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Isothermal remanent magnetization of Greenland ice: Preliminary results

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Abstract The magnetic mineral content of wind-transported dust should reflect atmospheric transport dynamics and conditions in its source areas, and could thus be used as an environmental proxy. To test the feasibility of determining the magnetic mineral content in polar ice, isothermal remanent magnetization (IRM) was measured on a small suite of Greenland ice samples of Holocene (interglacial) and Last Glacial Maximum (LGM) age. Although the extremely low dust concentrations limit weak field (susceptibility) measurements, all samples contained an easily measurable concentration of magnetic minerals that can be estimated using IRM intensity provided that special precautions are used. IRM experiments at liquid nitrogen temperatures indicate ice magnetic properties which are consistent with that expected from varying concentrations of magnetite or maghemite. Interestingly, the Holocene ice samples tend to have higher magnetic concentrations, despite having much lower total polar dust contents, than the few LGM ice samples tested thus far.

1. Introduction

Polar ice dust represents a pure eolian signal consisting of atmospheric aerosols deposited on the surface of the polar ice sheets. The variations in the dust contents in polar ice reflect changes in source areas and atmospheric conditions and therefore provide a very important source of information for paleoclimatic reconstruction. Dust concentration in polar ice can decrease by a factor of 10–100 from colder to warmer climatic periods such as glacial to interglacial ages [*Thompson,* 1977; *Hammer et al.,* 1985; *Hansson,* 1994]. These variations are found to be synchronous with the seasonal and long-term climate variations [*Hamilton and Langway,* 1967] which are interpreted as due to higher aridity in the dust source areas and/or a more vigorous atmospheric circulation during cold periods.

Analysis of polar ice dust can be done in several ways to obtain different kinds of data. Measurement of the concentration of the particles in the ice can be done by melting and extraction of the insoluble particles by any of several kinds of particle-counting techniques, such as by Coulter Counter [e.g., *Steffensen,* 1997], by laser-light scattering [e.g., *Ram and Illing,* 1994] or other optical counting methods [e.g., *Zielinski and Mershon,* 1997]. Some of these methods also yield the size-frequency distribution of the particles, which have, for example, been shown to vary as a function of climate in which the mode of the frequency distribution is larger during cold periods than during warm [*Steffensen,* 1997]. Some measurements can also be done directly on the ice itself, such as laser-light scattering [*Ram et al.,* 1995], which is rapid and has very high resolution but is limited to bubble-free ice and therefore not applicable to "young" (Holocene) ice. Electrical conductivity measurements (ECM) which depend on the pH of the ice is also done rapidly and directly on ice and can yield an indication of dust content because constituents of the dust react to changes in the pH of the ice [e.g., *Taylor et al.,* 1997]. As in the case of Coulter and other optical measurements, characterization of the dust particles themselves requires their extraction from the ice, which can be done either by melting or by lyophylization [*Biscaye et al.,* 1997], the latter method yielding particles that otherwise might be soluble in ice meltwater. Early attempts at determining the mineralogy of dust particles extracted from ice cores were done using transmission electron microscopy [*Gaudichet et al.,* 1986] and have been done more recently using combined scanning electron microscopy and energy-dispersive X-ray microprobe [*Maggi,* 1997]. The latter methods analyze individual dust grains, and, for overall sample characterization, depend on statistically significant numbers of particles. Analysis of bulk samples overcomes the statistical significance problem and can yield several kinds of analysis on the same sample, but requires larger samples of ice. Using this approach and combining analysis by x-ray diffraction and solid-source thermal ionization mass spectrometry, *Biscaye et al.* [1997] have determined the clay mineralogical and Sr-, Nd- and Pb-isotope compositions of LGM dust from Greenland to conclude that it was derived from the deserts of eastern Asia.

Because of the kinds of arid places it comes from, polar ice dust is likely to contain some fraction of highly magnetic iron oxides. The magnetic fraction can potentially be used as a tracer, which may reflect the total dust concentration as well as the availability of iron oxides in the dust source area. The concentration of the magnetic fraction in the ice can be estimated using some of the magnetic methods that have been successfully applied to environmental analysis of marine as well as wind-transported sediments such as the Chinese loess [e.g. *Verosub and Roberts,* 1995; *Heller and Evans,* 1995]. The magnetic techniques are non-destructive, relatively fast and in the case of ice, they are not influenced by its optical condition. The experimental procedures employed in a previous attempt to measure IRM on filtered samples of pre-industrial ice from Greenland [*Sahota et al.,* 1996] were inadequate to obtain significant results. Nevertheless, some special precautions have to be used in order to obtain reproducible results when measurements are made directly on ice samples. In this paper we present some preliminary results and discuss measurement problems and their solutions.

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Table 1. Concentration of magnetite in the Greenland ice samples. The calculation of the magnetite volume assumes that the carrier is PSD magnetite (Js = $4.8 \cdot 10^5$ A/m, $M_{RS}/M_S \approx 1/3$). The concentration is volumetric and assumes a sample volume of 15 cm^3.

Sample Names		*SIRM [Am^2]*	*Magnetite volume [cm^3]*	*Volume Concentration*
593I_217	Holocene	$1.055 \cdot 10^{-8}$	$6.59 \cdot 10^{-8}$	$4.4 \cdot 10^{-9}$
NG1_186	Holocene	$1.267 \cdot 10^{-8}$	$7.92 \cdot 10^{-8}$	$5.3 \cdot 10^{-9}$
R88_241	Holocene	$4.712 \cdot 10^{-9}$	$2.95 \cdot 10^{-8}$	$2.0 \cdot 10^{-9}$
NG1_202-203	Holocene	$3.519 \cdot 10^{-9}$	$2.20 \cdot 10^{-8}$	$1.5 \cdot 10^{-9}$
593I-209	Holocene	$2.083 \cdot 10^{-9}$	$1.30 \cdot 10^{-8}$	$8.7 \cdot 10^{-10}$
NB1_184-185	Holocene	$3.009 \cdot 10^{-9}$	$1.88 \cdot 10^{-8}$	$1.3 \cdot 10^{-9}$
LGM-3474	LGM	$3.364 \cdot 10^{-9}$	$7.01 \cdot 10^{-9}$	$4.7 \cdot 10^{-10}$
LGM-3471	LGM	$3.334 \cdot 10^{-9}$	$6.95 \cdot 10^{-9}$	$4.6 \cdot 10^{-10}$

2. Measurement procedures and results

Measurements were made on Greenland ice samples from the Holocene and from the Last Glacial Maximum (LGM), (Table 1). Cube samples with a volume of about 15 cm^3 were cut from the ice cores using a non-magnetic phosphor-bronze knife. Synthetic ice specimens were made by introducing a small amount of crushed natural magnetite powder with a grain size < 63 μm in an ice cube made of distilled water; a control synthetic specimen was made by gluing a similar amount of the magnetite powder to a microscope slide. It should be realized that the magnetite powder used in synthetic samples has much coarser grain size that expected in the natural Greenland ice dust which consists of grains with diameters smaller than 5-10 μm with a mode around 1.5 μm [*Steffensen*, 1997].

The intensity of the natural remanent magnetization (NRM) in the Greenland ice samples is low but measurable with a DC-Squid cryogenic magnetometer and ranges from about $7 \cdot 10^{-6}$ to $2 \cdot 10^{-5}$ A/m. Measurements of magnetic susceptibility of the natural ice samples gave large negative values which must be caused by the relatively high diamagnetic susceptibility of the ice "matrix" in conjunction with very low concentrations of minerals with ferromagnetic and paramagnetic susceptibilities. This prevents the use of susceptibility to estimate the concentration of magnetic grains. Instead, we used the isothermal remanent magnetization (IRM) progressively acquired using a pulse magnetizer to gain information on the magnetic mineralogy and to estimate the concentration of magnetic minerals. IRM is not influenced by the diamagnetism of ice and, if produced at sufficiently high fields, will maximize the resultant magnetization for greatest sensitivity.

We initially kept the ice samples at near-0°C (270K) during IRM acquisition and measurement. Results from IRM acquisition in representative natural ice samples from the LGM and Holocene are shown in Fig. 1. In both samples, the magnetization does not increase regularly with applied fields and displays erratic behavior with increasing fields in both intensity and direction of IRM produced.

Results from a synthetic ice sample made from distilled water and doped with crushed magnetite powder are consistent with those from the natural ice, considering the different grain size of the magnetic particles (Fig. 2). The IRM acquisition at 270K showed a relatively noisy acquisition curve with the IRM not completely stable at saturation, resembling, on an attenuated scale, the behavior of the natural ice. It was also observed that a succession of 1T-field pulses over a short time could cause the loss of the magnetization previously acquired with a single identical impulse.

The IRM acquisitions and measurements were repeated at 77K by immersing the samples in liquid nitrogen except for the short time needed to magnetize and measure them. Particular care was taken to execute these operations quickly to avoid excessive warming. The same synthetic sample magnetized and measured at 77K gave better results (Fig. 2) and its acquisition curve was then very similar to that of the slide sample which is taken as reference. Therefore, the presence of ice per se does not seems to influence the IRM acquisition curve.

IRM curves of natural ice samples re-measured at 77K also show a much more coherent behavior and gave reproducible IRM curves (Fig. 3). The IRM acquisition curves of the Greenland ice samples saturate below 0.3T, suggesting that the magnetic mineralogy is dominated by some form of magnetite or perhaps maghemite. The maximum IRM in the Holocene ice samples at 77K ranges from $1.4 \cdot 10^{-4}$ to $8.5 \cdot 10^{-4}$ A/m, while maximum IRM of the LGM samples is about $2.2 \cdot 10^{-4}$ A/m, surprisingly similar to the Holocene values (Table 1).

3. Interpretation of results

Classic rock magnetic theory cannot account for the unusual behavior of the natural ice samples. We qualitatively explain the results obtained at 270K in the natural samples as an effect of electromagnetic induction in the magnetic particles, whereby eddy currents induced by the rapid

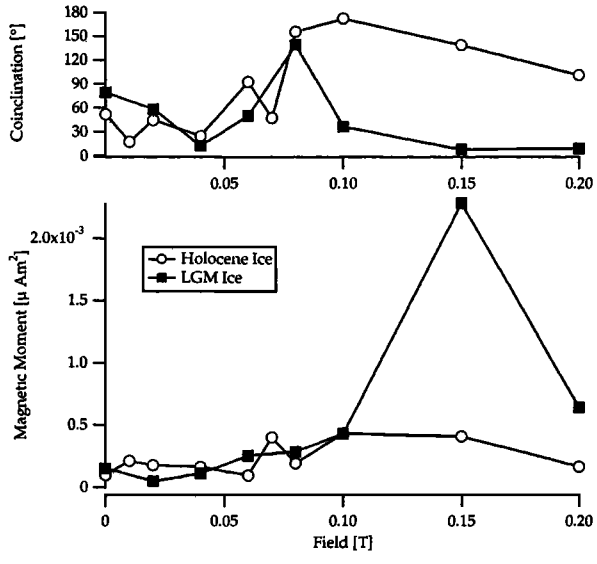

Figure 1. Typical result obtained attempting an IRM acquisition in natural ice at near-0 °C (270K), using a pulse field directed along the z sample axis. Both the intensity and the direction (measured as co-inclination with respect to the positive axis of the inducing field) of the magnetization show an erratic behavior.

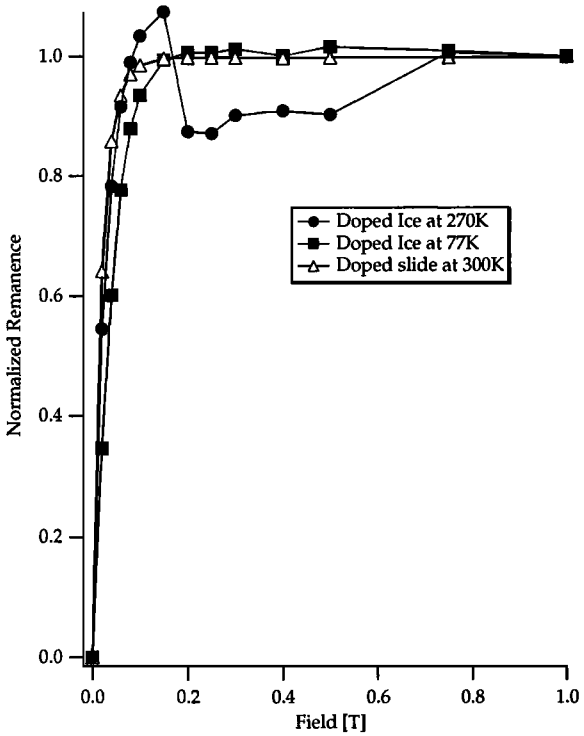

Figure 2. Acquisition of IRM in synthetic ice samples doped with magnetite powder and a reference specimen. For practical reasons the IRM in these samples was acquired as a backfield applying first a field of 1T and then increasing fields in the opposite direction. For a better comparison the curves have the backfield component subtracted and the intensity normalized.

variation of the field can potentially warm the grains. If the increase of temperature is large enough to melt a thin film of water around the particles, they may physically reorient after the field pulse and before the film of water is refrozen. Although it is difficult to model eddy currents, if we assume particles with constant shape and electric properties, the energy induced by the magnetic field should be proportional to the magnetic flux in the grain and therefore to its projected area in the plane normal to the inducing field. The increase of temperature in the particles depends on their thermal capacity (the product of the volume and the specific heat) and therefore is proportional to their volume. This different dependence of the competing energies on r^2 (the induction) and r^3 (the thermal capacity), where r is the particle's radius, would make this effect grain-size dependent and could explain the different behavior found comparing natural and synthetic ice samples.

This model would predict that more stable IRM results could be obtained using a solenoid or a magnet with a slow increasing and decreasing field in the magnetization process because of the smaller electromagnetic induction. Our attempt to magnetize one natural ice sample at near-0°C using a solenoid gave encouraging results, but they could not be considered definitive. It is also predicted that, because of the induction in magnetic particles, it will be extremely difficult to obtain useful reproducible results using AF demagnetization or ARM experiments on natural ice samples. An attempt to AF demagnetize a natural ice sample showed that the NRM can be reduced by 2/3 (close to the noise level of the magnetometer) with application of an AF field of only 4 mT. Such a low coercivity seems unrealistic especially when compared to the IRM acquisition curves. We therefore believe that the decrease of the NRM with AF demagnetization is most likely the effect of physical reorientation of the magnetic particles.

4. Discussion and Conclusion

Magnetic susceptibility is found to be ineffective to estimate the concentration of magnetic minerals in natural ice due to the relatively high diamagnetic (negative) susceptibility of water and ice. However, the concentration of magnetic particles in the Greenland ice samples is more than sufficient that their remanent magnetization can be readily measured with a cryogenic magnetometer. Nevertheless, there are peculiarities of the magnetization and demagnetization processes in ice that need to be considered for obtaining reliable measurements. Subject to confirmation, it appears that at temperatures close to the melting point of ice, the energy induced in fine-grained magnetic particles can cause them to become physically unblocked during the magnetization process due to melting of the immediately enclosing ice. This leads to non-reproducible results and imposes a severe limit to the application of most standard rock-magnetic techniques (especially ARM and AF demagnetization) to natural ice samples. This phenomenon based on electromagnetic induction and dissipation of eddy currents in the conductive magnetic grains can be greatly reduced by keeping the sample at low temperature during a

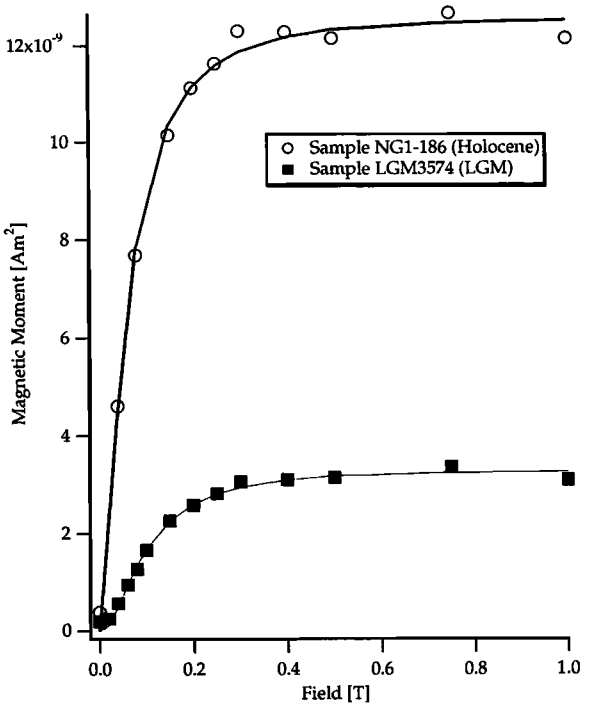

Figure 3. Typical IRM acquisition curve of 2 Greenland ice samples from the LGM and Holocene, made at liquid nitrogen temperature (77K). The continuous line represents the best-fit of a cumulative log-normal distribution curve often used to model IRM acquisition [*Robertson and France*, 1994]. Curve parameters are $\mu = 1.89$, $\sigma = 0.38$ and $\mu = 1.76$, $\sigma = 0.44$ for sample LGM3574 and NG1-186 respectively. Although there is still some "noise" the improvement from the near-0°C attempt is evident.

slow IRM magnetization process. The postulated "induced heating" effect should be dependent on the magnetic grain size and might prove to be a useful diagnostic tool.

In the measurement of ice samples from Greenland, reproducible results can be obtained by freezing the samples at liquid nitrogen temperature which evidently inhibits induction-related melting around the magnetic particles. The concentration of the magnetic fraction in the Greenland ice samples can be estimated from the IRM data assuming fine-grained magnetite with a nominal hysteresis ratio of Mr/Ms = ~0.33, where Mr is maximum IRM intensity and Ms is the saturation magnetization of magnetite ($4.8 \cdot 10^5$ A/m, neglecting for the moment its temperature dependence). Volume concentration ranges from $4.6 \cdot 10^{-10}$ to $5.3 \cdot 10^{-9}$ (see Table 1) corresponding approximately to 2.3 μg/kg and 26.5 μg/kg assuming a density of 5 g/cm^3 for the magnetite and 1 g/cm^3 for the ice. A qualitative comparison with the total dust content of about 40-80 μg/kg reported in some Holocene ice samples from Greenland [e.g. *Steffensen,* 1997] suggests that the magnetic minerals represent a significant fraction of the total dust during the interglacial. Interestingly, the smaller magnetic concentration in the few LGM samples we measured, assuming these samples also have much higher dust contents of 4000-7000 μg/kg as reported for some LGM samples, indicates that there could be an enormous difference in the magnetic/total-dust ratio from glacial to interglacial stages. Although any interpretation must be regarded as speculative with the small set of samples examined thus far, this potentially enormous glacial/interglacial difference might reflect changes in the glacial to interglacial availability of the magnetic component in the dust in the source area that was identified as eastern Asia by *Biscaye et al.* [1997]. It is also striking that despite the completely different environments, the ice magnetic properties may parallel the magnetic properties of the Chinese loess deposits where interglacial paleosols are generally found to be more magnetic than the glacial loess deposits [e.g., *Heller and Evans,* 1995].

Our preliminary data obviously need to be confirmed but it seems likely that ice magnetic properties can provide an independent tracer with a strong environmental signature that represents a peculiar and unique property of the ice dust.

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References

Biscaye P.E., F.E. Grusset, M. Revel, S. Van der Gaast, G.A. Zielinsky, A. Vaars, and G. Kukla, Asian provenance of glacial dust (stage 2) in the Greenland Ice Sheet Project 2 Ice Core, Summit, Greenland, *J. Geophys. Res.* 102, C12, pp. 26765-26781, 1997

Gaudichet, A., J.-R. Petit, R. Lefevre, and C. Lorius. An investigation by analytical transmission electron microscopy of individual insoluble micro-particles from Antarctic (Dome C) ice core samples. Tellus, Ser. B, 38, 250-261, 1986

Hamilton W.L. and C.C. Langway Jr, A correlation of microparticle concentrations with oxigen isotopes ratios in 700 years old Greenland ice, *Earth Plan. Sci. Lett.*, 3, 363-366, 1997

Hammer C.U., H.B. Clausen, W. Dansgaard, A Neftel., P. Kristinsdottir and E. Johnson, Continuous impurity analysis along the Dye 3 deep core, in *Greenland Ice Core: Goephysics, Geochemistry and the Environmen*, edited by Langway C.C., Oeschger H. and Dansgaard W , *Geophys. Monogr. Ser.* vol. 33 pp. 90-94 AGU Washington DC, 1985

Hanson M.E., The Renland ice core: a northern hemisphere record of aerosol composition over 120,000 years, *Tellus*, 46B, 390-418, 1994

Heller F., and M.E. Evans, Loess Magnetism, *Rev. Geophys.* 33, 211-240, 1995.

Maggi, V., Mineralogy of atmospheric microparticles deposited along the Greenland Ice Core Project ice core. *J. Geophys. Res.*, 102, 26,725-26,734, 1997.

Ram M., M. Illing, Polar ice stratigraphy from laser-light scattering: Scattering from meltwater, *J. Glac. Res. Lett.* 40, No136, 504-508, 1994

Ram M., M. Illing, P. Weber, G. Keonig, and M. Kaplan, Polar ice stratigraphy from laser-light scattering: Scattering from ice, *Geophys. Res. Lett.* 22, 24, 3525-3527, 1995

Robertson D.J., and D.E. France, Discrimination of remanence-carrying minerals in mixtures, using isothermal remanent magnetisation acquisition curves: *Phys. Earth Planet. Int.*, 82, 223-234, 1994.

Sahota J.T.S., P.A. Mayewsky, F. Oldfield and M.S. Twickler, Magnetic measurements of Greenland and Himalayan ice-core samples. *The Holocene* 6, 477-480, 1996

Steffensen J.P., The size distribution of microparticles from selected segments of the Greenland Ice Core Project ice core representing different climatic periods. *J. Geophys. Res.* 102, 26, pp. 26755-26763, 1997

Taylor, K.C., R.B. Alley, G.W Lamorey. and P.W. Mayewski, Electrical measurements on the Greenland Ice Sheet Project 2 Core, *J. Geophys. Res.*, 102, 26,511-26,517, 1997.

Thompson L.G., Variation in microparticle concentration, size distribution and elemental composition found in Camp Century, Greenland and Byrd Station, Antartica, deep ice cores, in *Proceeding Symposium on Isotopes and Impurities in Snow and Ice*, Grenoble, *IAHS Publ.* 118, pp. 351-363, Int. Assoc. for Hydrol. Washington DC, 1977

Verosub, K.L., and A.P. Roberts, Environmental magnetism: Past, present, and future *J. Geophys. Res.*, v. 100, p. 2175-2192, 1995.

Zielinski, G.A. and G.R. Mershon, Paleoenvironmental implications of the insoluble microparticle record in the GISP2 (Greenland) ice core during the rapidly changing climate of the Pleistocene-Holocene transition. *Geol. Soc. of America Bull.*, 109, 547-559, 1997.

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