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The magnetic record of the Late Glacial-Holocene transition in sediments from Grandfather Lake (Southwest Alaska)

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RESUMEN

Las mediciones preliminares de propiedades magnéticas en muestras de un núcleo de 8.5 m. de longitud del lago Granfather (suroeste de Alaska), indican que la magnetización remanente de estos sedimentos reside en magnetita con comportamiento de multidominio y grano grueso. Esto sugiere una señal magnética de cristal. El cambio abrupto en las propiedades magnéticas a 5.95 m de profundidad (ca. 9500 ^{14}C años), es probablemente el reflejo del comienzo del Holoceno templado. Los registros magnéticos y de polen muestran un patrón diferente bajo esta transición. Ello sugiere la ocurrencia de un ligero calentamiento al término de la última glaciación, seguido por el evento de enfriamiento Younger Dryas y el inicio del Holoceno. El primer evento de calentamiento y el Younger Dryas no están registrados en la señal magnética. Una explicación a esta discrepancia es que el impacto de estos eventos climáticos, si es que tuvieron algún efecto en el clima del suroeste de Alaska, es que fue limitado en esta región.

PALABRAS CLAVE: Propiedades magnéticas, sedimentos lacustres, Cuaternario, Grandfather Lake, Alaska.

ABSTRACT

Preliminary rock magnetic measurements on a 8.5 m long sediment core from Grandfather Lake, southwest Alaska, indicate that the remanence in these sediments is carried by large multi-domain magnetite grains. This suggests a detrital magnetic signal. An abrupt change in magnetic properties at 5.95 m depth (ca. 9500 ^{14}C yr.) probably reflects the beginning of the temperate Holocene. The magnetic and pollen records show different patterns below this transition. The latter suggests the occurrence of a first slight warming at the end of the Late Glacial period, followed by the Younger Dryas cooling event and the actual beginning of the Holocene. Neither the first warming event nor the Younger Dryas are recorded in the magnetic signal. One of the explanations for this discrepancy is that the impact of these climate events, if any, may have been limited in this region.

KEY WORDS: Magnetic properties, lake sediments, Quaternary, Grandfather Lake, Alaska.

INTRODUCTION

Magnetic properties reflect variations in concentration, composition and grain-size of magnetic minerals and can be used as a proxy for paleoclimate changes in marine, lacustrine and loess-paleosol sequences (Reynolds and King, 1995). This is demonstrated by spectral analysis of magnetic records that correlate with orbitally-driven climate cycles (see review by Berger, 1988) as well as by comparison of magnetic records with geochemical and biological proxies for climate (eg. Rosenbaum *et al*., 1996, Vlag *et al.*, 1997a). Environmental magnetism can be used in both marine and continental settings and may provide information about temporal responses of vegetational climate proxies, such as pollen, to climate change (eg. Rosenbaum *et al*., 1996).

In this paper, we present a magnetic record of the Late Glacial-Holocene Transition (LGIT) in the lacustrine sediments from southwest Alaska. After determining the magnetic mineralogy and comparing magnetic with previously presented pollen records (Hu *et al*., 1995), we discuss whether rock magnetism can be used for climate studies in the lacustrine sequence of Grandfather Lake of southwest Alaska.

GEOLOGICAL SETTING

Grandfather Lake is situated in southwestern Alaska (50° 48’ N, 158° 31’ W, 142 m altitude), at the foot of the Ahklun Mountains (Figure 1). The present maximum water depth in this moraine-dammed lake (0.35 m^2) is 20 m. The mean annual temperature in the nearby town of King Salmon is +0.7°C, with mean temperatures of –10.3° and +12.5°C in January and July, respectively. Annual precipitation ranges from 45 to 65 cm with 130 to 180 cm snowfall per year. The Ahklun Mountains and the Alaskan Range were covered with ice during the last glaciation (Figure 1).

In 1991, sediments were cored in the center of the lake with a modified Livingstone corer (Wright *et al.,* 1984). At 8.5 m sediment depth, the bedrock was encountered. A sample from 0.15 m (8.35 m depth) above bedrock yielded a conventional ^{14}C age of 12 870 ± 210. (Hu *et al*., 1995). Because of the difference between ^{14}C and calendar ages (Bard *et al*., 1993), this suggests that the lake was formed ca. 13 500 yr. BP. However, samples from 6.45 m and 7.04 m depth, which Hu *et al*. (1995) did not consider further, do not have a significant different radiocarbon age than the one at 8.35m

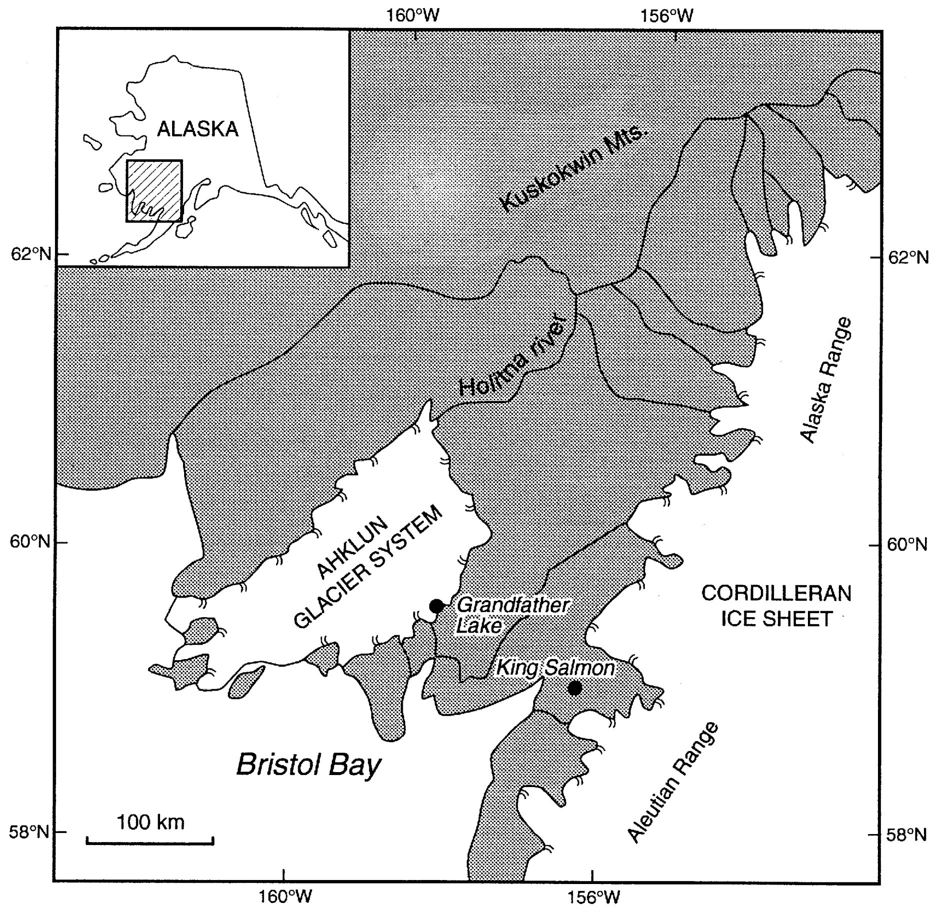

Fig. 1. Location of Grandfather Lake and the nearby town of King Salomon in southwest Alaska. White (gray) areas denote the glaciated (non-glaciated) areas during the last glacial (Lea, 1990). As reference the present day coast line is shown.

depth. This might indicate that ^{14}C ages in the 6.4-8.4 m depth interval are affected by a ^{14}C plateau, which is regularly observed at the end of the last Glacial period in high latitudes (e.g. Lotter *et al*., 1992). So, the ^{14}C ages may be inaccurate and should be interpreted with caution. As a consequence, we only mention radiocarbon ages in this paper and do not relate them to calendar ages.

The most important results of the palynological study by Hu *et al*. (1995) will be summarized in this paper . Sediment loss of ignition (LOI) between 90 and 550°C ranges between 5 and 10% at depths less than 5.95 m. Below this depth the LOI is less than 5%. The amount of biogenic silica is less than 2% of total sediment mass for sediments below 5.95 m depth and about 5% above this depth (Hu *et al*., 1995). Samples for LOI-measurements were collected from the same cores as the samples used for the palynological and magnetic study.

MEASUREMENTS

The cores were subsampled with 6.8 cm^3 paleomagnetic cubes. The low-field susceptibility χ was measured with a Bartington MS-2 susceptibility bridge. Anhysteretic remanent magnetization (ARM) was induced with a 99.9 mT alternating field (AF) superimposed on a 0.50 μT DC field. Isothermal remanent magnetization (IRM) was induced with a 1 T field, using an ASC (model IM-10) pulse magnetizer. Intensities of these remanences were measured with a Superconducting Rock Magnetometer (SRM). Hysteresis loops were measured with a Vibrating Sample Magnetometer (VSM) of Princeton Applied Research. A maximum field of 1 T was used for these measurements.

χ and IRM versus temperature curves were measured on 300 mg subsamples. The low-temperature behavior and frequency dependence of χ were measured with a LakeShore Susceptometer. With the same instrument χ was measured every 5 K at 400 and 4000 Hz, while warming the sample from 20 K up to 300 K. A Geofizika KLY-2 Kappa bridge and a CS-2 furnace were used to measure χ at high temperatures of 298-973 K (= 25-700 °C). Low-temperature behavior of IRM was measured with a Quantum Design SQUID

Magnetometer (MPMS2). With this instrument an IRM was induced with a 2.5 T field at 300 K; then the sample was cooled to 20 K and reheated to 300 K in a zero field.

RESULTS

Low-field susceptibilities range from 30 to 230.10^{-8} m^3/kg. ARM and IRM intensities vary between 0.01-0.32 and 2.9-26.1 mAm^2/kg, respectively. The saturation magnetization (M_s) ranges from 20.5 to 309.1 mAm^2/kg. Down-core records of M_s show the same trends as for χ, ARM and IRM (Figure 2). Hysteresis measurements reveal low remanence ratios (M_r/M_s=0.064-0.237) and high coercive ratios (H_{cr}/H_c=2.65-4.23) (Figure 2). According to Day *et al.* (1977), these values are close to the multi-domain range, which indicates for pure magnetite a magnetic grain size greater than about 10 µm (Day *et al.*, 1977). The coercive (H_c=6.4-12.6 mT) and remanent coercive forces (H_{cr}= 6.4-12.6 mT) (Figure 2) fall in the range corresponding to natural (titano)magnetites (eg. Day *et al.*, 1977). Proxies directly influenced by magnetic concentration (χ, ARM, IRM, M_s) and grain size indicators (ARM/IRM, M_r/M_s, H_{cr}/H_c, H_{cr}, H_c) show a dicontinuity at 5.95 m depth. Assuming a similar magnetic composition, the first indicates a lower magnetic concentration and the second a smaller grain size above this depth. The radiocarbon chronology suggests that this transition took place at ca. 9500 ^{14}C yr.

Susceptibility versus temperature curves (Figures 3a,c,e) show a Curie temperature of 580°C and a low-temperature phase transition at 110-120°K. The first corresponds with the Curie temperature of pure magnetite and the second with the crystallographic Verwey transition (Verwey, 1939) for magnetite. Unlike the underlying sediments, sediments above 5.95 m depth show much higher susceptibilities during cooling when the samples have been heated to 700°C (Figure 3a). We suspect that magnetite might have been formed from non-magnetic Fe-oxides and Fe-hydroxides. Formation of magnetite from iron sulfides is unlikely because there is no characteristic increase in susceptibility at 300-400°C during heating (Geiss, pers. comm.).

Low-temperature IRM and χ measurements do not reveal the presence of hematite and pyrrhotite, because of the absence of phase transitions at 263 K (e.g. Nagata *et al.*, 1964) and 34 K (e.g Rochette *et al.*, 1990). Absence of Curie temperatures at 320°C and 675°C in the high-temperature susceptibility curves agrees with an absence of these miner-

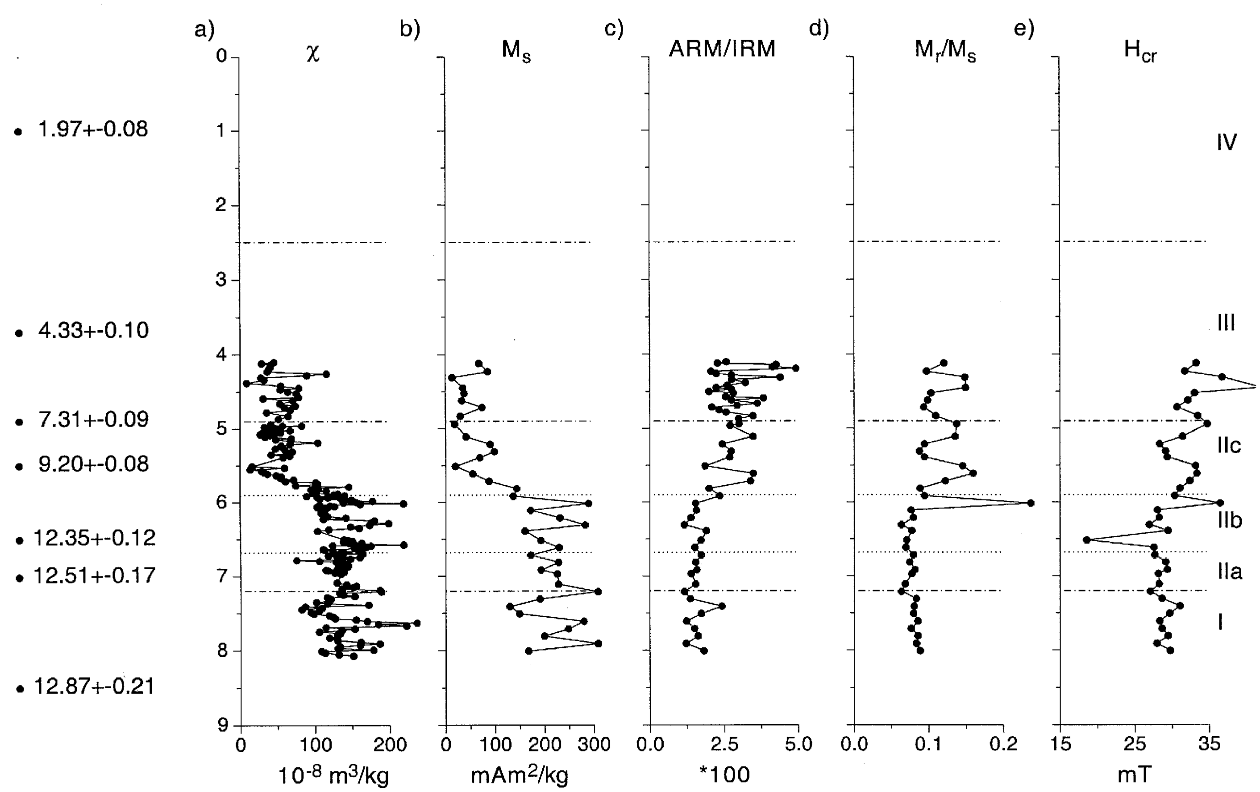

Fig. 2. Results of the magnetic measurements. (a) Low-field susceptibility (χ), (b) saturation magnetization (M_s), (c) anhysteretic divided by isothermal remanent magnetization (ARM/IRM), (d) remanence ratio (M_r/ M_s) and (e) remanent coercive force (H_{cr}) versus depth. Left column shows ^{14}C AMS datings.

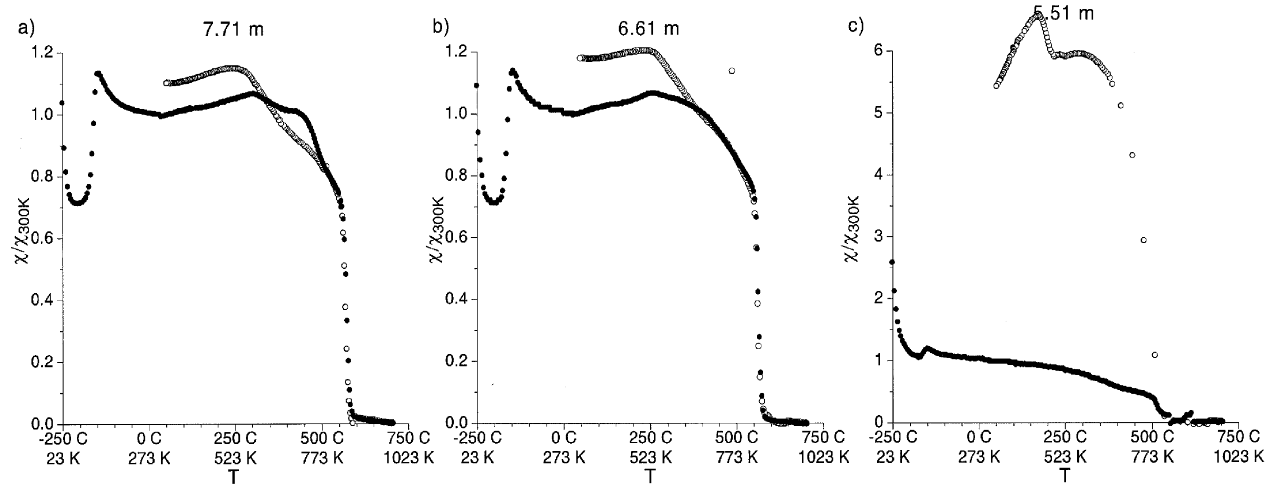

Fig. 3. Susceptibility versus temperature (χ-T) runs for samples at (a) 7.71 m, (b) 6.61 m and (c) 5.51 m depth. Susceptibilities in the temperature range 20 to 300°K (-273 up to 27°C) were measured with a LakeShore susceptometer and are normalized on the susceptibility at 300°K. Then susceptibilities in the temperature range 295 – 973°K (22 – 700°C) were measured with a KLY-2 Kappa Bridge. Both heating (closed circles) and cooling curves (open circles) were measured with this instrument. Susceptilities are normalized 300 K before heating.

als. The presence of large quantities of greigite seems unlikely, too. No change in susceptibility at 300-400°C is observed during heating. Magnetite is the only mineral which is identified by low-and high-temperature measurements. Therefore, we assume that pure magnetite is the dominant remanence carrier in these sediments.

When cooling a specimen with an IRM to 20 K and reheating it to 300 K in zero field, the loss of initial IRM is about 40% for sediments below 5.95 m depth against only 25% for the overlying sediments. Multi-domain (MD) magnetite loses part of its initial remanence when cooled and reheated through the isotropic point, 130 K (e.g. Nagata *et al*., 1964, Dunlop and Argyle, 1991). As this remanence loss increases with increasing grain size (e.g. Levi and Merill, 1978), the results from the IRM low temperature demagnetization cycle suggest coarse multi-domain grains for the Grandfather Lake sediments. This agrees with the lack of frequency dependence of susceptibility: The relative loss of the susceptibility between 400 and 4000 Hz, $\chi_{fd} = [(\chi_{400Hz}-\chi_{4000Hz})/\chi_{400Hz}]*100$, a proxy to detect ultrafine superparamagnetic grains, is less than 1%. Thus the low M_r/M_s and high H_{cr}/H_c ratios may indeed reflect large multi-domain grains.

COMPARISON WITH THE POLLEN SIGNAL

The similarity between pollen diagrams in Grandfather Lake and the nearby Ongivinuk Lake led Hu *et al*. (1995) to the conclusion that these records reflect the vegetation history in the northern Bristol Bay region. The Grandfather Lake sediments were divided in 6 pollen zones (I, IIa, IIb, IIc, III, IV). The lowest zone, zone I (8.5-7.1 m depth), is characterized by high percentages of *Cyperaceae* with smaller amounts of *Artimesia* (Figure 5) and *Poaceae*. This observation, the low organic matter content and low pollen accumulation rates in this interval led Hu *et al*. (1995) to conclude that herb-tundra vegetation was dominant. They suggested a cold and relatively moist climate during this period.

Summer temperatures are typically warmer in modern *Betula* shrub-tundra zones than in herb-dominated tundras (Bliss *et al*., 1981). Therefore, Hu *et al*. (1995) related the increase of *Betula* shrub in zone IIa (7.10-6.60 m depth) to a slightly warmer climate. Pollen percentages of *Betula*, *Cyperaceae* (Figure 5) and *Poaceae* suggest that the shrub cover in the Bristol Bay region during this time was comparable to that of the present-day North Slope (Hu *et al*. ,1995).

Betula pollen percentages are lower in zone IIb than in IIa, but percentages of *Artimesia* are slightly higher (Figure 5). As the low percentages of *Betula* might be due to lower summer temperatures this interval was related to climate cooling, possibly associated with the Younger Dryas cooling event (Hu *et al*., 1995).

In pollen zone IIc (5.85-4.80 m depth) *Betula* pollen percentages, pollen accumulation rates, *Galium* and *Sphagum* taxa either appear or increase and *Cyperaceae* decreases. These changes were attributed to a considerably warmer and humid climate marking the beginning of the Holocene (Hu *et al*., 1995). The large increase in *Alnus* (pollen zone III; 4.8 – 2.5 m) is often observed in Alaska around 7400 ^{14}C yr. and is generally attributed to a slightly more humid and cooler climate (Anderson and Brubaker, 1993).

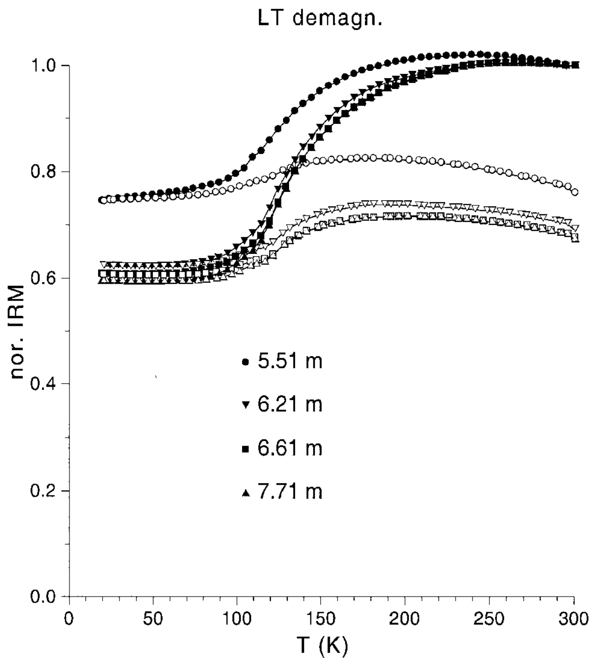

Fig. 4. Low-temperature demagnetization of the IRM. The IRM (isothermal remanent magnetization) was imparted at 300°K with a 2.5 T field and this remanence was cooled (closed symbols) to 20°K (-253°C) and then warmed (open symbols) to 300°K (27°C) in a zero field.

Summarizing, Hu *et al*. (1995) interpreted the vegetation history as (1) a cold climate during deposition of the lowermost sediments, followed by (2) a slight warming and (3) a colder episode, possibly associated with the Younger Dryas. The boundary between pollen zones IIb and IIc marks the end of the last glacial and the beginning of the Holocene.

Comparison with the magnetic signal (Figure 2 and 5) reveals no clear relationship between the pollen zones and the magnetic signal zones below 5.95 m depth. The magnetic signal significantly changes between pollen zones IIb and IIc, but the arrival of the *Alnus* pollen in the record is not accompanied by a significant change in magnetic properties.

DISCUSSION

Before interpreting the magnetic records in terms of environmental change, let us consider whether the magnetic signal could be related to (1) detrital input in the lake or (2) diagenetic processes in the sediments. Authigenic hematite, for example, indicates the occurrence of oxidation (e.g. Thompson and Oldfield, 1986) while pyrrhotite and greigite (Snowball and Thompson, 1990, Roberts and Turner, 1993) are indicative for reduction cycles. Magnetite is more likely to reflect a detrital signal. Authigenic fine (sub-micron) sized magnetite, however, may represent a past history of diagenesis (Tarduno, 1995).

The results of the high- and low-temperature experiments indicate that magnetite is the dominating magnetic mineral in Grandfather Lake. Low M_r/M_s and H_{cr}, H_c values and high H_{cr}/H_c ratios as well as the lack of frequency dependence of χ and the considerable remanence loss after a low-temperature demagnetization cycle all suggest a coarse grain size of the magnetite. Authigenic minerals such as hematite, pyrrhotite and greigite are not indicated by these measurements. The magnetite is probably detrital and not bacterial (Moskowitz *et al*., 1988), because the latter is often fine grained and has a frequency dependence of susceptibility. Detrital magnetite does not necessarily imply that the magnetic properties of the lake sediments can be directly related to those of the rocks and soils in the catchment area. For example a magnetic study of source materials and lake sediments in a volcanic crater in France showed that such a relationship is not straightforward (Vlag, 1996, Vlag *et al*., 1997b). Dissolution of small grains may explain the large grain size of the magnetite (Canfield and Berner, 1987). Due to a probable anoxic environment, dissolution is generally more effective in organic-rich sediments (Williams, 1992). In Grandfather Lake, however, one observes higher M_r/M_s, lower H_{cr}/H ratios and a smaller remanence loss during a low-temperature demagnetization cycle above 5.95 m (Figures 2 and 4). All these observations indicate a slightly smaller grain size for the more organic-rich sediments than for the organic-poor underlying sediments. This would not be expected if the large multi-domain grains were caused by dissolution.

At 5.95 m depth a large change in magnetic properties is observed. Above this depth magnetic concentration and the grain size decrease, while organic carbon and biogenic silica contents increase. Several magnetic studies report lower magnetic concentrations and smaller grain sizes during temperate periods compared to the glacial periods (e.g. Peck *et al*., 1994, Thouveny *et al*., 1994, Rosenbaum *et al*., 1996, Vlag *et al*., 1997a, Ortega-Guerrero *et al*., in press.). This may partly be related to soil formation. Soil formation leads to a lower erosion rate of the rocks in the catchment area and therefore to a lower detrital input of magnetic minerals from these rocks into the lake (e.g. Thouveny *et al.*, 1994). Secondary magnetic minerals can also form in soils (eg. Dearing *et al.,* 1997), but the first effect is often dominating (e.g. Thouveny *et al*., 1994). Formation of organic matter and biogenic silica in the lake may further dilute the magnetic mineral in the sediments, leading to an even lower magnetic concentration. As secondary soil minerals generally have a small grain size (Dearing *et al*., 1997), soil formation may also explain the small grain size above 5.95 m depth. The arrival of Alnus pollen in the region at ~7400 ^{14}C yr. (4.85 m depth) is not reflected by clear changes in magnetic concentration or grain size.

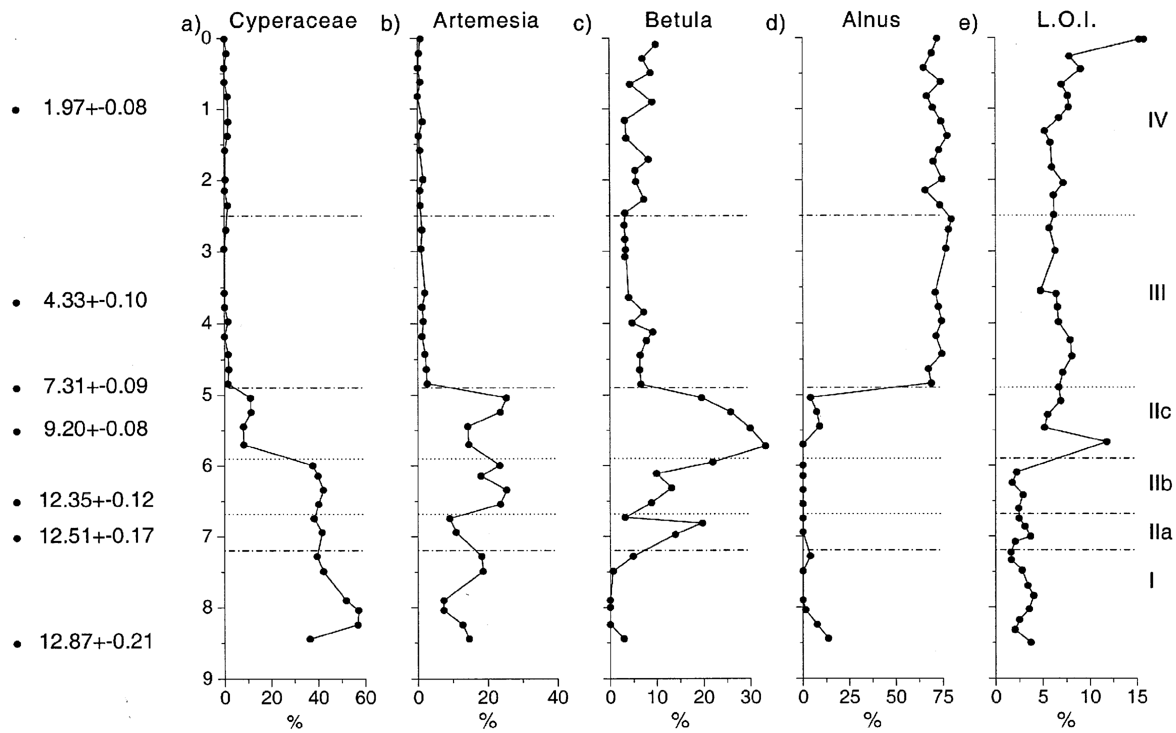

Fig. 5. Results of the pollen study. Data from Hu *et al*. (1995). (a) *Betula*, (b) *Alnus*, (c) *Cyperaceae*, (d) *Artemisia* pollen and (e) loss-on-ignition. A volcanic ash layer is situated between 3.04 and 3.50 m depth, explaining the absence of pollen data. Left column shows ^{14}C ages.

Pollen data suggest three distinct phases at the end of the last glacial period. The magnetic signal, however, shows only 'high' magnetic concentrations in the 8.5-5.95 m depth interval. As the magnetic signal is probably detritus, the concentration variations in this interval may be related to changes in detrital input. Therefore, the concentration peaks below 5.95 m depth may reflect a series of abrupt cooling events during the LGIT (e.g. Alley *et al*., 1993) and one such event (6.05 m depth ?) the Younger Dryas. This hypothesis can be tested by an improved chronolgy in this interval and by magnetic records of the LGIT from nearby lakes. However, pollen zone IIa, attributed by Hu *et al*. (1995) to this cooling event, cannot be distinguished on the basis of magnetic records. This may be explained as follows. (1) The impact of the Younger Dryas event in southwest Alaska, if any, was limited: It resulted in changes in the tundra vegetation of the region, but did not modify the erosion mechanism or the hydrology in the Grandfather Lake catchment area. (2) The impact of the first warming event (pollen zone IIa) was small. It resulted in the arrival of the *Betula* shrub within the region, but it didn't affect the detrital deposition process. (3) Magnetic concentration peaks in pollen zones I and IIb may reflect variations in detrital input during cold climate periods and the (coincidental?) absence of such peaks in pollen zone IIa may be due to an average warmer climate. (4) The changes the *Betula* pollen percentages are not directly linked to climate change.

Note that organic matter and biogenic silica contents are similar in pollen zone IIa and in the under - and overlying pollen zones. This suggests that the lake chemistry did not systematically change. It supports the arguments proposed to explain the discrepancy between pollen and magnetic records. Finally, the ice-sheets of the nearby Akhlun Mountains and the more distant Alaska Range were still present at the end of the Last Glacial period (Lea, 1990). This might have affected the environmental changes near Grandfather Lake during the Late Glacial-Holocene transition and should be taken into account when comparing the environmental proxies of Grandfather Lake with global climate records of the LGIT.

The transition between pollen zones IIb and IIc (5.95 m depth) is the only transition which is visible in both the pollen and magnetic records. It must represent the most significant environmental change during the studied time period, because vegetation and sediment deposition and/or diagenesis in the lake were affected. As the pollen and magnetic signals indicate a more temperate climate above this limit and taking into account the age of the transition (ca. 9500 ^{14}C yr.), it is likely that the 5.95 m depth interval marks the beginning of the Holocene. The sharp transition in magnetic parameters suggest that like in Greenland (e.g. Dansgaard *et al*., 1989, Johnsen *et al*., 1992) the end of the last glaciation might have been abrupt.

CONCLUSIONS

Preliminary magnetic measurements suggest the presence of a detrital magnetic signal in the sediments from Grandfather Lake. This signal is carried by coarse-grained magnetite. The rapid and significant change in the magnetic records at 5.95 m depth (~9500 ^{14}C yr.) suggests a rapid transition from a cold climate to the temperate Holocene. The magnetic records do not match with the pollen zones of Hu *et al*. (1995) below this transition. This shows the importance of a multi-disciplinary approach. Our finding may imply that either the impact of some warming-cooling events was limited, or some proxies are not directly influenced by climate.

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