–172.

Goldschmidt, V.M., 1933. Grundlagen der quantitativen Geochemie. Fortschr. Mineral. Kristallogr. Petrog. 17, 112.

Gorring, M., Kay, S.M., 2001. Mantle processes and sources of Neogene slab window magmas from southern Patagonia, Argentina. J. Petrol. 42, 1067–1094.

Gorring, M., Singer, B., Gowers, J., Kay, S.M., 2003. Plio-Pleistocene basalts from the Meseta del Lago Buenos Aires, Argentina: evidence for asthenosphere–lithosphere interactions during slab window magmatism. Chem. Geol. 193 (3–4), 215–235.

Grousset, F.E., Biscaye, P.E., 2005. Tracing dust sources and transport patterns using Sr, Nd and Pb isotopes. Chem. Geol. 222, 149–167.

Grousset, F.E., Biscaye, P.E., Revel, M., Petit, J.R., Pye, K., Joussame, S., Jousel, J., 1992. Antarctic (Dôme C) ice-core dust at 18 k.y. B.P., isotopic constrains on origins. Earth Planet. Sci. Lett. 11, 175–182.

Hawkesworth, C.J., Norry, M.J., Roddick, P.E., Baker, P.E., Francis, P.W., Thorpe, R.S., 1979. $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, and incompatible element variations in calc-alkaline Andesites and Plateau lavas from South America. Earth Planet. Sci. Lett. 42, 45–57.

Jacobsen, S.B., Wasserburg, G.J., 1980. Sm–Nd isotopic evolution of chondrites. Earth Planet. Sci. Lett. 50, 139–155.

Kay, S.M., Ardolino, A.A., Franchi, M., Ramos, V., 1993. El origen de la Meseta de Somón Curá: Distribución y geoquímica de sus rocas volcánicas máficas. XII Congreso Geolológico Argentino y II Congreso de Exploración de Hidrocarburos, Buenos Aires.

Kilian, R., Behrmann, J.H., 2003. Geochemical constraints on the sources of Southern Chile Trench sediments and their recycling in arc magmas of the Southern Andes. J. Geol. Soc. (Lond.) 160, 57–70.

Lapido, O., Pereyra, F.X., 1999. Cuaternario de la Patagonia Extraandina. In: Caminos, R. (Ed.), Geologia Argentina, SEGEMAR, Buenos Aires, pp. 704–709.

López-Escobar, L., Kilian, R., Kempton, P., 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. Rev. Geol. Chile 20 (1), 33–55.

Lunt, D.J., Valdes, P.J., 2001. Dust transport to Dome C, Antarctica at the last glacial maximum and present day. Geophys. Res. Lett. 28 (2), 295–298.

Naranjo, J.A., Stern, C.R., 1998. Holocene explosive activity of Hudson Volcano, southern Andes. Bull. Volcanol. 59, 291–306.

Orihashi, Y., Naranjo, J.A., Motoki, A., Sumino, H., Hirata, D., Anma, R., Nagao, K., 2004. The Quaternary volcanic activity of Hudson and lautaro volcanoes, Chilean Patagonia: new age constraints from K–Ar ages. Rev. Geol. Chile 31 (2), 207–224.

Pankhurst, R.J., Rapela, C.W., 1995. Production of Jurassic rhyolite by anatexis of the lower crust of Patagonia. Earth Planet. Sci. Lett. 134, 23–36.

Pankhurst, R.J., Leat, P.T., Sruoga, P., Rapela, C.W., Márquez, M., Storey, B.C., Riley, T.R., 1998. The Chon Aike province of Patagonia and related rocks in West Antarctica: a silicic large igneous province. J. Volcanol. Geotherm. Res. 81, 113–136.

Pankhurst, R.J., Weaver, S.D., Hervé, F., Larrondo, P., 1999. Mesozoic–Cenozoic evolution of the North Patagonian Batholith in Aisén, southern Chile. J. Geol. Soc. (Lond.) 156, 673–694.

Parada, M.A., Lahsen, A., Palacios, C., 2001. Ages and geochemistry of Mesozoic–Eocene back-arc volcanic rocks in the Aysén region of the Patagonian Andes, Chile. Rev. Geol. Chile 28 (1), 25–46.

Pasquini, A.I., Depetris, P.J., Gaiero, D.M., Probst, J.-L., 2005. Material sources, chemical weathering and physical denudation in the Chubut River basin (Patagonia, Argentina): implications for Andean Rivers. J. Geol. 113, 451–469.

Pin, C., Briot, D., Bassin, C., Poitrasson, F., 1994. Concomitant separation of strontium and samarium–neodymium for isotopic analysis in silicate samples, based on specific extraction chromatography. Anal. Chim. Acta 298, 209–217.

Prospero, J.M., Ginoux, P., Torres, O., Nicholson, E.E., Gill, T., 2002. Environmental characterization of global sources of atmospheric soil dust identified with NIMBUS-7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol products. Rev. Geophys. 40 (1), 1002. doi:10.1029/2000RG000095.

Rabassa, J., Clapperton, C.M., 1990. Quaternary glaciations of the southern Andes. Quat. Sci. Res. 9, 153–174.

Ramos, V.A., Kay, S.M., 1992. Southern Patagonian Plateau basalts and deformation: backarc testimony of ridge collision. Tectonophysics 205, 261–282.

Rapela, C.W., Spalletti, L.A., Merodio, J.C., Aragón, E., 1988. Temporal evolution and spatial variation of early Tertiary volcanism in the Patagonian Andes (40°S–42°30′S). J. South Am. Earth Sci. 1, 75–88.

Rapela, C.W., Pankhurst, R.J., Fanning, C.M., Hervé, F., 2005. Pacific subduction coeval with the Karoo mantle plume: the Early Jurassic Subcordilleran Belt of northwestern Patagonia. In: Vaughan, A.P.M., Leat, P.T., Pankhurst, R.J. (Eds.), Terrane accretion processes at the Pacific Margin of Gondwana. Special Publication of the Geological Society of London, London, vol. 36, pp. 217–239.

Richard, P., Shimizu, N., Allegre, C.J., 1976. $^{143}Nd/^{144}Nd$, a natural tracer: an application to oceanic basalts. Earth Planet. Sci. Lett. 34, 13–22.

Riley, T.R., Leat, P.T., Pankhurst, R.J., Harris, C., 2001. Origins of large volume rhyolitic volcanism in Antarctica Peninsula and Patagonia by crustal melting. J. Petrol. 42 (6), 1043–1065.

Scasso, R., Corbella, H., Tiberi, P., 1994. Sedimentological analysis of the tephra from the 12–15 August 1991 eruption of Hudson volcano. Bull. Volcanol. 56, 121–132.

Sigmarsson, O., Martin, H., Knowles, J., 1998. Melting of subducting oceanic crust from U–Th disequilibria in austral Andean lavas. Nature 394, 566–569.

Smellie, J.L., 1999. The upper Cenozoic tephra record in the South Polar Region: a review. Global Planet. Change 21, 51–70.

Smith, J., Vance, D., Kemp, R.A., Archer, C., Toms, P., King, M., Zárate, M., 2003. Isotopic constraints on the source of Argentinean loess with implications for atmospheric circulation and the provenance of Antarctic dust during recent glacial maxima. Earth Planet. Sci. Lett. 212 (1–2), 181–196.

Stern, C.R., 2004. Active Andean volcanism: its geologic and tectonic setting. Rev. Geol. Chile 31 (2), 161–206.

Walter, H.J., Hegner, E., Diekmann, B., Kuhn, G., Rugters Van Der Loeff, M.M., 2000. Provenance and transport of terrigenous sediment in the South Atlantic Ocean and their relations to glacial and interglacial cycles: Nd and Sr isotopic evidence. Geochim. Cosmochim. Acta 64, 3813–3827.

Zárate, M.A., 2003. Loess of southern South America. Quat. Sci. Rev. 22 (18–19), 1987–2006.