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Multiple sources supply eolian mineral dust to the Atlantic sector of coastal Antarctica: Evidence from recent snow layers at the top of Berkner Island ice sheet

Aloys Bory [a,*], Eric Wolff [a], Robert Mulvaney [a], Emil Jagoutz [b], Anna Wegner [c], Urs Ruth [c], Harry Elderfield [d]

[a] British Antarctic Survey, Cambridge CB3 0ET, UK
[b] Max-Planck-Institut für Chemie, 55122 Mainz, Germany
[c] Alfred-Wegener-Institut für Polar- und Meeresforschung, 27568 Bremerhaven, Germany
[d] University of Cambridge, Department of Earth Sciences, Cambridge CB2 3EQ, UK

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ABSTRACT

The Sr and Nd isotopic composition of dust extracted from recent snow layers at the top of Berkner Island ice sheet (located within the Filchner–Ronne Ice Shelf at the southern end of the Weddell Sea) enables us, for the first time, to document dust provenance in Antarctica outside the East Antarctic Plateau (EAP) where all previous studies based on isotopic fingerprinting were carried out. Berkner dust displays an overall crust-like isotopic signature, characterized by more radiogenic $^{87}Sr/^{86}Sr$ and much less radiogenic $^{143}Nd/^{144}Nd$ compared to dust deposited on the EAP during glacial periods. Differences with EAP interglacial dust are not as marked but still significant, indicating that present-day Berkner dust provenance is distinct, at least to some extent, from that of the dust reaching the EAP. The fourteen snow-pit sub-seasonal samples that were obtained span a two-year period (2002–2003) and their dust Sr and Nd isotopic composition reveals that multiple sources are at play over a yearly time period. Southern South America, Patagonia in particular, likely accounts for part of the observed spring/summer dust deposition maxima, when isotopic composition is shifted towards "younger" isotopic signatures. In the spring, possible additional inputs from Australian sources would also be supported by the data. Most of the year, however, the measured isotopic signatures would be best explained by a sustained background supply from putative local sources in East Antarctica, which carry old-crust-like isotopic fingerprints. Whether the restricted East Antarctic ice-free areas produce sufficient eolian material has yet to be substantiated however. The fact that large (>5 μm) particles represent a significant fraction of the samples throughout the entire time-series supports scenarios that involve contributions from proximal sources, either in Patagonia and/or Antarctica (possibly including snow-free areas in the Antarctic Peninsula and other areas as well). This also indicates that additional dust transport, which does not reach the EAP, must occur at low-tropospheric levels to this coastal sector of Antarctica.

1. Introduction

The striking dust records retrieved from Antarctic and Greenland ice cores represent some of our most valuable clues for atmospheric circulation modification over the last few Pleistocene glacial and interglacial climate cycles (Mayewski et al., 1997; Fuhrer et al., 1999; Petit et al., 1999; Ruth et al., 2003; Lambert et al., 2008), and also contribute to documentation of changes in continental paleoenvironments (Sugden et al., 2009), in iron inputs to the ocean (Wolff et al., 2006), as well as in the hydrological cycle (Fuhrer et al., 1999; Ruth et al., 2003; Lambert et al., 2008). Atmospheric transport models coupled to global circulation models (GCM), however, have so far failed to reproduce quantitatively the most prominent features of these records, specifically the large increases in mineral dust content observed in polar ice during cold periods such as the Last Glacial Maximum (LGM) (Mahowald et al., 1999; Lunt and Valdes, 2002). Interpreting ice core dust records, and using them for modelling purposes, requires at first a good understanding of the dust provenance and its possible temporal variability.

Based largely on strontium (Sr) and neodymium (Nd) isotope analyses, ice core studies on the East Antarctic Plateau (EAP), Dome C and Vostok mainly, have shown that the bulk of the dust deposited on the EAP during glacial periods likely originated in southern South America (hereafter SSA) (Grousset et al., 1992; Basile et al., 1997; Delmonte et al., 2004a; Delmonte et al., 2008a). The precise locations of the dust source areas within SSA are, nonetheless, still debated (Gaiero, 2007; Sugden et al., 2009; Delmonte et al., 2010), and the dataset for interglacials (i.e. when dust input to Antarctica is low) is rather poor (Delmonte et al., 2007), although identifying possible difference of dust provenance between glacials and interglacials is

* Corresponding author. Present address: Géosystèmes, Université des Sciences et Technologies de Lille/CNRS (UMR 8157), 59655 Villeneuve d'Ascq Cedex, France; also at: Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA. Tel.: +33 3 20 43 65 47; fax: +33 3 20 43 49 10.
E-mail address: aloys.bory@univ-lille1.fr (A. Bory).

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essential for the interpretation of ice core dust records and for validation of GCM outputs. A few tentative measurements of Holocene and marine isotopic stage 5.5 (MIS 5.5) levels (Delmonte et al., 2007) suggest that additional sources may play a role (Revel-Rolland et al., 2006; Delmonte et al., 2008b; Gaiero, 2008), as also supported by changes in mineralogical (Gaudichet et al., 1992) and elemental (Gaudichet et al., 1992; Marino et al., 2008; Gabrielli et al., 2010) compositions, as well as in magnetic properties (Lanci et al., 2008).

The provenance of the dust deposited in the other regions of the Antarctic continent remains, on the other hand, unknown to date or, in any case, speculative. Improving our understanding of the provenance of the dust deposited on the Antarctic continent, both at present and throughout the last climatic cycles, is thus required, especially in the Atlantic sector of East Antarctica where several new ice cores have been recently obtained (Berkner Island (Ronne Ice Shelf) (Mulvaney et al., 2007), Dronning Maud Land (EPICA Community Members, 2006), Dome F (Watanabe et al., 2003)), and in West Antarctica, where no data are yet available.

Snow pits, which allow the sampling of a large surface area, are best suited for material-demanding Sr and Nd isotopic analyses and they enable us to obtain data at a temporal resolution unattainable with ice cores. Pit samples have, for instance, proved particularly effective to further our understanding of present day dust provenance in central Greenland (Bory et al., 2002, 2003a). Mineral particles were therefore extracted from recent snow layers on Berkner Island in order to investigate the dust provenance in this sector of coastal Antarctica. Results presented here are the first to document dust provenance in Antarctica outside the EAP.

2. Methods

The sampling site (79°34′S, 45°39′W; altitude: 899 m a.s.l.; Fig. 1a,b) was set up during the 2003–2004 summer field work season about 2 km to the southeast of the British Antarctic Survey (hereafter B.A.S.) Berkner Drilling Project camp on Berkner Island south dome (Thyssenhöhe), in the most favourable sector to avoid possible pollution by camp activities (upwind from the camp according to prevailing summer wind directions and in the opposite direction to the aircraft landing/take off area). Wind at Berkner has generally a marked eastern component, reflecting the fact that the island sits at the edge of the ice-shelf, which is within the easterly flow regime that is found around much of the continent. North-easterly winds are the most frequent year round and also the strongest (wind speeds ≥ 20 m s^{-1} a few meters above ground level were not uncommon throughout our studied period), followed by south-easterly winds. Westerly winds are infrequent and generally weak.

The entire sampling area was covered with a clean plastic sheet before any action, including putting up the pre-cleaned laboratory tent under which all further operations were conducted following careful clean-lab procedures to prevent contamination. Snow-pit dimension and sampling layer thickness were optimized in order to achieve sub-seasonal temporal resolution while collecting sufficient material for Sr and Nd isotopic analyses (i.e., ≥ 50 μg of dust). Snow accumulation rates in this coastal area of Antarctica are high (~40–50 cm yr^{-1} of snow; 130 ± 37 mm yr^{-1} water equivalent (Ruth et al., 2004)) compared to values for the central EAP (<30 mm yr^{-1} water equivalent (Parrenin et al., 2007)). Layers of ~7.5 cm thickness (from 6.5 to 10 cm; details in the electronic Appendix) were thus excavated from a three-meter long and one-meter wide snow pit using a stainless steel saw (two 1.5-m deep trenches were dug 1 m apart to facilitate excavating snow layers in between). The chosen thickness seemed also appropriate to smooth out potential disturbances by post depositional-processes (i.e., sastrugi) considering the very high snow accumulation rate at that site. Numerous horizons (due to differences in snow grain size for instance) were actually visible on both sides of the snow-pit, providing evidence for limited post-depositional disturbances and therefore suggesting that each sampled layer represented a rather homogenous time period. Thirteen successive layers, plus one surface fresh-snow deposit, were obtained and melted on site in a FEP-lined stainless steel tank equipped with heating pads and set on a hot plate (electricity was produced using a generator positioned 50 m away and always maintained downwind from the tent), producing in each case about 60 L of water. The melt water was then passed through polycarbonate filters (0.4-μm porosity) in order to collect impurities. The loaded filters were saved wet in about 12 mL of their corresponding melt water in PFA 15-mL Savillex beakers until their treatment back in the lab.

For each of the fourteen samples, melt water was aliquoted twice for $\delta^{18}O$ and ion concentration measurements. In addition, the one-meter deep snow pit wall was also sampled continuously at two centimetres intervals (using 20 mL polystyrene accuvettes) down the entire depth for higher temporal resolution analyses of $\delta^{18}O$ as well as dust particle size measurements.

All subsequent procedures were carried out in clean lab facilities at the Max Planck Institute for Chemistry (hereafter M.P.I.) in Mainz, Germany. Mineral dust, estimated to range between ~60 and ~300 ng per sample from available data on Berkner dust concentration [J.-R. Petit, personal communication, 2003], was separated from the filters by ultrasonication in their original Savillex beakers. After removal of the filters, samples were dried down and then digested in a concentrated $HF/HClO_4$ (5:1) acid mixture in their closed Savillex beakers on a hot plate (~120 °C). Sr (and REE) chemical separation was carried out in quartz glass cation exchange column using AG 50 W-X8 resin, 100–200 mesh, hydrogen form (Biorad Laboratories, Richmond, California, USA). Quartz glass cation exchange column filled with Di-(2-ethylhexyl)phosphoric acid (HDEHP)-coated Teflon was next used to separate Nd from the other REE. Samples were put through columns twice in order to enhance Sr and Nd purification. Analytical procedures are fully detailed elsewhere (Basile, 1997; Basile et al., 1997; Delmonte, 2003; Delmonte et al., 2004a).

Isotopic analyses were completed by thermo-ionization mass spectrometry (TIMS) on a single collector Finnigan Mat 261 customized by Emil Jagoutz and co-workers for the measurement of small samples (i.e., less than 1 ng of Nd) (Bogdanovski, 1998). This instrument has been used successfully for most previous analyses of Antarctic ice core dust (Basile, 1997; Delmonte et al., 2004a). Purified Sr was loaded on single W filament where it was mixed with a TaF_5 solution to enhance Sr ionisation efficiency (Birck, 1986). Purified Nd was loaded on single Re filaments, and Nd was measured as NdO^+ by oxygen leaking in the source of the mass spectrometer to achieve higher sensitivity. Extremely slow filament warming procedures ensured the removal of organics and other residual impurities preceding Nd isotopic ratio measurements. $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$ and $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. Measured E & A $^{87}Sr/^{86}Sr$ and La Jolla $^{143}Nd/^{144}Nd$ standards yielded 0.707977 ($\pm 33 \cdot 10^{-6}$, 2σ external reproducibility, $n = 5$), and 0.511858 ($\pm 25 \cdot 10^{-6}$, 2σ external reproducibility, $n = 4$) (Goldstein et al., 2003). Considering the accuracy required in this study, data need not to be normalized with respect to certified numbers 0.70800 and 0.51186, respectively. Sr and Nd total yields were estimated by isotopic dilution of a small aliquot of each sample using an $^{84}Sr + ^{150}Nd$-enriched spike (LAMEZ). Carefully monitored analytical blanks were less than 1% of Sr and Nd weights and were considered negligible. For convenience, $^{143}Nd/^{144}Nd$ was expressed as $\varepsilon_{Nd}(0)$, the deviation from the chondritic value ($^{143}Nd/^{144}Nd = 0.512638$) in parts per 10000 (Wasserburg et al., 1981).

Since each sample included, in addition to the filtered particles, the dry-residue of ~12 mL melt water, possible sea-salt derived Sr contribution was estimated from $[Na^+]$ and $[Cl^-]$ measurements assuming that both ions were entirely seawater-derived and using seawater Sr/Cl and Sr/Na ratios of $4.15 \cdot 10^{-4}$ and $4.33 \cdot 10^{-4}$, respectively. Ion measurements were carried out at B.A.S. by ion