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Magnetization of polar ice: a measurement of terrestrial dust and extraterrestrial fallout

L. Lanci[a,*], B. Delmonte[b], D.V. Kent[c,d], V. Maggi[b], P.E. Biscaye[d], J.-R. Petit[e]

[a] Dept. DISTEVA, University of Urbino, Italy
[b] Dipartimento di Scienze Ambientali, University of Milano-Bicocca, Milano, Italy
[c] Department of Earth & Planetary Sciences, Rutgers University, Piscataway, NJ, USA
[d] Lamont–Doherty Earth Observatory, Palisades, NY, USA
[e] Laboratoire de Glaciologie et de Géophysique de l'Environnement, Saint Martin d'Hères, France

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ABSTRACT

Laboratory-induced remanent magnetization of polar ice constitutes a measurement of the magnetization carried by the ferromagnetic dust particles in the ice. This non-destructive technique provides a novel kind of information on the dust deposited on the surface of polar ice sheets. Measurements made on ice samples from Greenland (North GRIP ice core) and Antarctica (Vostok and EPICA-Dome C ice cores) allowed the recognition of a fraction of magnetic minerals in ice whose concentration and magnetic properties are directly related to that of insoluble dust. The source of this fraction of magnetic minerals thus appears closely related to terrestrial dust transport and deposition and its magnetic properties are informative of the dust provenance areas. The rock-magnetic properties of the dust may reflect distinct changes of dust source areas from glacial to interglacial periods in agreement with and adding further information to the isotopic ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) analyses. A second magnetic fraction consists of particles of nanometric size, which are superparamagnetic at freezer temperature and whose concentration is independent of the mass of aerosol dust found in the ice. The source of these nanometric-sized magnetic particles is ascribed to fallout of "meteoric smoke" and their concentration in ice was found to be compatible with the extraterrestrial fallout inferred from Ir concentrations. The diameter of the smoke particles as inferred from magnetic measurements is in the range of about 7–20 nm.
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1. Introduction

Polar ice sheets are among the most detailed and direct archive of atmospheric aerosol, providing a record of mineral dust which is of aeolian origin and mostly windblown from continental areas over very long distances. The concentration of dust entrapped in polar ice, its grain size and physical properties, vary over geological time scales as modulated by synergic factors directly or indirectly related to climatic conditions. Dust flux and particle size are probably controlled by a combination of factors such as source-area conditions and extent, dust transport (advection time and life-time), and accumulation of snow over polar areas.

The concentration of mineral dust is extremely low in Greenland and Antarctic ice. Glacial/interglacial changes in dust concentration recorded in ice cores range from about 1×10^4 ppb–50 ppb in the interior of Greenland (e.g. Steffensen, 1997; Svensson et al., 2000; Ruth et al., 2003) and from up to 700–800 ppb to about 10 ppb in central East Antarctica (e.g. Petit et al., 1999; Lambert et al., 2008). Thus, dust concentration decreased by a factor of 10–100 from colder to warmer climate periods (glacial/interglacial periods); most of the increase in dust concentration in Antarctica during glacial periods with respect to Holocene climate has been related to the synergetic change of source productivity, transport efficiency and accumulation rate over the Antarctic ice sheet, that are all climate dependent (e.g. Petit and Delmonte, 2009).

Arctic ice records originate predominantly from the many Greenland ice sheet drilling sites (e.g. Langway et al., 1985, and reference therein). Hamilton and Langway (1967) interpreted the dust variations in Greenland ice as mainly due to higher aridity in the dust source areas and/or a more vigorous atmospheric circulation in the Northern hemisphere during cold intervals. Based on mineralogical and isotopic ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) analysis of dust from Greenland ice cores, and comparison with samples from possible Northern hemisphere source areas, those arid source areas have been found to be the deserts of Eastern Asia from the Last Glacial period through the present (Biscaye et al., 1997; Svensson

* Corresponding author.
E-mail address: luca.lanci@uniurb.it (L. Lanci).

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et al., 2000; Bory et al., 2002; Lupker et al., 2010). Aeolian sediment transported from these source areas is also considered the source of the extensive loess deposits in the Chinese loess plateau, some of the fine-grained fraction of which has been transported as far as Greenland, especially during loess-depositing, glacial episodes (Biscaye et al., 1997).

The best known dust records from Antarctica came from the Vostok and EPICA (European Project for Ice Coring in Antarctica) ice cores. Vostok provided the first dust record of the last 420,000 years (e.g. Petit et al., 1999) and revealed that the dust input to Antarctica was maximum during glacial periods, lower during stadials and interstadials, and minimum in interglacials. The EPICA-Dome C ice core provided several high-resolution dust records (Delmonte et al., 2008; Lambert et al., 2008) and to date represents the longest polar ice core record (EPICA-Community-Members, 2004; Jouzel et al., 2007), which extends into the Early Pleistocene. Dust content in these sites has been extensively studied for concentration (Petit and Delmonte, 2009) and isotopic ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) composition (e.g. Grousset et al., 1992; Basile et al., 1997; Delmonte et al., 2008, 2010), which was compared with possible source areas from the Southern hemisphere (Revel-Rolland et al., 2006; Gaiero, 2007; Gaiero et al., 2007) in order to gather information on dust provenance. Isotopic studies suggested that Patagonia has been the most important source for dust in the central part of the East Antarctic ice sheet during Pleistocene glacial ages. However the isotopic fingerprint of ice core dust is well documented only for dust deposited during Pleistocene glacials (Basile et al., 1997) and only scarce information exists for interglacials and modern dust (Delmonte et al., 2007; Bory et al., 2010; Gabrielli et al., 2010; Vallelonga et al., 2010).

Iron oxides are magnetic minerals, which are able to carry a remanent magnetization. They are common in nature and constitute typically a small fraction of terrigenous minerals. The most common and chemically stable magnetic minerals are hematite (γFe_2O_3), maghemite (αFe_2O_3) and magnetite (Fe_3O_4). They are likely to be found in the aerosol reaching polar regions, which is mostly composed of terrigenous dust originating in desert areas; as a consequence, polar ice is expected to show the characteristic magnetic properties of these minerals that may reflect their provenance and transport history. Investigating the magnetization of ice is thus a method to obtain information about polar ice mineral dust.

The extremely low concentration of magnetic minerals in ice inhibits the possibility to study the natural remanent magnetization. Currently the information obtained from the study of ice cores is limited to the concentration and the nature of the magnetic fraction of aerosol dust. These properties can potentially be used as tracers that may reflect the total dust concentration as well as the availability of iron oxides in the dust source area.

Meteoritic material provides another possible source of magnetic minerals in polar ice. The magnetic minerals are nanometer-sized particles, which are part of the meteoritic smoke that results from the vaporization of micrometeorites as they enter the atmosphere. Because of the strong magnetization of meteorites (e.g. Suavet et al., 2009), the meteoritic smoke can account for a significant fraction of ice magnetization even far from placer deposits and especially during interglacial periods when the deposition of dust in the polar regions is greatly reduced. If the magnetization carried by extraterrestrial material (meteoritic) is distinguished from the terrestrial (dust) fraction, it may provide an estimate of meteoritic accretion (Winckler and Fischer, 2006).

In this paper we review the investigations on the magnetic properties of terrestrial airborne dust in polar regions and their insight on the dust provenance, as well as the information that they provided on meteoritic accretion.

2. Magnetization of polar ice

To our knowledge the first published work that described attempts to measure magnetization in polar ice is the study of Funaki and Sakai (1991) who successfully studied the acquisition of natural remanent magnetization in ice samples with a high concentrations of magnetic mineral from a tephra deposit in the Southern Victoria Land, East Antarctica. Sahota et al. (1996) measured Isothermal Remanent Magnetization (IRM) and coercivity of remanence in samples obtained by melting ice and snow from Greenland and Himalayan ice cores through filter paper although samples from Greenland did not give relevant results due to their very low dust concentration. A few years later Funaki (1998) successfully measured natural remanent magnetization and IRM on ice samples from placer deposits (referred to as “dirt” ice) on the Antarctic coast in order to identify micrometeoritic contents. Thanks to the high concentration of magnetic particles in these ice samples, Funaki (1998) was able to measure and stepwise demagnetize the natural remanent magnetization of the highly magnetic “dirt” ice. These ice samples from placer deposits had saturation IRM of about 70–80 mA m^2/kg (Funaki, 1998) that was several orders of magnitude larger than the saturation IRM measured by Funaki in the so-called “clean” ice from the Mizuho Station ice core.

Subsequent experiments on ice magnetism (Lanci et al., 2001, 2004) have shown that the acquisition of remanent magnetization in ice samples and its measurements need peculiar precautions in order to obtain consistent and repeatable results. In particular Lanci et al. (2001) noticed that an IRM in ice induced at “freezer” temperature (about 255 K) produced erratic results in the intensity and direction of the remanent magnetization. This unexpected behavior was tentatively explained as the effect of the physical reorientation of the magnetic particles in the ice matrix by their local heating due to electromagnetic induction. Whatever the reason of this peculiar behavior, Lanci et al. (2001) found that repeatable results could be obtained by inducing IRM at lower temperatures, which evidently keeps the magnetic particles more solidly frozen in the ice and thereby inhibiting physical rotations. Further experiments have shown that it is possible to perform reliable measurements of IRM at $\sim$255 K if the magnetization was previously induced at lower temperature. This effect and the need to keep the ice sample frozen limit the kind of rock-magnetic experiments that can be performed on ice samples.

With the above-mentioned limitations, polar ice samples can be given IRMs that can be measured in the laboratory (Lanci et al., 2001). To deal with the extremely low magnetic moment of ice, the samples had to be carefully cleaned before measurements similarly to what is routinely done in geochemical analyses. The cleaning procedure performed in samples of polar ice cores included scraping the external part of the sample with a non-magnetic knife and multiple baths in ultra-pure water in order to melt, and thus remove, the potentially contaminated external part of the samples. The introduction of extra baths and the use of a class 100 laminar flow hood in Lanci and Kent (2006) and subsequent works have noticeably reduced noise in the remanence measurements relative to earlier results.

The extremely low ice magnetizations also require the verification of the background noise level of the measurement procedure. Lanci et al. (2004) measured artificial ice samples made with ultra-pure water that were treated exactly as natural ice samples and subject to the same cleaning, cooling, magnetization and measurement procedure. Results gave an average mass magnetization of about 3 nA m^2/kg and a repeatability for each samples ranging from 5% to 15% (σ), which was considered satisfactory given the very low magnetic moments ($6–30 \times 10^{-11}$ A m^2) of these

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