Quaternary Science Reviews 29 (2010) 256–264

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Geographic provenance of aeolian dust in East Antarctica during Pleistocene glaciations: preliminary results from Talos Dome and comparison with East Antarctic and new Andean ice core data

B. Delmonte [a,*], P.S. Andersson [b], H. Schöberg [b], M. Hansson [c], J.R. Petit [d], R. Delmas [d], D.M. Gaiero [e], V. Maggi [a], M. Frezzotti [f]

[a] DISAT-University Milano-Bicocca, Piazza della Scienza, 1, 20126 Milano, Italy
[b] Laboratory for Isotope Geology, Swedish Museum for Natural History, Box 50007, 104 05 Stockholm, Sweden
[c] Department of Physical Geography and Quaternary Geology, Stockholm University, S-106 91 Stockholm, Sweden
[d] L.G.G.E.-C.N.R.S-Université Joseph Fourier, UMR 51230, BP 96, 38402 St Martin d'Hères Cedex, France
[e] CIGeS/CICTERRA/CONICET Centro de Investigaciones Geoquímicas y Procesos de la Superficie Facultad de Ciencias Exactas Físicas y Naturales, Universidad Nacional de Córdoba, Avda. Vélez Sársfield 1611, X5016CGA Córdoba, Argentina
[f] ENEA ACS-CLIMOSS Laboratory for Climate Observations – SP. Anguillarese, 301, I-00123 Roma, Italy

A R T I C L E I N F O

Article history:
Received 26 November 2008
Received in revised form
29 April 2009
Accepted 11 May 2009

A B S T R A C T

The strontium and neodymium isotopic signature of aeolian mineral particles archived in polar ice cores provides constraints on the geographic provenance of dust and paleo-atmospheric circulation patterns. Data from different ice cores drilled in the centre of the East Antarctic plateau such as EPICA-Dome C (EDC, 75°06′S; 123°21′E) and Vostok (78°28′S, 106°48′E) suggested a uniform geographic provenance for dust during Pleistocene glacial ages, likely from southern South America (SSA). In this work the existing dust isotopic data from EDC have been integrated with new data from Marine Isotopic Stage (MIS) 14 (about 536 ka before 1950AD) and in parallel some first results are shown for the new TALDICE ice core which was drilled on the edge of the East Antarctic Plateau (Talos Dome, 72°48′S, 159°06′E) on the opposite side with respect to SSA. Interestingly, the isotopic composition of TALDICE glacial dust is remarkably similar to that obtained from glacial dust from sites located in the East Antarctic interior.

Overall, the glacial dust isotopic field obtained from six East Antarctic ice cores matches well South American data obtained from target areas. In this respect, it was recently suggested that dust exported long-range from South America originates from Patagonia and from the Puna–Altiplano plateau. To test this hypothesis, we analysed the isotopic composition of dust from an ice core drilled on the Illimani glacier (Bolivia, 16°37′S, 67°46′W; 6350 m a.s.l.) in order to obtain information on the isotopic composition of regional mineral aerosol uplifted from the Altiplano area and likely transported over a long distance.

Altogether, ice core and source data strongly suggest that the westerly circulation pattern allowed efficient transfer of dust from South America to the East Antarctic plateau under cold Quaternary climates. Isotopic data support the hypothesis of a possible mixing of dust from Patagonia and from the Puna–Altiplano plateau. Interestingly, high glacial dust inputs to Antarctica are characterized by less radiogenic Nd values, an issue suggesting that enhanced dust production in Patagonia was associated with the activation of a secondary source. Still, Patagonia was the most important supplier for dust to central East Antarctica during Quaternary glaciations.

1. Introduction

Aeolian deflation of continents spreads mineral dust over a long distance around the globe. The smallest particles can be transported long-range up to high polar latitudes and they can be entrapped in snow and ice layers. Under optimal glaciological conditions polar ice cores preserve continuous, undisturbed and

* Corresponding author. Tel.: +39 (0)2 6448 2846; fax +39 (0)2 6448 2895.
E-mail addresses: barbara.delmonte@unimib.it (B. Delmonte), Per.Andersson@nrm.se (P.S. Andersson), Hans.Schoberg@nrm.se (H. Schöberg), margareta.hansson@natgeo.su.se (M. Hansson), petit@lgge.obs.ujf-grenoble.fr (J.R. Petit), delmas@lgge.obs.ujf-grenoble.fr (R. Delmas), dgaiero@efn.uncor.edu (D.M. Gaiero), valter.maggi@unimib.it (M. Maggi), frezzotti@casaccia.enea.it (M. Frezzotti).

0277-3791/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quascirev.2009.05.010

detailed stratigraphic records of mineral dust that can be used as proxies for paleoclimate and paleowinds (e.g. Ruth et al., 2003; EPICA Community Members, 2004, 2006). The eastern side of the Antarctic ice sheet is unique in this respect as the low accumulation rate and the considerable ice thickness allow recovery of very old dust and climate sequences.

To date, the longest ice core sequences from East Antarctica have been obtained from sites located in the interior of the plateau (Fig. 1a), such as EPICA (European Project for Ice Coring in Antarctica) – Dome C (onwards EDC, 75°06′S, 123°21′E; 3233 m a.s.l.), Vostok (78°28′S, 106°48′E; 3488 m a.s.l., Petit et al., 1999) and Dome Fuji (77°19′S, 39°42′E; 3810 m a.s.l., Watanabe et al., 2003).

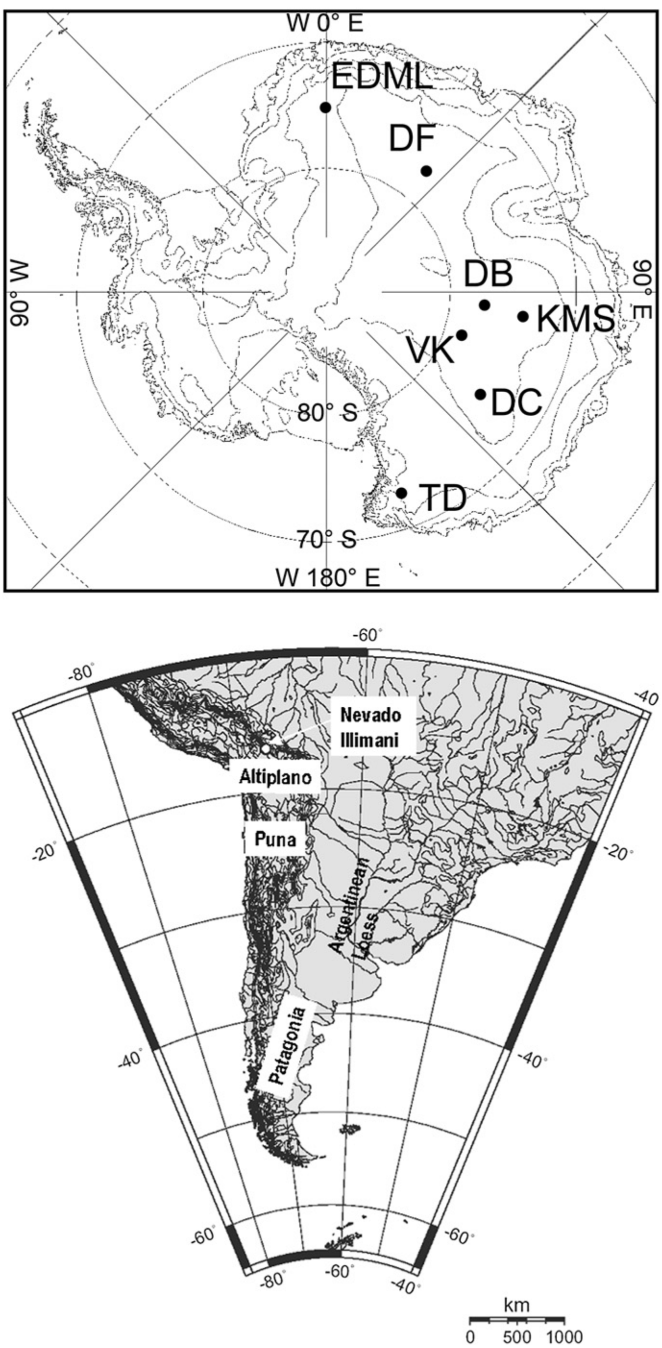

Fig. 1. (a) Map of Antarctica with location of the drilling sites cited in the text: Vostok (VK), Dome C (DC), Dome B (DB), Komsomolskaia (KMS), Talos Dome (TD), Dome Fuji (DF) and EPICA-Dronning Maud Land (EDML).(b) Map of South America with location of Illimani glacier (Bolivia), and the potential source regions mentioned in the text.

Recently a new ∼1620 m deep ice core has been recovered at Talos Dome (TALDICE ice core, 72°48′S; 159°05′E, 2316 m a.s.l.), which is a topographic dome located on the edge of the East Antarctic Plateau facing the South Pacific sector of the Southern Ocean (Urbini et al., 2008). As the mean annual accumulation rate at the site is relatively high (∼8 cm water equivalent per year over the last 200 years) this ice core is potentially suitable for a detailed documentation of the last climatic cycle in a sector of the Antarctic plateau subjected to different climate conditions.

The first undisturbed ∼3200 m of the ∼3260 m deep EDC ice core provide the longest and best-detailed record of climate and dust ever obtained from polar ice, going back in time to ∼800 ka before 1950AD or Marine Isotopic Stage (MIS) 20 (Jouzel et al., 2007; Lambert et al., 2008, Fig. 2). The records obtained from EDC and the other deep ice cores from central East Antarctica provide unequivocal evidence that deflation over continental areas, long-range transport and deposition of mineral dust responded to the major climate changes during the Quaternary (Petit et al., 1999; Delmonte et al., 2008). Because of the remoteness of the continental sources, the concentration of insoluble microparticles in Antarctica is extremely low, about 15 ppb (or $\mu g_{dust}/kg_{ice}$) at EDC and Vostok during the Holocene and earlier interglacials, ∼50 times more (∼800 ppb) on average during full glacial conditions, and intermediate levels (∼100 ppb) during interstadials (Lambert et al., 2008, Fig. 2).

Here we investigate the provenance of aeolian dust windborne to East Antarctica during Pleistocene glacial times in order to contribute to the understanding of the paleo-dust cycle and to set constraints to atmospheric general circulation models (AGCM) where dust is used as a tracer (Andersen et al., 1998). This target is achieved by using the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic composition of dust (Grousset and Biscaye, 2005). The first Sr and Nd isotopic data on ice core dust were provided in 1992 by Grousset and co-authors; that work was followed by a number of similar studies expanding the ice core sampling in time and in space (Basile et al., 1997; Delmonte et al., 2004a, b, 2008) and documenting the signature of dust from the Potential Source Areas (onwards PSAs, Smith et al., 2003; Revel-Rolland et al., 2006; Gaiero, 2007; Gaiero et al., 2007).

Overall, literature data available today corroborate the idea of a dominant southern South American (SSA) origin for dust reaching central east Antarctica during late Quaternary glacial ages, while the question remains open for dust from interglacial periods which display some different signature and properties (Delmonte et al., 2007; Lanci et al., 2008; Marino et al., 2008; Gabrielli et al., this volume). On the basis of geochemical data from Patagonia (Gaiero et al., 2007) and from non-Patagonian materials exported from SSA (Gaiero, 2007), there has been a recent emphasis on the role of Patagonia and the Puna (22°–26°S) and Altiplano (22°–10°S) Andean plateaus (Fig. 1b, onwards PAP) as sources for mineral dust exported long-range from South America during glacial times.

We present the first Sr and Nd isotopic data obtained from dust of the peripheral TALDICE ice core for the time interval 35–70 ka B.P corresponding to MIS 3 that we compare to data from ice cores located in central East Antarctica. A glacial dust isotopic field is constructed on the basis of all Antarctic ice core data available from the literature. This isotopic field is compared with the signature of dust from interglacial ice and with dust from potential source regions. Thus we are also able to test the hypothesis cited above (Gaiero, 2007) that both Patagonia and the PAP could be sources for glacial dust in Antarctica by comparing the isotopic composition of Antarctic dust with literature data for different south American sub-regions (the Puna–Altiplano,

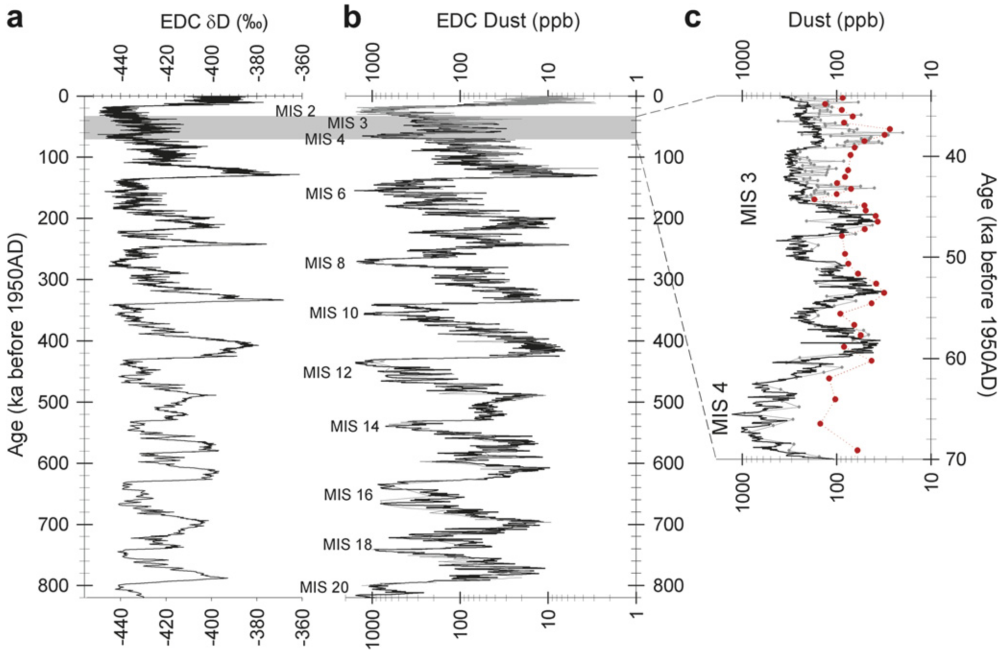

Fig. 2. Climate and dust records from East Antarctica. (a) EDC δD (per mil) record (Jouzel et al., 2007) spanning ~800 ka and showing Pleistocene glacial–interglacial cycles.(b) EDC mineral dust concentration record (Lambert et al., 2008) obtained by Coulter Counter (CC, grey line) and by Laser Sensor (LS, black line).(c) Zoom of the EDC dust profile (grey line: CC; black line: LS) from 34 to 70 ka before 1950AD (MIS 3) and first CC dust measurement from the TALDICE ice core (red dots, this work).

Patagonia, the Pampas) as well as with new isotopic data on dust from the Nevado Illimani ice core (Bolivia, Cordillera Oriental, 16°37′S, 67°46′W, 6350 m a.s.l., see Fig. 1b). Actually, the aeolian mineral dust trapped into the Illimani glacier can be considered as representative for local and regional material deflated from the Puna–Altiplano (Correia et al., 2003; De Angelis et al., 2003; Ramirez et al., 2003).

Finally, we present a synthesis of the Nd isotopic variability of glacial dust obtained from six East Antarctic ice cores for the Upper Pleistocene and from EDC and Vostok ice cores for the Middle and Lower Pleistocene. For EDC, the relationship between Nd isotopic composition of glacial dust and mineral dust input to the site will be discussed in terms of source contribution.

2. Materials and methods

Ice core samples from the Talos Dome ice core (TALDICE) were selected between 1000 and 1300 m depth (37 levels) according to ice core availability. This depth corresponds to the glacial MIS 3 and spans from ~35 to ~70 ka before 1950AD according to a preliminary dating (Buiron and Parrenin, pers. comm.). From the deep EDC ice core, only one sample corresponding to MIS 14 was selected between ~2905 and ~2921 m depth, in order to complement existing data (Delmonte et al., 2008). From the 136.7 m depth Illimani ice core two ice core sections were selected at 23 and 51 m depth (corresponding to ~1950 and 1930AD), where no acid layers of volcanic origin were detected (De Angelis et al., 2003).

Table 1
Isotopic data presented in this work.

EAST ANTARCTICA									
Ice core	Coordinates	ka before 1950AD	Size (μm)	$^{87}Sr/^{86}Sr$	$\pm 2\sigma * 10^{-6}$	$^{143}Nd/^{144}Nd$	$\pm 2\sigma_{mean} * 10^{-6}$	$\varepsilon_{Nd}(0)$	2σ
E. Antarctica, TALDICE-MIS 3, #TDG1	72°48′S, 159°06′E	About 52	<5	0.709025	13	0.512494	24	−2.8	0.5
E. Antarctica, TALDICE-MIS 3, #TDG2	72°48′S, 159°06′E	About 52	<5	0.708574	13	0.512710	18	1.4	0.4
E. Antarctica, EDC-MIS 14	75°06′S; 123°21′E	About 536	<5	0.709198	13	0.512587	41	−1.0	0.8
ANDEAN CORDILLERA									
Ice core	Coordinates	Age of sample		$^{87}Sr/^{86}Sr$	$\pm 2\sigma * 10^{-6}$	$^{143}Nd/^{144}Nd$	$\pm 2\sigma * 10^{-6}$	$\varepsilon_{Nd}(0)$	2σ
Bolivia, Illimani (#277f; #309f)	16°37′S, 67°46′W	About 1950–1930AD	<8	0.713172	13	0.512163	9	−9.3	0.4
Bolivia, Illimani (#310f; #311f)	16°37′S, 67°46′W	About 1950–1930AD	<8	0.713960	13	0.512180	14	−8.9	0.4
Bolivia, Illimani (#312f; #313f)	16°37′S, 67°46′W	About 1950–1930AD	<8	0.715400	13	0.512108	12	−10.3	0.4
Bolivia, Illimani (#314f; #315f)	16°37′S, 67°46′W	About 1950–1930AD	<8	0.715232	13	0.512187	16	−8.8	0.4
Bolivia, Illimani (#317f; #318f)	16°37′S, 67°46′W	About 1950–1930AD	<8	0.714658	13	0.512180	14	−8.9	0.4
Bolivia, Illimani (#309b)	16°37′S, 67°46′W	About 1950–1930AD	Bulk	0.712478	13	0.512201	15	−8.5	0.4
Bolivia, Illimani (#314b)	16°37′S, 67°46′W	About 1950–1930AD	Bulk	0.711443	16	0.512173	7	−9.1	0.4

1st column: ice core location and name. 2nd column: geographic coordinates. 3rd column: age of sample. 4th column: size fraction of dust analysed for Sr and Nd isotopic composition (bulk = all size included). 5th and 6th columns: $^{87}Sr/^{86}Sr$ isotopic composition $\pm 2\sigma * 10^{-6}$. Internal precision, $2\sigma_{mean}$,(2 standard errors of the mean) is used if it exceeds the external (Goldstein et al., 2003). External precision, 2σ, based upon reproducibility for low-level (~50 ng) Sr 987 standard runs, 0.710224 ± 0.000013 ($n = 9$). 7th and 8th columns: $^{143}Nd/^{144}Nd$ isotopic composition $\pm 2\sigma_{mean} * 10^{-6}$ (2 standard errors of the mean). 9th column: Nd isotopic ratios expressed as epsilon units. $\varepsilon_{Nd}(0) = [(^{143}Nd/^{144}Nd)_{sample}/(^{143}Nd/^{144}Nd)_{CHUR} - 1] \cdot 10^4$; CHUR, chondritic uniform reservoir with $^{143}Nd/^{144}Nd = 0.512638$. 10th column: epsilon error estimates are based upon reproducibility for the nNdβ standard in the range 6–16 ng, 0.511891 ± 0.000020 ($n = 8$). Internal precision is used if it exceeds the external (Goldstein et al., 2003).

Ice core samples were decontaminated and melted in the clean room at LGGE-CNRS (Laboratoire de Glaciologie et Géophysique de l'Environnement, Grenoble, France) following the procedure described in Delmonte et al. (2004a). An aliquot of each sample was dedicated to Coulter® Counter (CC) measurements of microparticle concentration and size distribution. For the Antarctic melt water samples, insoluble mineral dust was extracted through filtration of the liquid on a 0.4 μm Nuclepore polycarbonate track-etched membrane and by sonication of each membrane in ∼10 mL Milli-Q® water. For the Bolivian Illimani ice core, conversely, the CC measurements on melt water samples confirmed presence of large dust particles having mode of particle mass-size distribution from 6 to 10 μm (as noted already by Ramirez et al., 2003). Therefore, the fine fraction (<8 μm) of Illimani ice core dust was isolated by first removing the coarse fraction from the liquid (porosity of filter: 8 μm) and by extracting the fine fraction from the filtrate (porosity of filter: 0.4 μm). Particles were removed from the filter through sonication in pure water, as for the Antarctic samples. In this work five size-selected (0.4 μm < Ø < 8 μm) and two "bulk" (all size included) Illimani dust samples have been analysed for Sr and Nd isotopic composition.

The liquid containing concentrated dust was evaporated at the Laboratory for Isotope Geology (LIG) of the Swedish Museum of Natural History in Stockholm, and the amount of mineral dust was estimated by weighing. Because of the very low dust concentration in ice we obtained ∼200 μg of dust for the Antarctic samples and slightly higher values on average for the Andean samples. The chemical treatment of the samples including mineral dust digestion and element separation (Rb–Sr, Sm–Nd) using ion exchange chromatography was performed at LIG, where a special line dedicated to the treatment of very tiny samples was developed. After total spiking with a mixed $^{147}Sm/^{150}Nd$ spike and a ^{84}Sr enriched spike, the samples were dissolved and purified following the protocol described in Delmonte et al. (2008). Isolated Nd and Sr were analysed with a Thermo Scientific TRITON, thermal ionisation mass spectrometer, run in static mode using rhenium filaments and rotating gain compensation. Neodymium was analysed applying double filament technique and Aquadag colloidal graphite, whereas strontium was loaded on single filaments with tantalum oxide activator. Measured ^{144}Nd and ^{150}Nd intensities were corrected for samarium interference using $^{144}Sm/^{149}Sm = 0.222486$ and $^{150}Sm/^{149}Sm = 0.533992$, while measured ^{87}Sr intensities were corrected for Rb interference using $^{87}Rb/^{85}Rb = 0.38600$. Concentrations and ratios were reduced according to the exponential fractionation law and using normalizing ratios $^{146}Nd/^{144}Nd = 0.7219$

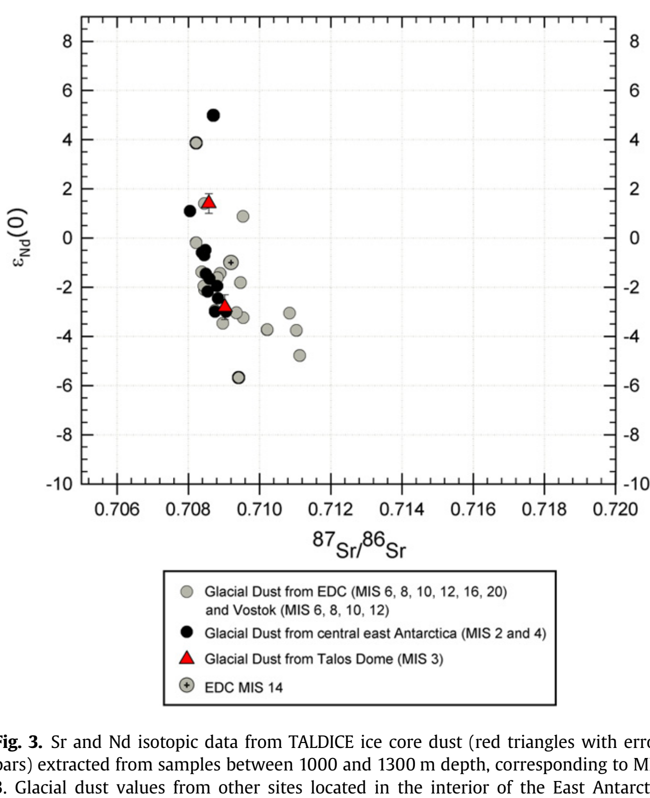

Fig. 3. Sr and Nd isotopic data from TALDICE ice core dust (red triangles with error bars) extracted from samples between 1000 and 1300 m depth, corresponding to MIS 3. Glacial dust values from other sites located in the interior of the East Antarctic Plateau are shown for comparison. Black circles: glacial dust (MIS 2 and 4) from five central East Antarctic ice cores: Vostok (78°28′S, 106°48′E; 3488 m a.s.l.), EDC (75°06′S, 123°21′E; 3233 m a.s.l.), Dome B (77°05′S, 94°55′E), Komsomolskaia (KMS, 74°05′S, 97°29′E, 3500 m a.s.l.), and the old ice core drilled in Dome C (74°39′S, 124°10′E; 3240 m a.s.l., Lorius et al., 1979). Grey circles: glacial dust from EDC (MIS 6, 8, 10, 12, 16, 20) and from Vostok (MIS 6, 8, 10, 12). Grey circle with cross: new EDC sample from MIS 14. Data sources: Grousset et al. (1992); Basile et al. (1997); Delmonte et al. (2004a, b, 2008 and this work).

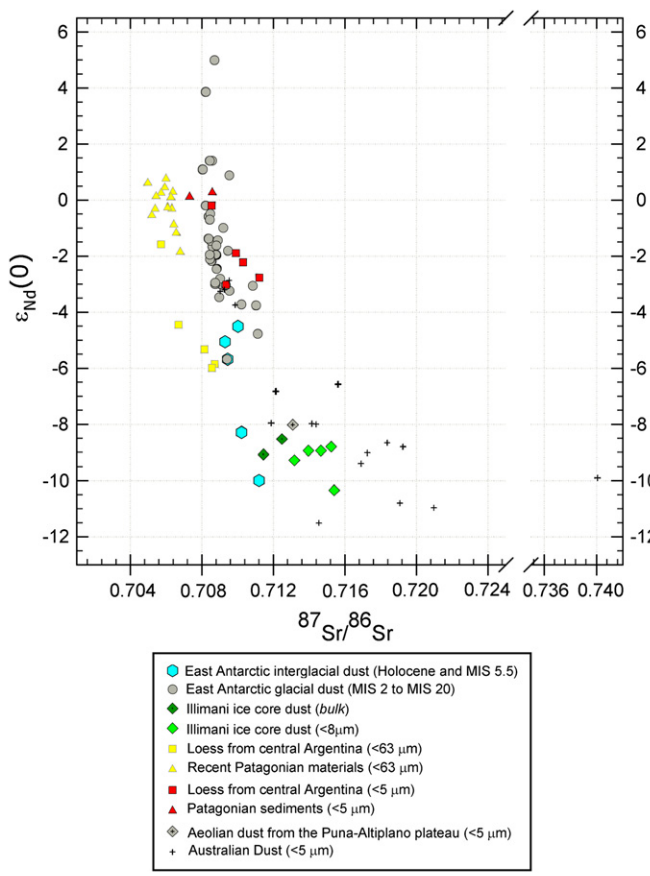

Fig. 4. Comparison of East Antarctic ice core dust and potential source areas from the Southern Hemisphere. Grey circles: Sr and Nd isotopic signature of Pleistocene glacial dust from six different ice cores drilled on the East Antarctic plateau (as in Fig. 3). Cyan hexagons: EDC and Vostok interglacial dust from the Holocene and from MIS 5.5 (Delmonte et al., 2007). South American and Australian data are reported for comparison. Red and yellow triangles (up): Patagonian sediments (size fractions <5 and <63 μm respectively; data from Delmonte et al., 2004a, Gaiero et al., 2007). Red and yellow squares: loess from central Argentina (size fractions <5 and <63 μm respectively; data from Delmonte et al., 2004a and from Gaiero, 2007). Grey diamond with cross: aeolian dust event on Buenos Aires (Delmonte et al., 2004a) recognized by Gaiero (2007) as originating from the Puna–Altiplano plateau. Green diamonds: dust (XX Century) extracted from the Illimani ice core (dark green hexagons: bulk samples; light green diamonds: <8 μm fraction). Black crosses: East Australian dust (<5 μm size fraction) from Revel-Rolland et al. (2006). The isotopic match between ice core glacial dust and south American samples from Patagonia and the Pampas can be better appreciated when the Sr isotopic correction for size (+0.0028 $^{87}Sr/^{86}Sr$ units according to Gaiero (2007) is applied to the <63 μm samples.

and $^{88}Sr/^{86}Sr = 8.375209$. Analysis of standards and error estimates are reported in Table 1. The total blank for Nd is <10 pg and for Sr <80 pg.

3. Results and discussion

3.1. Isotopic signature of Talos Dome and East Antarctic dust

The concentration of dust in the TALDICE ice core between 1000 and 1300 m depth (MIS 3) shows fluctuating values around a mean of 70 ppb (Fig. 2). This value is roughly ~40% the dust concentration at EDC and Vostok during the same climatic period, possibly due to a higher mean annual accumulation rate at the site. The mass-size distribution of the dust particles at Talos Dome is mostly within the size interval <5 μm in diameter, as for EDC and other sites located in central Antarctica, and the size distribution can be approximated by a lognormal regression with a mode of ~2 μm. Still, a few samples contain dust particles larger than 5 μm. The isotopic signature of the two glacial MIS 3 dust samples from Talos Dome is reported in Table 1 and shown in Fig. 3, where it is compared with literature data from glacial MIS 2 and MIS 4 obtained from five other ice cores drilled in central East Antarctica. Moreover, the isotopic composition of older glacial dust measured from the Vostok and the EDC ice cores is also reported for comparison. The isotopic similarity between Talos Dome and central East Antarctic sites is remarkable, suggesting a common dust source over the whole plateau during late Pleistocene glaciations.

From Fig. 3, the isotopic field of ice core glacial dust from the Upper Pleistocene (MIS 2, 3 and 4) constructed on the basis of six independent East Antarctic ice cores looks comparable to that from older (Middle and Lower Pleistocene) glacials (MIS 6–MIS 20) based on data from Vostok and EDC. For EDC, the dataset from Delmonte et al. (2008) is now supplemented with the new value obtained in this work for MIS 14 ($^{87}Sr/^{86}Sr = 0.709198 \pm 0.000013$ and $\varepsilon_{Nd}(0) = -1 \pm 0.8$, see Table 1). Overall, the complete isotopic dataset which is presented for glacial dust in Antarctica (Fig. 4) allows us to draw an isotopic field which is narrow for Sr ($^{87}Sr/^{86}Sr = 0.709002 \pm 0.000782$) and relatively large for Nd ($\varepsilon_{Nd}(0) = -1.5 \pm 2.2$). Similarly, an interglacial dust field is constructed on the basis of data from the Holocene and the Last Interglacial (Fig. 4, data from Delmonte et al., 2007). While this latter displays a slightly different Sr and Nd isotopic composition, a similar feature is observed: a low Sr isotopic variability ($^{87}Sr/^{86}Sr = 0.710030 \pm 0.000759$) and a more important isotopic

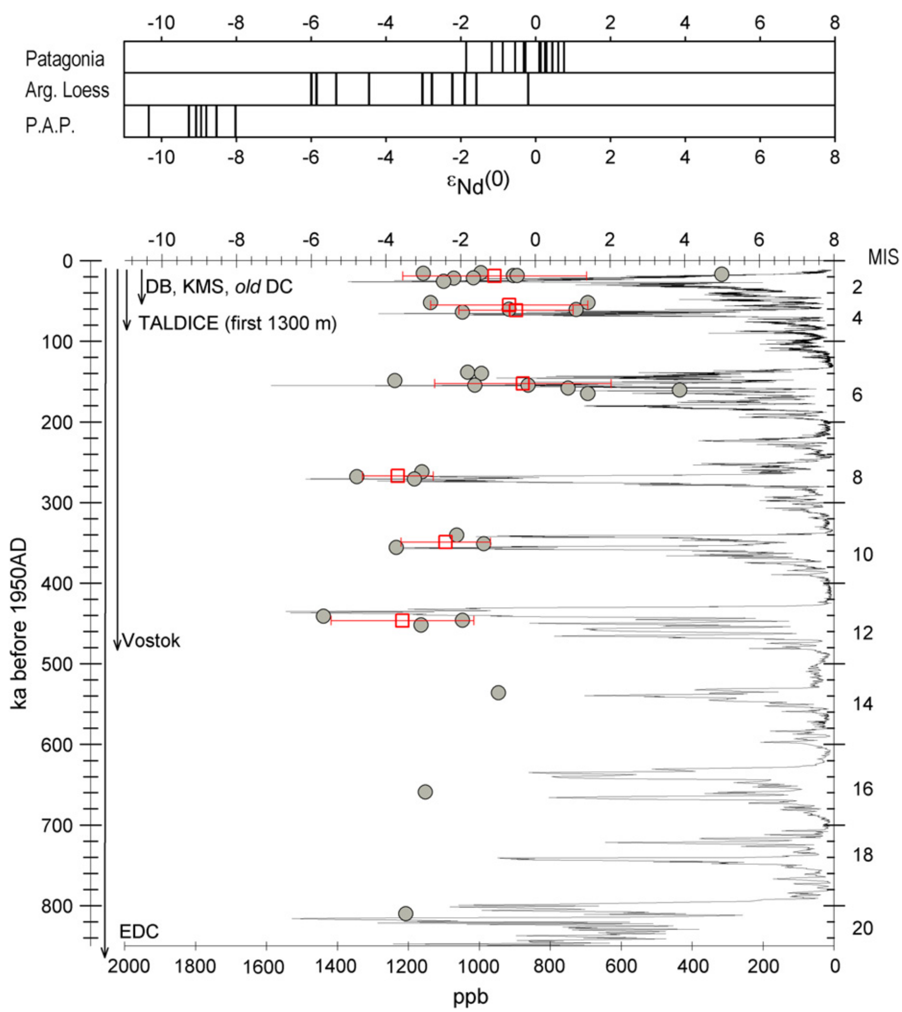

Fig. 5. EDC dust (LS) profile (Lambert et al., 2008) and Nd isotopic ($\varepsilon_{Nd}(0)$) composition of glacial dust. Grey circles: Nd isotopic signature ($\varepsilon_{Nd}(0)$) of Pleistocene glacial dust from six different ice cores from East Antarctica: Dome B (MIS 2), Komsomolskaia (MIS 2 and last climatic transition), "old" Dome C (DC) ice core (MIS 2), TALDICE (MIS 3), Vostok (MIS 4, 6, 8, 10 and 12) and EDC (MIS 2, 4, 6, 8, 10, 12, 14, 16 and 20). Red squares: average $\varepsilon_{Nd}(0)$ value calculated per each glacial MIS (2, 3, 4, 6, 8, 10 and 12) with standard deviation of data. On top of the figure the $\varepsilon_{Nd}(0)$ value of Patagonian materials, Argentinean loess and mineral dust from PAP is reported in a bar plot, each bar corresponding to one sample. The Nd isotopic differences between these three areas in SSA can be appreciated when looking at the position and density of bars.

variability for Nd around significantly lower values ($\varepsilon_{Nd}(0) = -6.7 \pm 2.3$).

3.2. *Dust from Nevado Illimani ice core: an attempt to document the Puna–Altiplano dust source*

In Fig. 4 we compare the isotopic fields defined for glacial and interglacial ice core dust to target samples collected within potential source regions that are active today and/or have been active during the Quaternary.

The very first attempts to characterize the Southern Hemisphere continental source areas in terms of Sr and Nd isotopic fingerprint (e.g. Basile et al., 1997; Delmonte et al., 2004a) were characterized by the use of poorly-classified samples; these studies allowed definition of a broad geochemical distinction among continents, pointing to SSA as the dominant supplier for mineral dust to East Antarctica during glacial times. However, only recently some important advances have been made in this respect, and target source areas within South America (e.g. Gaiero, 2007; Gaiero et al., 2007) and Australia (Revel-Rolland et al., 2006) have been much investigated. The study of Gaiero (2007) pointed to Patagonia and to the high-altitude PAP as primary sources for dust exported from South America to Antarctica. While the isotopic signature of Patagonian and Argentinean materials has been strongly investigated and is now well documented (Fig. 4), dust data from the Puna–Altiplano area are scarce. To overcome this lack of data, we measured aeolian dust extracted from the Illimani glacier, located in the Eastern Bolivian Andes about 6350 m of altitude. The mineral dust transported to Illimani glacier and entrapped in the ice layers is of local and regional origin, and particles exceeding 15 μm diameter have been frequently observed (Correia et al., 2003; J.C. Simoes, pers. comm.). Implicit in this work is to consider the dust from Illimani ice core as representative for mineral aerosol produced within the PAP area, which potentially is susceptible to long distance transport up to high latitudes of the southern hemisphere.

The average isotopic ratios from two Illimani ice core bulk samples (see Fig. 4 and Table 1; $^{87}Sr/^{86}Sr$ 0.711961 ± 0.00073; $\varepsilon_{Nd}(0) = -8.8 \pm 0.4$) are similar to those obtained from the fine (<8 μm) fraction of dust ($^{87}Sr/^{86}Sr = 0.714484 \pm 0.00093$; $\varepsilon_{Nd}(0) = -9.3 \pm 0.6$). These latter, however, displays slightly higher Sr ratios than bulk samples, a difference due to the well-known Sr isotopic fractionation with respect to the grain size. The $\Delta^{87}Sr/^{86}Sr$ (~0.0025) we deduce is close to the $\Delta^{87}Sr/^{86}Sr$ of ~0.0028 units given by (Gaiero, 2007) for particles between bin <63 μm and bin <5 μm diameter.

Considering the Illimani ice core data together with one sample of an aeolian dust event occurred in Buenos Aires in 1997 (Delmonte et al., 2004a) and recognized by Gaiero (2007) as originating from the PAP, a broad isotopic field for the PAP area can be obtained (Fig. 4). Although the Salar de Uyuni area is recognized as a present-day active dust source (e.g. Prospero et al., 2002), sediments from this sector (~20°S) show lower Sr isotopic ratios and less radiogenic Nd values compared to Illimani dust (Gaiero et al., in preparation). However, the isotopic composition of Illimani dust samples is very similar to volcanic rocks from the Altiplano–Puna volcanic complex (APVC) located in the northern Puna sector (21°S–24°S) (Ort et al., 1996; Lindsay et al., 2001) and to volcanic rocks from Cerro Galán further south (26°S, Francis et al., 1989). Paleo-eolian and modern eolian landforms are a common feature in the PAP area between 19° and 28°S. The 1993 Lascar eruption located in the APVC (23°40′S) was recorded in the Illimani ice core (De Angelis, 2003) and wind-eroded ignimbrites of likely late Pliocene to Pleistocene age are observed in the APVC and Cerro Galán areas (e.g. Goudie and Wells, 1995).

The comparison between all Antarctic glacial dust data available today and data from target PSA samples shows that – apart from two Antarctic glacial samples displaying very highly radiogenic Nd values – the whole collection of Antarctic ice core glacial samples matches the Patagonian and Pampean loess isotopic fields. The fit can be better appreciated when a Sr isotopic correction of ~0.0028 units is applied to data from materials having size <63 μm. Gaiero (2007) explained the signature of Antarctic glacial dust and that of Argentinean loess as a mixture of dust from Patagonia and from the Altiplano. However, it is still unclear if the Argentinean loess itself represents a (secondary) dust source for Antarctica during Quaternary glaciations or if it is merely a depositional environment (e.g. Zarate, 2003). We must underline that despite the consistent works recently made on South American potential source sub-regions, there are some smaller regions of SSA that are still not documented, as the Salar de Uyuni area (Gaiero, in preparation) for instance; also, some data on glacial lake sediments from Tierra del Fuego dating back to the last glacial period recently appeared (Sugden et al., 2009).

Taking into account on one hand the available data from Patagonia and on the other hand the new data from Illimani along with the aeolian dust event of august 1997 as representative for the Altiplano–Puna Andean plateaus, it can be observed in Fig. 4 that most Antarctic glacial data lie between these two isotopic end-members, along the hypothetical mixing line drawn by Gaiero (2007).

Overall, the Patagonian fingerprint appears dominant for Antarctic glacial samples, with some minor differences that will be discussed in Section 3.3. In fact, the glacial and periglacial processes related to Patagonian glaciations account for the enhanced dust production during cold times, while the presence of numerous enclosed basins allowed deposition and renewal of fine material

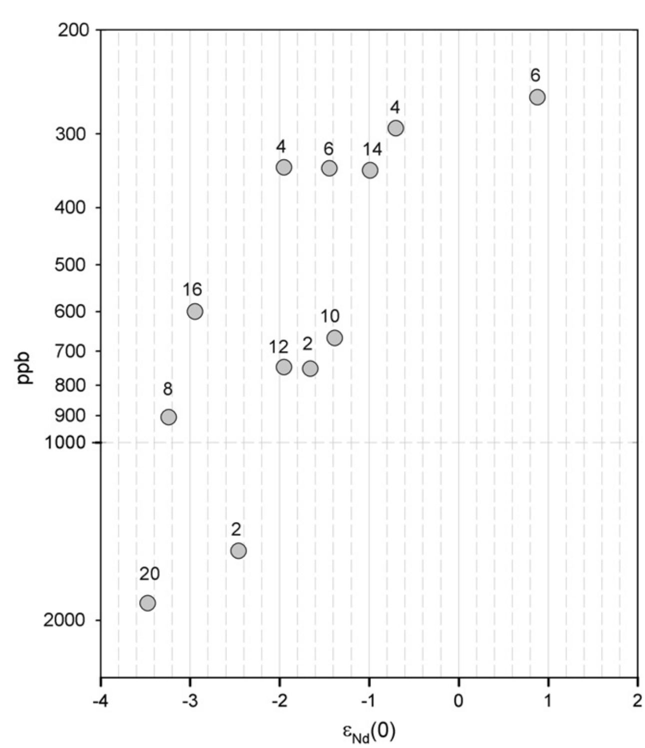

Fig. 6. Glacial dust $\varepsilon_{Nd}(0)$ isotopic value vs. dust concentration into EDC ice core. The $\varepsilon_{Nd}(0)$ value for dust each glacial sample from EDC ice core is plotted vs. the dust concentration (log scale) measured inside the sample used for geochemical measurements (i.e. in the meltwater sample, before dust extraction). Numbers close to each grey circle refer to the climatic stage (MIS) of each glacial sample.

potentially available to aeolian deflation (Gaiero, 2007; Sugden et al., 2009). Moreover, during glacial sealevel lowstands the Argentine continental shelf was exposed, and potentially available for aeolian deflation.

Questions remain on the sources of dust in central East Antarctica during interglacial periods, as the very small set of data from Vostok and EDC (Holocene and MIS 5.5) show a very low radiogenic Nd isotopic composition, suggesting a weakening of contribution the Patagonian end-member. In turn, this can be understood as a more important contribution from another end-member, which could be either East Australia (Revel-Rolland et al., 2006) or the low-latitude high Andean plateaus. Glacial/interglacial differences at EDC were also observed in the elemental composition of dust (see Marino et al., 2008 for major elements and Gabrielli et al., this volume for Rare Earth Elements) as well as in the concentration and mineralogy of magnetic minerals (Lanci et al., 2008). At this stage, it is difficult to draw general conclusions on interglacial dust in Antarctica, as additional data from interglacial ice as well as new data from target potential source areas including non-glaciated regions of peripheral Antarctica would be essential for solving this puzzle (e.g. Bory et al., 2005, in preparation; Delmonte et al., in preparation).

3.3. Pleistocene glaciations and dust fingerprinting

The available dataset of glacial dust from EDC and other East Antarctic ice cores allows discussion of the trend and the variability of the isotopic signature over several glaciations of the Pleistocene. As Sr isotopic ratios vary within a very narrow range, only the variability of Nd isotopic ratios ($\varepsilon_{Nd}(0)$) is considered at this step.

In Fig. 5 the dust concentration measured all along the EDC ice core (Lambert et al., 2008) is reported along with the $\varepsilon_{Nd}(0)$ ratios measured on six different ice cores from East Antarctica. These are the Dome B (DB), the Komsomolskaia (KMS) and the "old" Dome C (DC) and ice cores for the last glacial period and the last climatic transition (Grousset et al., 1992; Delmonte et al., 2004b), the Talos Dome ice core for MIS 3 (this work), the Vostok ice core for glacials from MIS 4 to MIS 12 (Basile et al., 1997; Delmonte et al., 2004a, 2008), and the EDC ice core for glacial ages from MIS 2 to MIS 20 (Delmonte et al., 2004a, 2008 and this work); from this latter, only data from MIS 18 are still missing. For each glacial, the average $\varepsilon_{Nd}(0)$ ratio along with its standard deviation is also reported. The Nd isotopic composition of ice core dust shows a high variability also inside each glacial stage (as it can be observed for MIS 2); however, when average values are taken into account, then MIS 8, 12 and 20 apparently display less radiogenic Nd isotopic values compared to MIS 2, 3, 4 and 6.

Ice core data are compared with the Nd isotopic composition for different SSA sub-regions (bars in the upper part of Fig. 4, each bar corresponding to one sample). For these latter, it can be observed that typical $\varepsilon_{Nd}(0)$ values for Patagonian materials are included in the $-2 < \varepsilon_{Nd}(0) < +0.8$ interval, while low radiogenic Nd isotopic ratios are characteristic for the Puna–Altiplano ($-10 < \varepsilon_{Nd}(0) < -8$) and intermediate values ($-6 < \varepsilon_{Nd}(0) < -0.2$) are typical for the Argentinean loess (see Fig. 4), as already observed by previous authors (e.g. Gaiero, 2007). Thus, the comparison between the SSA

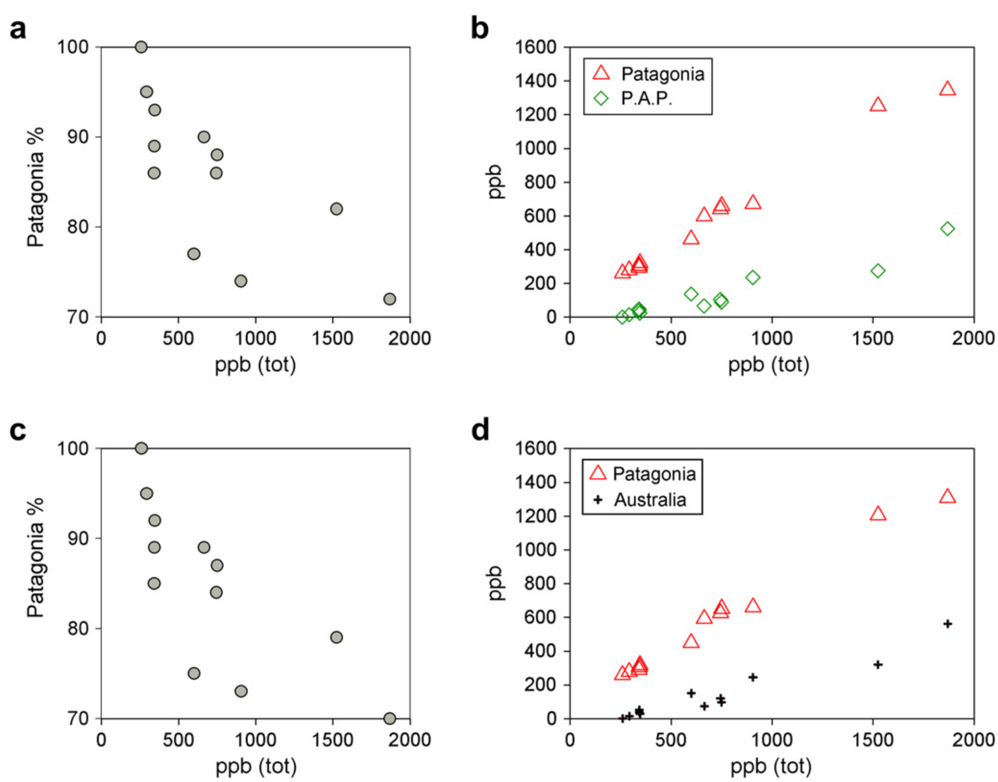

Fig. 7. Tentative assessment of the relative (%) and absolute (ppb) contribution of Patagonian dust in the EDC ice core during Pleistocene glacial ages, plotted vs. the total dust input to EDC. In (a) the relative (%) contribution of Patagonian dust per each glacial stage at EDC is estimated from the mixing hyperbola drawn by Gaiero (2007) between Patagonia and the PAP sources. In (b) these percentages are applied on the total dust concentration of the samples and the absolute (ppb) amount of dust coming from each source is estimated. In (c) the same exercise is performed by calculating the relative (%) Patagonian contribution from a mixing hyperbola between a Patagonian and an East Australian end-member, this latter defined as in Revel-Rolland et al., 2006. In (d) the percentages are applied to the total dust load and the contribution from Patagonia and Australia is quantitatively assessed. The similarity between the two cases, respectively when a PAP (a, b) or when an Australian (c, d) end-member is considered, is due to the similar Nd (and to a lesser extent Sr) isotopic composition of these two source areas.

and the ice core Nd isotopic composition suggests that low radiogenic Nd isotopic values can be associated to a relatively weaker Patagonian contribution.

In order to understand this issue, we compare the Nd isotopic composition of each EDC glacial sample vs. the dust concentration (or flux, this latter not reported) measured by CC technique inside the same sample (Fig. 6). Data interestingly show that the lowest Nd isotopic ratios are associated to the most severe glacial dust inputs to EDC (or to the highest dust fluxes). This evidence suggests that during intense glacial dust input to East Antarctica the Patagonian contribution was probably higher in absolute terms but supplemented by the contribution from a secondary source having a low radiogenic Nd isotopic composition that influenced the overall isotopic composition of the dust deposited in Antarctic snow and ice layers.

With respect to this second (low radiogenic) source, it is hard to discriminate between a PAP and an Australian end-member, as these two regions are quite similar from a Sr and Nd isotopic point of view. A tentative assessment of the relative (%) and absolute (ppb) contribution from Patagonia during glacial stages is made in Fig. 7. When considering a mixing between a Patagonian and a PAP end-member (Figs. 7a,b) as defined by Gaiero (2007), the relative contribution from Patagonia can be estimated from 100 to 70% during each glacial stage at EDC, the lower percentages corresponding to higher dust inputs. When these percentages are applied to the total dust load (Fig. 7b) one can observe that in absolute terms, during periods of high dust input to Antarctica the Patagonian source was actually more active. Similarly, when considering a mixing between Patagonian and Australian dust, this latter defined as in Revel-Rolland et al. (2006), one finds a similar range of values (Figs. 7c,d). As the dust input to Antarctica increases, the Patagonian source decreases from 100 to about 70% (and vice versa Australia), but in absolute terms the Patagonian source becomes stronger (Fig. 7d).

Regardless of where the second end-member comes from, this study confirms that Patagonia was the dominant source for dust in central East Antarctica during late Quaternary glaciations, and that intense dust inputs to EDC reflect a stronger Patagonian dust production associated with the activation of another source playing a secondary role.

4. Conclusions

During the last glacial period the source for windborne aeolian dust to Talos Dome and to the sites located in the interior of the East Antarctic plateau was likely the same. However, more data are needed at this step in order to test this evidence and provide constraints to AGCM.

Comparison with data from potential source regions, and in particular with new and literature data from sub-regions inside South America, confirms that the isotopic signature of glacial dust in Antarctica is well-represented by a mixing between a Patagonian end-member and a second one which can be located on the high subtropical Andean plateaus.

The dust input to central East Antarctica during Pleistocene glaciations and the isotopic fingerprint of mineral dust are somewhat related over the last 800 ka. In particular, data suggest that the strengthening of the Patagonian source during most intense glaciations was accompanied by parallel activation of a secondary source playing a minor but non-negligible role. When Sr and Nd isotopic data are considered, this secondary source can be either the Puna–Altiplano area or East Australia.

In this study we confirm that Patagonia was generally the most important source for dust in East Antarctica during Late Quaternary glacial ages, the westerly circulation allowing efficient dust transfer from South America to Antarctica during cold periods over the last 800,000 years.

Acknowledgements

This work was carried out at the Swedish Museum of Natural History and was supported by SYNTHESYS funding (project SE-TAF-4807) made available by the European Community – Research Infrastructure Action under the FP6 “Structuring the European Research Area” Programme.

This work is a contribution to the European Project for Ice Coring in Antarctica (EPICA), a joint European Science Foundation/European Commission scientific programme, funded by the EU and by national contributions from Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland and the United Kingdom. The main logistic support was provided by IPEV and PNRA (at Dome C) and AWI (at Dronning Maud Land). This is EPICA publication no. 223.

The Talos Dome Ice core Project (TALDICE), a joint European programme, is funded by national contributions from Italy, France, Germany, Switzerland and the United Kingdom. Main logistic support was provided by PNRA. This is TALDICE publication no. 5

Special thanks to P. Ginot for providing samples from the Illimani ice core, to Prof. D. Sugden and Dr. S. Jamieson for useful discussion. Thanks to F. Grousset, A. Bory and E. Wolff for improving this manuscript through careful review.

References

Andersen, K.K., Armengaud, A., Genthon, C., 1998. Atmospheric dust under glacial and interglacial conditions. Geophys. Res. Lett. 25, 2281–2284.

Bory, A., Jagoutz, E., Wegner, A., Ruth, U., Mulvaney, R., Wolff, E., 2005. Temporal Variability in the Provenance of Recent Mineral Dust Deposits on Berkner Island, Antarctica, Eos Trans. AGU, 86(52), Fall Meet. Suppl., Abstract PP33C-1580.

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 Antarctica (Vostok and Dome C) during glacial stages 2, 4 and 6. Earth Planet. Sci. Lett. 146, 573–589.

Correia, A., Freydier, R., Delmas, R., Simoes, J.C., Taupin, J.-D., Dupre, B., Artaxo, P., 2003. Trace elements in South America aerosol during 20th century inferred from a Nevado Illimani ice core, Eastern Bolivian Andes (6350 m a.s.l. Atmos. Chem. Phys. 3, 1337–1352.

De Angelis, M., Simoes, J.C., Bonnaveira, H., Taupin, J.-D., Delmas, R., 2003. Volcanic eruptions recorded in the Illimani ice core (Bolivia): 1918–1998 and Tambora periods. Atmos. Chem. Phys. 3, 1725–1741.

Delmonte, B., Andersson, P.S., Hansson, M., Schoberg, H., Petit, J.R., Basile-Doelsch, I., Maggi, V., 2008. Aeolian dust in East Antarctica (EPICA-Dome C and Vostok): provenance during glacial ages over the last 800 ka. Geophys. Res. Lett. L07703, 35.

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, 63–87.

Delmonte, B., Petit, J.R., Andersen, K.K., Basile-Doelsch, I., Maggi, V., Lipenkov, V., 2004b. Dust size evidence for opposite regional atmospheric circulation changes over East Antarctica during the last climatic transition. Clim. Dyn 23, 427–438. DOI 410.1007/s00382-00004-00450-00389.

Delmonte, B., Petit, J.R., Basile-Doelsch, I., Jagoutz, E., Maggi, V., 2007. Late Quaternary Interglacials in East Antarctica from ice core dust records. In: Sirocko, F., Claussen, M., Litt, T. (Eds.), The Climate of Past Interglacials. Elsevier, Amsterdam, pp. 53–73.

Delmonte, B., Andersson, P.S., Hansson, M., Schoberg, H., Petit, J.R., Basile-Doelsch, I., Maggi, V., 2008. Aeolian dust in East Antarctica (EPICA-Dome C and Vostok): provenance during glacial ages over the last 800 ka. Geophys. Res. Lett. L07703, 35.

EPICA Community Members, 2004. Eight glacial cycles from an Antarctic ice core. Nature 429, 623–628.

EPICA Community Members, 2006. One-to-one coupling of glacial climate variability in Greenland and Antarctica. Nature 444, 195–198.

Francis, P.W., Sparks, R.S.J., Hawkesworth, C.J., Thorpe, R.S., Pyle, D.M., Tait, S.R., Mantovani, M.S.M., McDermott, F., 1989. Petrology and geochemistry of volcanic rocks of the Cerro Galan Caldera, Northwest Argentina. Geological Magazine 126, 515–547.

Gaiero, D.M., 2007. Dust provenance in Antarctic ice during glacial periods: from where in southern South America? Geophys. Res. Lett 34, L17707.

Gaiero, D.M., Brunet, F., Probst, J.-L., Depetris, P.J., 2007. A uniform isotopic and chemical signature of dust exported from Patagonia: rock sources and occurrence in southern environments. Chem. Geol. 238, 107–120.

Goldstein, S.L., Deines, P., Oelkers, E.H., Rudnick, R.L., Walter, L.M., 2003. Standards for publication of isotopic ratio and chemical data in Chemical Geology. Chem. Geol. 202, 1–4.

Goudie, A.S., Wells, G.L., 1995. The nature, distribution and formation of pans in arid zones. Earth Sci. Rev. 38, 1–69.

Grousset, F., 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., Jossaume, S., Jouzel, J., 1992. Antarctic (Dome C) ice-core dust at 18 k.y. B.P.: isotopic constraints and origins. Earth. Planet. Sci. Lett. 111, 175–182.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J.M., Chappellaz, J., Fischer, H., Gallet, J.C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J.P., Stenni, B., Stocker, T.F., Tison, J.L., Werner, M., Wolff, E.W., 2007. Orbital and millennial Antarctic climate variability over the past 800,000 years. Science 317, 793–797.

Lambert, F., Delmonte, B., Petit, J.R., Bigler, M., Kaufmann, P.R., Hutterli, M. Stocker, T.F., Ruth, U., Steffensen, J.P., Maggi, V., 2008. New constraints on the dust-climate couplings from the 800,000-year EPICA Dome C ice core. Nature 452 (7187), 616–619. doi:10.1038/nature06763.

Lanci, L., Delmonte, B., Maggi, V., Petit, J.R., Kent, D.V., 2008. Ice magnetization in the EPICA-Dome C ice core: implication for dust sources during glacial and interglacial periods. J. Geophys. Res. Atmos 113, D14207. doi:10.1029/2007JD009678.

Lindsay, J.M., Schmitt, A.K., Trumbull, R.B., De Silva, S.L., Siebel, W., Emmermann, R., 2001. Magmatic evolution of the La Pacana Caldera system, Central Andes, Chile: compositional variation of two cogenetic, large-volume felsic ignimbrites. J. Petrol 42, 459–486.

Lorius, C., Merlivat, L., Jouzel, J., Pourchet, M., 1979. A 30,000 yr isotope climatic record from Antarctic ice. Nature 280, 644–648.

Marino, F., Castellano, E., Ceccato, D., De Deckker, P., Delmonte, B., Ghermandi, G., Maggi, V., Petit, J.-R., Revel-Rolland, M., Udisti, R., 2008. Defining the geochemical composition of the Epica Dome C ice core dust during the last Glacial–Interglacial cycle. Geochem. Geophys. Geosyst 9, Q10018. doi:10.1029/2008GC002023.

Ort, M.H., Coira, B.L., Mazzoni, M.M., 1996. Generation of a crust-mantle magma mixture: magma sources and contamination at Cerro Panizos, central Andes. Contrib. Mineral. Petrol 123, 308–322.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., Stievenard, M., 1999. Climate and atmospheric history of the past 420000 years from the Vostok ice core, Antarctica. Nature 399, 429–436.

Prospero, J.M., Ginoux, P., Torres, O., Nicholson, S.E., 2002. Environmental characteristics of global sources of atmospheric soil dust derived from the NIMBUS-7 TOMS absorbing aerosol product. Rev. Geophys 40. doi:10.1029/2000RG000092.

Ramirez, E., Hoffmann, G., Taupin, J.D., Francou, B., Ribstein, P., Caillon, N., Ferron, F.A., Landais, A., Petit, J.R., Pouyaud, B., Schotterer, U., Simoes, J.C., Steivenard, M., 2003. A new Andean deep ice core from Nevado Illimani (6350m), Bolivia. Earth Planet. Sci. Lett. 212, 337–350.

Revel-Rolland, M., De Dekker, P., Delmonte, B., Hesse, P., Magee, J.W., Basile-Doelsch, I., Grousset, F., Bosch, D., 2006. Eastern Australia: a possible source of dust in East Antarctica interglacial ice. Earth Planet. Sci. Lett. 249, 1–13.

Ruth, U., Wagenbach, D., Steffensen, J.P., Biggler, M., 2003. Continuous record of microparticle concentration and size distribution in the central Greenland NGRIP ice core during the last glacial period. J. Geophys. Res. 108, 4098–4110.

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

Sugden, D.E., McCulloch, R.D., Bory, A.J.-M., Hein, A.S., 2009. Influence of Patagonian glaciers on Antarctic dust deposition during the last glacial. Nat. Geosci 2, 281–285.

Urbini, S., Frezzotti, M., Gandolfi, S., Vincent, C., Scarchilli, C., Vittuari, L., Fily, M., 2008. Historical behaviour of Dome C and Talos Dome (East Antarctica) as investigated by snow accumulation and ice velocity measurements. Global Planet. Change 60, 576–588.

Watanabe, O., Jouzel, J., Johnsen, S., Parrenin, F., Shoji, H., Yoshida, N., 2003. Homogeneous climate variability across East Antarctica over the past three glacial cycles. Nature 422, 509–512.

Zarate, M., 2003. Loess of southern South America. Quaternary Sci. Rev. 22, 1987–2003.