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Magnetic properties of aerosol dust in peripheral and inner Antarctic ice cores as a proxy for dust provenance

L. Lanci [a],*, B. Delmonte [b]

[a] Department of Base Science and Fundamentals, University of Urbino "Carlo Bo", Urbino, Italy
[b] Department of Earth and Environmental Sciences, University of Milano-Bicocca, Milano, Italy

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ABSTRACT

We use laboratory-induced remanent magnetization of polar ice to measure the rock-magnetic properties of the aerosol dust directly in ice samples. Former studies on Vostok and EPICA-Dome C ice core, recovered on the inner East Antarctic ice sheet, revealed that glacial and interglacial periods of the latter are characterized by distinct magnetic mineralogies at Dome C, which might reflect different dust source areas. In this work we present the first results on glacial and Holocene samples from the TALDICE ice core, collected at the peripheral site of Talos Dome located at high-elevation on the ice sheet close to some ice-free areas of the Transantarctic mountains. Magnetic properties of interglacial samples from both Dome-C and Talos Dome ice cores turned out to have peculiar characteristics that suggest an enhanced concentration of Fe-rich minerals in the aerosol dust, compared to Vostok. The most likely explanation for the extremely high dust magnetization measured in interglacial samples is the presence of volcanic material, although occasional occurrence of meteoritic material (micrometeorites) cannot be ruled out. The volcanic nature of the Holocene aerosol dust and its variability between sites provides further constrains on dust geographic provenance that are complementary to geochemical and physical evidences. Moreover, the calculations of the flux of the highly magnetic dust provide information on wind transport toward the continent interior during the Holocene.

1. Introduction

In central East Antarctica most of the variability of aerosol dust concentration in ice associated to glacial/interglacial cycles was related to the supply of mineral particles from the remote continental sources of the southern hemisphere, to the snow accumulation rate, and to the atmospheric transport efficiency (e.g., Petit and Delmonte, 2009). Aerosol dust suspended in the troposphere and transported over long distances is uniformly dispersed and can reach the most inner and high-elevation sites in East Antarctica.

According to the current view, the sources of the windborne dust reaching central East Antarctica during glacial times have uniform geochemical properties and consequently their major source area, South America, seem to be relatively well defined (e.g., Basile et al., 1997; Delmonte et al., 2004; Gabrielli et al., 2010). Conversely, the provenance of the aerosol dust reaching Antarctica during interglacial times is not well resolved. A major difficulty in the analysis of interglacial dust is related to the extremely low dust concentrations in firn and ice cores (Petit and Delmonte, 2009). This problem is overcome by magnetic measurements, which are sensitive to extremely small dust concentrations. Magnetic methods, which are particularly effective in recognizing Fe-rich material such as volcanic dust and highly oxidized soils, can thus be used as a tool to discriminate among aerosol dust sources. A considerable difference between glacial and interglacial dust properties was shown by magnetic measurements at Dome-C site (EPICA Dome-C ice core) by Lanci et al. (2008a, 2008b, 2012) which also suggest the volcanic nature of the interglacial dust based on its high values of the dust IRM. This finding is in accordance with the recent growing consensus to the hypothesis that local (Antarctic) source could contribute significantly to the dust supply during interglacial periods and that these sources are volcanic in nature (e.g., Gabrielli et al., 2010; Vallelonga et al., 2010; Delmonte et al., 2013). However, despite the general understanding of long-distance aeolian dust transport to Antartica, little information is available on the transport and deposition of mineral aerosol originating locally in marginal ice-free areas toward the Antarctic interior.

The aeolian transport of particles from Antarctic ice-free areas towards the interior of the ice cap can represent a significant additional aerosol source when the long-range transport is less efficient, such as during interglacials, and its study might provide information about the behavior of regional atmospheric circulation in the past. Understanding the spatial extent where local sources can influence the dust budget on the ice sheet and the climatic condition when this occurred is also helpful for better defining the atmospheric dust cycle in Antarctica and for the interpretation of the dust history at different sites. Here we show new results from TALDICE (TALos Dome Ice CorE drilling project) ice core and compare them with revised data from Vostok and Dome-C

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* Corresponding author. Tel.: +39 0722 303391.
E-mail address: luca.lanci@uniurb.it (L. Lanci).

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in order to gather information on the areal distribution during different climatic stages and, indirectly, on the aerosol dust provenance and transport.

2. Material and methods

We measured new ice samples from TALDICE ice core, drilled at Talos Dome (72°49′S, 159°11′E; 2315 m a.s.l.) in the Ross Sea sector of East Antarctica, Northern Victoria Land (Fig. 1). A total of 26 TALDICE ice samples weighting from ~20 to ~40 g were taken at core depths ranging from 490 m to 1292 m, corresponding to the current interglacial period and glacial Marine Isotopic Stage (MIS) 3 and 4 (Stenni et al., 2011). Dating for TALDICE (TALDICE-1 chronology) was set up using stratigraphic tie points, implementing a new probabilistic inverse approach for ice core dating based on Bayesian inference aiming at finding the best compromise between an ice flow model scenario setup a priori and chronological information from tie points, and evaluating the quality of the chronology a posteriori (Buiron et al., 2011).

Standard sample preparation consisted of core cutting and decontamination with ultra-pure water in clean room (e.g., Lanci et al., 2012).

The Isothermal Remanent Magnetization (IRM) acquisition and measurement procedure for ice samples from Talos Dome ice core are equivalent to that described in previous papers (e.g., Lanci and Kent, 2006; Lanci et al., 2012). IRMs were induced in whole-ice samples at low temperature. In order to avoid the immersion of ice samples in liquid nitrogen with consequent fracturing, samples were cooled in liquid nitrogen vapours until reaching a stable temperature of about 170 K. Repeatable results indicate that this temperature is sufficient to prevent the physical rotation of magnetic particles in the ice matrix (Lanci et al., 2001, 2012). Ice samples were magnetized using a pulse magnetizer and the remanent magnetization was measured using a 2G superconducting magnetometer with DC-SQUID sensors at the ALP laboratory. The measurement procedures were performed as quickly as possible to avoid significant re-warming of the samples.

An IRM in a maximum field of 1 T was first induced in each sample; subsequent IRMs were induced in the opposite direction with stepwise increasing fields to allow the calculation of the coercivity of remanence (H_{cr}); the exact field value of H_{cr} is interpolated between zero-crossing IRM values. The maximum IRM was also remeasured after allowing the sample to re-equilibrate to the freezer temperature (~255 K) for about 4 h; the increase in temperature from 170 K to 255 K causes thermal relaxation of the remanent magnetization carried by very small magnetic particles, thereby decreasing the remanent magnetization. The fraction of magnetic particles whose remanent magnetization relaxes at freezer temperature is referred to as superparamagnetic and the IRM carried by this fraction can be calculated as the difference between magnetic measurements taken before and after thermal relaxation. We refer to the fraction of IRM that remains after warming to ca. 255 K as $IRM_{255\ K}$ to distinguish it from the IRM acquired at 170 K ($IRM_{170\ K}$), which includes the superparamagnetic fraction. Previous studies (Lanci and Kent, 2006; Lanci et al., 2007, 2012) have argued that most of the superparamagnetic fraction of the polar ice is carried by particles of extraterrestrial origin and for this reason it is disregarded in this study. Ice samples were returned after magnetic measurements for dust concentration measurements.

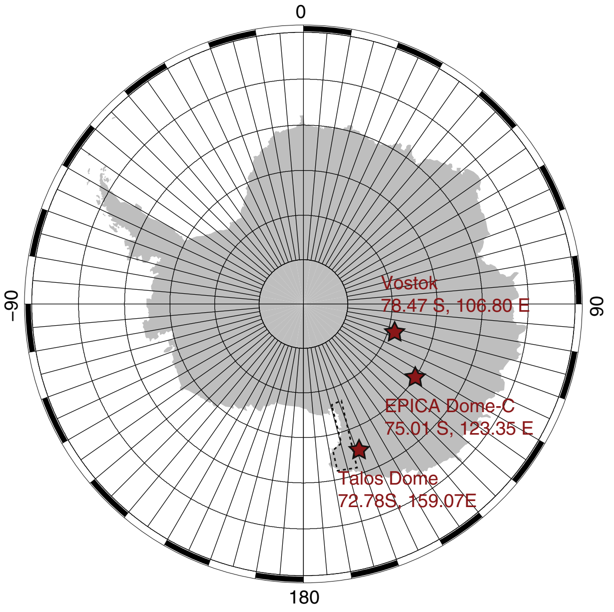

Fig. 1. Location map of the three Antarctic cores considered in this study. The dashed polygon represent the possible source area of volcanic dust according to Delmonte et al. (2013)).

Insoluble Dust Concentration (IDC) and size distribution were analyzed on the same sample measured for magnetic properties, after additional decontamination of ice in clean room and melting at room temperature. Insoluble microparticles were measured with a Multisizer™ 3 Coulter Counter® which can detect insoluble material with equivalent spherical diameters of 1 to about 30 μm. The dust mass was calculated assuming that mineral grains have an average density of 2.5 g/cm^3. The dust concentrations obtained in our samples are perfectly compatible with the extensive measurements published by Albani et al. (2012). The dust volume-size distribution from TALDICE shows the typical lognormal distribution with a variable modal value around 2 μm, as observed in Dome C, but also peculiar characteristics related to the presence of dust particles larger than 5 μm in diameter, representing only a very low number of counts but contributing significantly to the total dust mass and flux (Albani et al., 2012; Delmonte et al., 2010, 2013).

Dust magnetization in ice samples was computed by dividing the ice $IRM_{255\ K}$ by the IDC measured in the very same samples, in the case of Talos Dome, or in adjacent ice samples, as in the case of EPICA-Dome-C (Lanci et al., 2008a, 2008b). In the Vostok ice core, the averaged values of dust concentration for each group of samples were obtained from the published data of Petit et al. (1999) as explained in Lanci et al. (2012). Unfortunately only an incomplete set of H_{cr} measurements was available for the Vostok samples.

Both magnetic and dust concentration measurements have analytical errors that, in samples with the lowest concentrations, might lead to notable uncertainties in the values of dust $IRM_{255\ K}$. Possible sources of errors are: i) errors in determination of the magnetic moment, and ii) errors in the determination of the dust mass. Between these two the second one is generally the largest; the magnetic moment can be measured very precisely with cryogenic magnetometers and the routinely repeated measurements, which would account for possible temperature bias and laboratory contamination, demonstrate that differences do not exceed 10%. Errors in dust mass measurements made with the Coulter counter are related to the extremely small dust concentrations in Holocene ice; for example, in the case of EPICA-Dome C the internal variability among three replicate and consecutive dust mass measurements was around 20% for the Holocene (Delmonte et al., 2002). Furthermore, possible errors arise from the unknown dust density, and from the insensitivity to very fine (<1 μm) grains and the consequent underestimation of the dust mass in the smallest size bins. We approximate that, in the worst-case scenario and considering the 2 sources of errors as independent, the dust $IRM_{255\ K}$ could be overestimated by a maximum of 25%.

3. Results and discussion

A strong linear relationship between Ice-$IRM_{255\ K}$ and IDC indicates uniform magnetic properties and the slope of the regression line can be taken as the average measurement of the Dust-$IRM_{255\ K}$. We use this criterium on the Vostok ice core, where the correlation is highly significant (Fig. 2a), to argue that no major magnetic mineralogy changes