Aeolian dust in East Antarctica (EPICA-Dome C and Vostok): Provenance during glacial ages over the last 800 kyr

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[1] Aeolian mineral dust archived in Antarctic ice cores represents a key proxy for Quaternary climate evolution. The longest and most detailed dust and climate sequences from polar ice are provided today by the Vostok and by the EPICA-Dome C (EDC) ice cores. Here we investigate the geographic provenance of dust windborne to East Antarctica during Early and Middle Pleistocene glacial ages using strontium and neodymium isotopes as tracers. The isotopic signature of Antarctic dust points towards a dominant South American origin during Marine Isotopic Stage (MIS) 8, 10, 12, and back to MIS 16 and 20 as deduced from EDC core. Data provide evidence for a persistent overall westerly circulation pattern allowing efficient transfer of dust from South America to the interior of Antarctica over the last 800 kyr. Some small but significant dissimilarity between old and recent glacial ages suggests a slightly reduced Patagonian contribution during ancient glaciations. **Citation:** Delmonte, B., P. S. Andersson, M. Hansson, H. Schöberg, J. R. Petit, I. Basile-Doelsch, and V. Maggi (2008), Aeolian dust in East Antarctica (EPICA-Dome C and Vostok): Provenance during glacial ages over the last 800 kyr, *Geophys. Res. Lett.*, *35*, L07703, doi:10.1029/2008GL033382.

1. Introduction

[2] The assessment of atmospheric dust changes in Quaternary times and the identification of the major dust source areas are key issues for paleoclimate research [*Kohfeld and Harrison*, 2001] and fundamental inputs for GCM simulations [e.g., *Mahowald et al.*, 1999]. While the Late Pleistocene and the Holocene paleo-dust cycle is well documented by means of numerous ice cores recovered in central East Antarctica [*Bigler et al.*, 2006; *Delmonte et al.*, 2004a, 2004b], only the Vostok (78°28′ S, 106°48′ E) ice core [*Petit et al.*, 1999; *Raynaud et al.*, 2005] and the EPICA (European Project for Ice Coring in Antarctica) ice core [*EPICA Community Members*, 2004; *Wolff et al.*, 2006; *Jouzel et al.*, 2007] drilled in Dome C (EDC, 75°06′ S, 123°21′ E) allow extension of the climate record far back in time into the Middle and Early Pleistocene.

[3] Aeolian minerals reaching the East Antarctic plateau are windborne long-range from the austral continental landmasses and transported through the mid-to-high troposphere. Because of the remoteness of the sources, concentrations in ice are extremely low and changed according to the rhythm of Pleistocene glaciations (Figure 1). Typical levels are $\sim$15 μg kg^{-1} (ppb) at both EDC and Vostok sites during interglacials and $\sim$800 μg kg^{-1} during ice age periods. The glacial/interglacial dust concentration ratio is $\sim$50 on average, corresponding to a factor $\sim$25 in flux [*Lambert et al.*, 2008] as the snow accumulation rate was reduced in cold periods. Relatively high concentrations during glacial ages reflect the enhanced atmospheric dust load related to aridity over continental areas, consistent primary dust production, reduction of the atmospheric cleansing and hydrological cycle [e.g., *Yung et al.*, 1996]. Weathering and glacial grinding played a major role, while the contribution of the exposed continental shelf during low stand sea level periods is controversial [*Basile et al.*, 1997; *Wolff et al.*, 2006; *Zarate*, 2003; *Gaiero*, 2007]. Conversely, only modest changes in the overall mean transport (surface wind, atmospheric circulation and meridional transport over Antarctica) between glacial and interglacial stages are suggested by recent modelling studies [*Krinner and Genthon*, 2003].

[4] Understanding the geographic origin of continental dust reaching Antarctica today and under different climate conditions is essential for tracking past changes in environmental and atmospheric circulation regimes. This target can be achieved by using suitable tracers as the Sr and Nd isotopic composition of dust, which is distinctive of the source regions and conservative between the source and the sink area [e.g., *Grousset and Biscaye*, 2005]. Antarctic dust consists of common detrital minerals such as clays, quartz and feldspars [*Gaudichet et al.*, 1988]. Since the first ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd ($\varepsilon_{Nd}(0)$) isotopic ratios on dust extracted from ice dating the Last Glacial Maximum ($\sim$18 kyr B.P.) it became clear that the dominant source area was the Argentine Patagonia [*Grousset et al.*, 1992]. Following isotopic studies [*Basile et al.*, 1997; *Delmonte et al.*, 2004a, 2004b] corroborated the idea of a dominant South American origin for dust in East Antarctica during Late Quaternary glacial ages, extending the sampling to different East Antarctic drilling sites. To date, Sr and Nd isotopic data are reasonably documented for recent glacial stages (MIS 2, 4 and 6), but very scarce for MIS 8, 10 and 12 and absent before. This work has investigated and extended the provenance record for dust in East Antarctica further back into ancient Pleistocene glacial ages prior to

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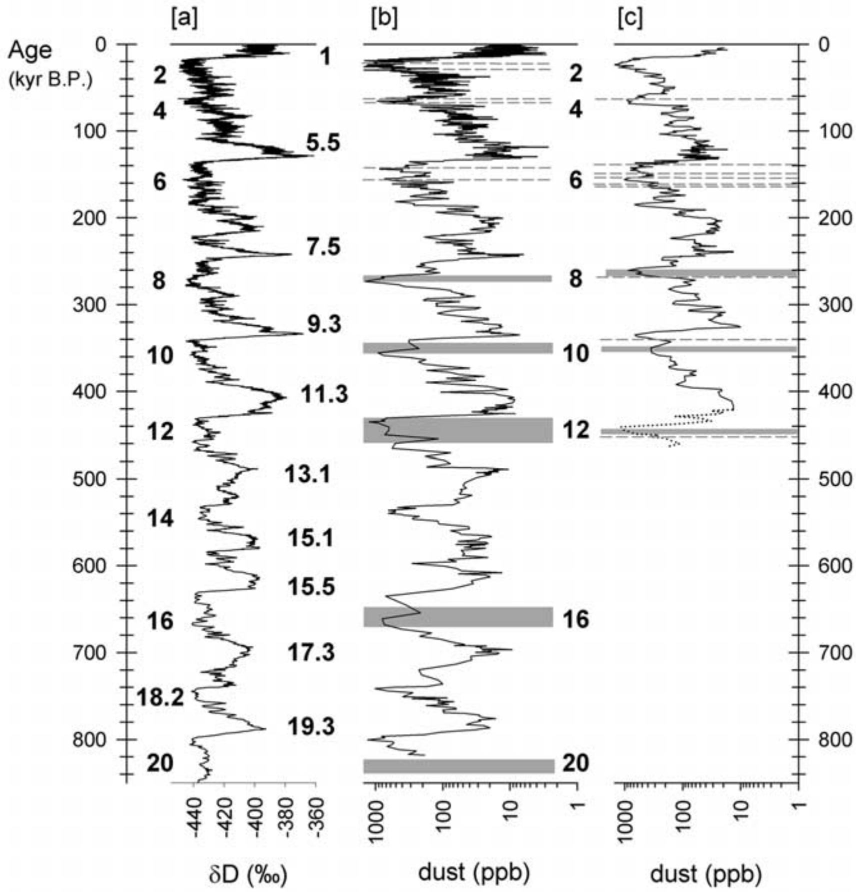

Figure 1. EDC and Vostok dust and climate records. (a) Deuterium record from the EDC ice core [*Jouzel et al.*, 2007] showing Quaternary climate variations in Antarctica back to MIS 20.2. (b) EDC dust concentration from Coulter Counter measurements [*Lambert et al.*, 2008]. Data are plotted on EDC3 age scale [*Parrenin et al.*, 2007] and expressed as μg of mineral dust per kg of ice (ppb). (c) Vostok dust concentration record plotted on GT4 timescale [*Petit et al.*, 1999]. The dotted line represents the recent extension of the climatic record [*Raynaud et al.*, 2005]. The short-dashed horizontal lines indicate the mean age of glacial samples analysed in former studies [*Basile et al.*, 1997; *Delmonte et al.*, 2004a]. Grey boxes refer to the samples selected in this study. Numbers correspond to Marine Isotopic Stages (MIS), even numbers indicating glacial ages, and odd numbers indicating interglacial stages.

MIS 6 and over an unprecedented time period using Sr and Nd isotopes.

2. Materials and Methods

[5] A total of 8 samples representing MIS 8, 10, 12, 16 and 20 for EDC and MIS 8, 10 and 12 for Vostok have been prepared (Table S1[1]). The ice sections were selected after preliminary check (ECM and Sulphate profile) that no volcanic tephra layer was present in the chosen ice pieces; this in order to avoid any influence of material ejected by sporadic volcanic activity on the composition of background dust deflated from continental landmasses. The sample treatment and the procedure for dust extraction follow the protocols adopted in former analyses [*Basile et al.*, 1997; *Delmonte et al.*, 2004a]. For each sample, a ~15 ml aliquot of liquid was dedicated to microparticle concentration and size distribution measurements (see auxiliary material). The extremely low amount of dust extracted from each sample, spanning from ~120 μg to ~600 μg (Table S1) made necessary the development of a dedicated line for chemical treatment of such tiny samples and for Sr and Nd extraction (described in detail in the auxiliary material). Neodymium was analysed as NdO^+ on a five collector Finnigan® MAT261 thermal ionisation mass-spectrometer (TIMS) in multi dynamic mode, while Strontium was analysed on a Thermo Scientific TRITON TIMS using Ta-oxide activator.

3. Results and Discussion

3.1. East Antarctic Glacial Dust

[6] Results from this work are reported on Figure 2 (and Tables S2 and S3) along with bibliographic data. Overall, the isotopic field of Pleistocene Antarctic glacial dust (MIS 2 to 20, n = 31) is circumscribed around a mean $^{87}Sr/^{86}Sr$ value of 0.709009 and a mean $\varepsilon_{Nd}(0)$ value of −1.60. The isotopic fields for EDC (MIS 2 to MIS 20, n = 11, mean $^{87}Sr/^{86}Sr$ = 0.708836; mean $\varepsilon_{Nd}(0)$ = −1.85) and for Vostok (MIS 4 to

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033382.

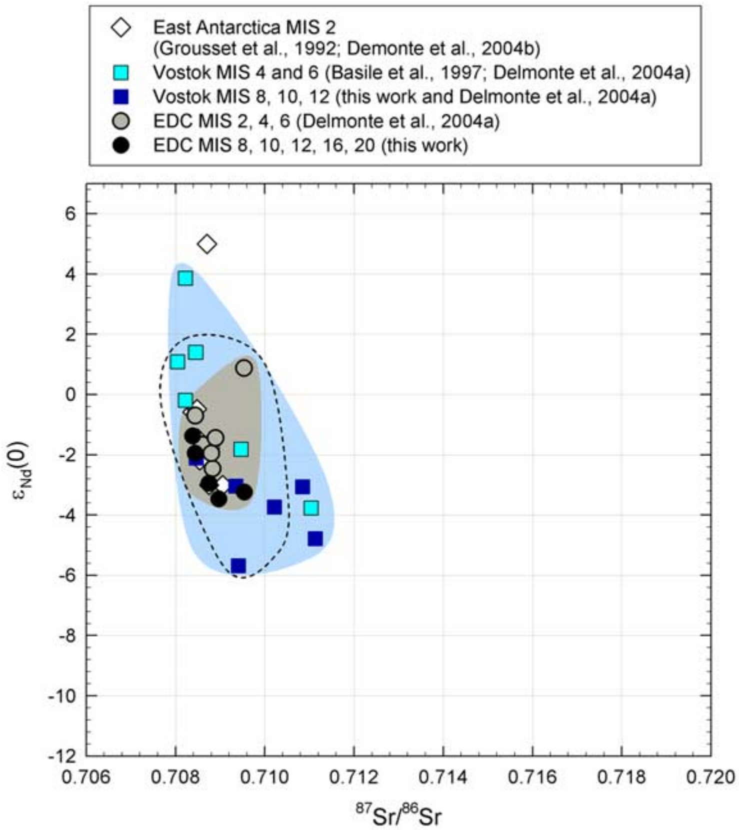

Figure 2. The $^{87}Sr/^{86}Sr$ versus $\varepsilon_{Nd}(0)$ isotopic signature of East Antarctic glacial dust. Black circles, EDC samples from MIS 8, 10, 12, 16 and 20 (this work); grey circles, EDC samples from MIS 2, 4, and 6 [*Delmonte et al.*, 2004a]; blue squares, Vostok samples from MIS 8, 10, and 12 [*Delmonte et al.*, 2004a; this work]; cyan squares, Vostok samples from MIS 4 and 6 [*Basile et al.,* 1997; *Delmonte et al.*, 2004a]; and white diamonds, samples from MIS 2 obtained from other East Antarctic drilling sites (*old* Dome C [*Grousset et al.*, 1992], Dome B and Komsomolskaya [*Delmonte et al.*, 2004b]). The grey and cyan areas indicate the EDC and the Vostok isotopic fields arbitrarily drawn on the basis of available data; the dashed line embraces the data included in the Mean ± $2\varepsilon\sigma$ interval calculated on the whole population of samples (see text). Data are reported in Table S2.

MIS 12, n = 13, mean $^{87}Sr/^{86}Sr$ = 0.709359; mean $\varepsilon_{Nd}(0) = -1.80$) glacial dust clearly overlap (Figure 2), extending the idea of a common provenance for aeolian mineral dust to the two sites at least over the last ~450 kyr (back to MIS 12) which is the time period common to the two records. Yet, when single climatic stages are considered some differences arise between the two ice cores, but these must be interpreted taking into account the very different time-representativeness of each EDC and Vostok sample (see Table S1 and auxiliary material). About 84% of data fall into the $0.707377 < {}^{87}Sr/^{86}Sr < 0.710641$ and $-6.1 < \varepsilon_{Nd}(0) < +2.9$ interval (Mean ± 2σ see dashed line in Figure 2). From the whole dataset available today, the $\varepsilon_{Nd}(0)$ values of two samples from previous studies, one from the *old* Dome C core [*Grousset et al.*, 1992] and the other from the Vostok ice core [*Basile et al.*, 1997], look unusually high. Although these values suggest a possible volcanic contribution, the authors discarded volcanic ash layers (ECM profile) when selecting the cores [*Basile et al.*, 1997] and therefore there is no reason to exclude these points from the dataset.

[7] Detailed inspection of the data reveals some slight differences in $^{143}Nd/^{144}Nd$ between recent glacial ages (MIS 2, 4 and 6) and older glacials, these latter being slightly less radiogenic in Nd with respect to the former ones (Figures 2 and 3). From the whole dataset, the mean $^{87}Sr/^{86}Sr$ value for MIS 2, 4 and 6 is 0.708789, and the mean $\varepsilon_{Nd}(0)$ about -0.7 (n = 20). From MIS 8 to 20 (n = 11) the mean $^{87}Sr/^{86}Sr$ is 0.709409 and the $\varepsilon_{Nd}(0)$ is -3.22, thus giving an average $\Delta\varepsilon_{Nd}(0)$ of ~2.5. Considering the two ice cores separately, the $\Delta\varepsilon_{Nd}(0)$ between recent and old glacials is ~3.6 for Vostok and ~1.4 for EDC (Figure 3). These differences are small, but the presence of the same evidence in three bibliographic data from Vostok MIS 8, 10 and 12 [*Delmonte et al.*, 2004a] likely rules out the possibility of a bias introduced by the different analytical procedure adopted in the present work and the previous ones as a cause.

3.2. Geographic Provenance

[8] The source identification is made comparing glacial dust with samples from the potential source areas (onwards PSA). These consist of mixed sediments collected from Southern Hemisphere regions that are (primary or secondary) active sources for mineral aerosol, or have been in the past [e.g., *Grousset and Biscaye*, 2005]. Moreover, PSA samples require analysis at grain sizes equivalent to those recovered

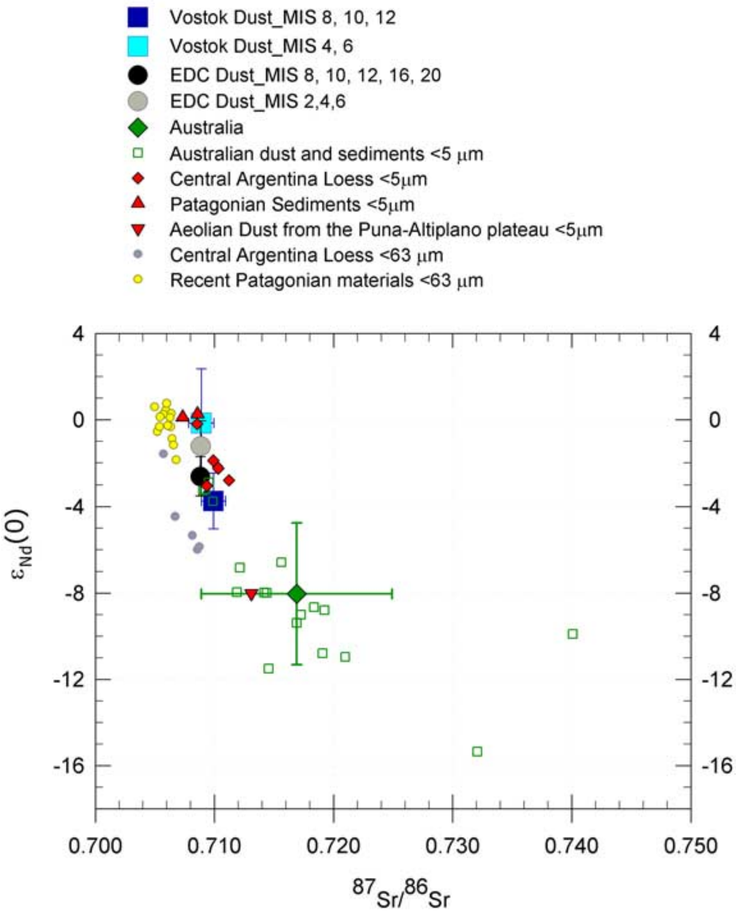

Figure 3. Mean Isotopic composition of EDC and Vostok glacial dust during recent and ancient glacial ages and comparison with data from Australia and South America. The mean $^{87}Sr/^{86}Sr$ and $\varepsilon_{Nd}(0)$ isotopic composition of EDC and Vostok glacial dust (with standard deviation) has been calculated for recent glacials (MIS 2 to 6 for EDC, grey circle; MIS 4 and 6 for Vostok, cyan square) and for older times (MIS 8, 10, 12, 16, and 20 for EDC, black circle; MIS 8, 10, and 12 for Vostok, blue square). Red triangles, fine-grained (<5 μm) Patagonian sediments (triangle up) and Aeolian dust from the P.A.P. (triangle down) [*Gaiero*, 2007; *Delmonte et al.*, 2004a]; red diamonds, fine (<5 μm) Argentinean Loess samples [*Delmonte et al.*, 2004a]; grey circles, Pampean Loess samples, <63 μm fraction [*Gaiero*, 2007]; and yellow circles, recent patagonian materials (top soils, river sediments, aeolian dust) from [*Gaiero et al.,* 2007], <63 μm fraction. Green squares, fine-grained (<5 μm) samples from PSA in East Australia [*Revel-Rolland et al.*, 2006]. Green diamond, average and standard deviation of Australian samples.

from the ice core themselves, as aeolian minerals reaching Antarctica typically consist of single, micrometric-sized grains having diameter smaller than 5 μm and well-sorted around a modal value of 2 μm. Indeed, a non-negligible Sr isotope fractionation is known to occur in function of particle size [*Gaiero*, 2007; *Gaiero et al.*, 2007; *Revel-Rolland et al.*, 2006; *Delmonte et al.*, 2004a, 2004b; *Basile et al.*, 1997] and a $^{87}Sr/^{86}Sr$ increase of ~0.0028 units has been observed between 63 μm and 2 μm dust particles [*Gaiero*, 2007].

[9] Earlier investigations on Southern Hemisphere PSA samples [*Revel-Rolland et al.*, 2006; *Delmonte et al.*, 2004a; *Basile et al.*, 1997; *Grousset et al.*, 1992] revealed that the isotopic field defined by fine-grained (<5 μm) samples from South America encompassed entirely that of Antarctic glacial dust. Therefore that region was considered the dominant supplier for dust during late Quaternary cold stages. In this respect, the new data from this work allow extending this evidence all the way back to MIS 20, providing the first evidence for a basically persistent atmospheric transport and dust provenance over the last 800 kyr.

[10] The pioneering investigations on the Southern Hemisphere PSA however did not allow discriminating specific source areas inside southern South America. Only recently, it has been pointed out [*Gaiero et al.*, 2007; *Gaiero*, 2007] that the two most active source areas for dust exported long-range from South America to high southern latitudes both at present [*Prospero et al.*, 2002] and in the past [*Zarate*, 2003] are the North of Patagonia and likely a high-altitude source area located on the Puna-Altiplano Plateau (P.A.P.). Conversely, the Argentinean Loess region was likely not a dust source during Pleistocene glaciations as suggested by geomorphological and paleoclimatic evidences [*Zarate*, 2003; *Gaiero*, 2007].

[11] It can be observed (Figure 3) that the isotopic composition of ice core dust matches that of fine-grained

(<5 μm) Loess samples from central Argentina. In the line of *Gaiero*'s [2007] hypothesis, the Argentinean Loess deposits and the Antarctic dust originate from the same primary sources, their isotopic composition revealing a mixing between Patagonian sediments and aeolian dust from a second source having upper crustal signature, as the P.A.P. (see Figure 3). Equally, the coarse size fraction (<63 μm) of Argentinean Loess and Patagonian materials (Figure 3) shows a good matching with the ice core dust composition when a Sr isotopic fractionation for size is considered [*Gaiero*, 2007]. The same conclusion can be drawn when isotopic data from bulk (all size included) South American samples from different bibliographic sources are considered [*Smith et al.*, 2003; *Gallet et al.*, 1998].

3.3. Old and Recent Glaciations

[12] The slight differences between old and recent glacials (Figure 3) most likely result from modest changes in the relative dust mixing. Hypothesizing that Antarctic dust consists of a mixture of mainly two end-members, one possibility is a change in the composition of dust exported from South America. In this case, the ~95% contribution of Patagonian dust estimated for MIS 2 to 6 is reduced to ~85% for older glacial times, when average values are taken into account. These percentages vary when single MIS are considered, spanning from an almost pure Patagonian contribution during MIS 2 and MIS 4 to ~75–80% during MIS 8.

[13] Alternatively, one can assume a mixture between South America and East Australia [*Revel-Rolland et al.*, 2006] (Figure 3). Taking into account the East Australian end-member characterised by the mean of all available fine (<5 μm) Australian samples [*Revel-Rolland et al.*, 2006] and the Patagonian samples [*Gaiero*, 2007], then the almost pure Patagonian signature (~95%) which can be inferred for MIS 2, 4 and 6 is reduced to 70–90% on average during older glacial times.

[14] In both cases, the isotopic difference among glacial ages likely reflects a minor contribution of Patagonian dust to East Antarctica during glacial ages older than MIS 6 (~130–190 kyrs B.P.). This in turn can be reflective of changes in dust transport patterns or changes in primary dust production. The 500-kyrs long record of aeolian dust size from EDC [*Lambert et al.*, 2008], which is a parameter directly linked to transport, does not show any significant difference between MIS 2, 4, 6 and MIS 8, 10, 12, suggesting that changes in transport are probably not responsible for the observed geochemical variations. A slight reduction in the Patagonian source strength during ancient glacial ages and/or a relatively more important contribution from other South American provinces is a reasonable hypothesis. A weaker Patagonian source ultimately opens the possibility for reduced production of fine glacial material in relation to the varying glacier coverage [e.g., *Singer et al.*, 2004]. Unfortunately, the lack of long continental records makes difficult further assessment of these parameters for the Middle and Early Pleistocene.

[15] The new data provide evidence for a persistent westerly circulation pattern over Antarctica allowing efficient transfer of dust from South America to the interior of the East Antarctic plateau during Pleistocene glacial ages back to 800 kyr B.P.

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