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The rock magnetic signal of climate change in the maar lake sequence of Lac St Front (France)

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SUMMARY

Rock magnetic properties of the maar lake sediments of Lac St Front (Massif Central, France) reflect environmental changes during the last climatic cycle. High magnetic concentrations are measured in the sediments deposited under glacial climatic conditions, while lower concentrations correspond with more temperate climatic periods. Low- and high-temperature measurements indicate that the remanence is carried by (titanium-poor) magnetite. However, some maghemite and haematite is present in sediments deposited under temperate conditions.

Normalized intensities and coercivities of the anhysteretic remanent magnetization (ARM) are clearly higher for the sediments deposited during the temperate climatic periods of the Eemian, St Germain I, II and Mid-glacial than for glacial sediments, but other magnetic parameters hardly differ between these groups. Due to slight differences in magnetic composition and possible effects of grain interactions, it is not straightforward to relate this different ARM behaviour to magnetic grain-size variations. For the Holocene sediments, rock magnetic parameters indicate a larger grain size. This trend is also suggested by granulometric experiments with an optical laser granulometer. Dissolution of smaller grains is the most likely explanation for this larger grain size.

Changes in magnetic composition and grain size are extremely limited for the glacial sediments, but magnetic concentration varies considerably. Magnetic concentration maxima in the glacial sediments of Lac St Front correlate with those of the nearby Lac du Bouchet (Thouveny *et al.* 1994). Correlating the susceptibility records of these sequences with the $\delta^{18}\text{O}$ record of the GRIP ice cores (Thouveny *et al.* 1994) suggests that magnetic concentration maxima may correspond with short cold climatic episodes, associated with Heinrich events.

Key words: climate, maar lakes, magnetite, Massif Central, rock magnetism.

1 INTRODUCTION

It has been previously demonstrated that rock magnetic records of loess (e.g. Heller & Liu 1986; Banerjee 1994), marine sediments (e.g. Bloemendal & DeMenocal 1989) and lake sediments (e.g. Thouveny *et al.* 1994; Peck *et al.* 1994) reflect environmental changes. The maar lake sediments of Lac du Bouchet and Lac St Front (Massif Central, France) are attractive for environmental studies because the deposition rate is high and the source of sedimentation, the ancient crater wall,

has remained the same throughout the different climatic periods (Thouveny *et al.* 1994; Williams, Thouveny & Creer 1996). Due to the high magnetic concentration, these sediments are especially attractive for magnetic measurements. Thouveny *et al.* (1994) also showed that the susceptibility records of these lacustrine sequences, which reflect magnetic concentration, correspond with a regional climatic signal. The principal aim of this paper is to verify whether environmental changes in the maar lake sediments of Lac St Front result not only in magnetic concentration variations but also in changes in magnetic grain size and composition.

Variations in the most commonly used basic rock magnetic parameters (hysteresis parameters and ratios of various labora-

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tory-induced magnetizations) may result from both grain-size and compositional changes. To reduce this disadvantage of magnetic measurements, a combination of several rock magnetic methods has been used in this study. Such a multimethod approach leads, of course, to a better interpretation of the rock magnetic and environmental signal.

In the first part of this paper, the results of the individual rock magnetic methods (thermomagnetic runs, frequency dependence of susceptibility, hysteresis measurements and properties of laboratory-implanted remanent magnetizations) are presented. In a second step, the results of the various rock magnetic methods will be compared. Finally, the reflection of environmental changes in the rock magnetic signal will be discussed.

2 SITE

Lac St Front (longitude 3°E, latitude 45°N) is located in the Velay region of the French Massif Central. The lake fills a maar (a phreatomagmatic explosion crater), has a diameter of 600 m and is situated at an altitude of 1230 m. Its catchment area consists only of the ancient crater wall. A small outlet is situated at the southwestern shore of the lake.

In 1991, three cores were collected from the central area of the lake. These cores have lengths of 60, 47 and 22 m. The longest core (core B) is incomplete in the lowermost 13 m. In the upper part of the sedimentary column, piston core sections of 8 cm diameter and 1 m length were recovered (core A down to 35 m, cores B and C down to 22 m). A 'Mazier' corer, consisting of a rotating bit and a hollow drill stem, was used to core the harder underlying sediments. Sections of 6 cm diameter and 1.5 m length were recovered with this corer.

The core sections were stored in the cold-room of the Laboratoire de Géologie du Quaternaire prior to sampling. The cores were then split and subsampled every 2.5 cm with 8 cm³ cubic plastic boxes.

3 SUSCEPTIBILITY AND CLIMATIC SIGNAL

Down-core records of the low-field susceptibility (χ : mass normalized, K : volume normalized) are similar for all cores. Therefore, intercore correlation was based on the susceptibility records. High susceptibilities ($\chi > 500 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$) occur in a grey-brown clayey to silty-clayey lithology (Fig. 1). In these intervals, the total organic carbon content is less than 1 per cent (Rhoujjati 1995) and the percentage arboreal/non-arboreal pollen (corrected for *Pinus*) is low (Andrieu *et al.* 1995). Both the total organic carbon content and the arboreal/non-arboreal pollen percentage are considerably higher in low-susceptibility intervals (Fig. 1). Based on these three signals, it was concluded that high susceptibilities correspond to cold and low susceptibilities to more temperate climatic periods. A similar susceptibility signal is observed in the nearby Lac du Bouchet (Thouveny *et al.* 1994). The basic idea explaining the susceptibility variations as a function of environmental changes is as follows. During cold climatic periods a steppe vegetation dominated in this region (Reille & de Beaulieu 1990). Such an environment leads to high clastic erosion, caused by freeze-thaw weathering, and small input of organic matter. During temperate climatic periods the slopes of the catchment area are covered with vegetation and erosion is reduced by a

slowing of freeze-thaw weathering and increased binding of the surface. Hence, the input rate of detrital magnetic minerals decreases, but at the same time the organic-matter input increases. This results in lower susceptibilities per unit volume (and mass) in the sediments.

To determine sedimentation rates and ages of the sediments, the Lac St Front sequence was correlated with that of Lac du Bouchet (Fig. 2). For the latter sequence a depth-time transformation, based on ¹⁴C ages, vegetational climatic markers and correlation with oceanic $\delta^{18}\text{O}$ records, exists (Thouveny *et al.* 1994). As both lakes lie only 40 km apart, are situated at about the same altitude and have a similar geological setting, it is assumed for this correlation that the susceptibility records of both lakes are dominantly influenced by a regional climatic signal. As only major susceptibility minima (representing the major temperate periods) correlate, this correlation provides only a first-order idea of the age and deposition rate of the Lac St Front sediments (Fig. 2). At the same time, this correlation indicates that the contribution of local effects (for example turbidite layers, discontinuous sedimentation, etc.) to the susceptibility record cannot be neglected. For the 11.2–22 m depth interval, the validity of the susceptibility correlation could be verified by a correlation between the palaeomagnetic records (Vlag *et al.* 1996a). A disturbed magnetic fabric in Lac St Front prevented a correlation of the palaeomagnetic records at greater depths.

Up to 35 m depth, the most striking susceptibility minima of Lac St Front correlate with those of Lac du Bouchet (Thouveny *et al.* 1994; Vlag *et al.* 1996a) (Fig. 2). Assuming continuous sedimentation, the sedimentation rate was $\approx 40 \text{ cm kyr}^{-1}$ during the glacial periods of stage 2 (11.2–16.6 m) and 4 (22.5–33 m). The Holocene sediments cover an interval of 11.2 m in Lac St Front, but an interval of only 1.1 m in Lac du Bouchet. This is because in their present-day situations the first lake is eutrophic and the latter is oligotrophic (Thouveny *et al.* 1994). Pollen analysis suggests the presence of a hiatus at the Full Glacial Holocene limit in Lac St Front (Andrieu *et al.* 1995). This hiatus is further suggested by radiocarbon dating 45 cm above this limit, which reveals an age of $7.98 \pm 0.17 \text{ ka}$. Several small low-susceptibility intervals are observed between 17 and 22 m. These can be related to the temperate climatic periods of the Mid-glacial (that is isotopic stage 3). The low-susceptibility intervals measured in a compacted organic gyttja lithology around 34 m depth correspond with the interstadial St Germain II.

Below 35 m depth, the susceptibility correlation between Lac St Front and Lac du Bouchet is not straightforward. In Lac du Bouchet a succession of a high-, a low-, a high- and a second older low-susceptibility interval is observed (Fig. 2). These intervals correspond with the glacial Melisey II, interstadial St Germain I, glacial Melisey II and the Eemian interglacial, respectively. At the corresponding depth in the Lac St Front sequence, only one large low-susceptibility interval is observed (Fig. 2). These low susceptibilities were dominantly measured in a compacted organic gyttja lithology, but some small clayey layers and from 40 m depth some diatom-rich gyttja layers are also observed in this interval. Pollen studies suggest that the upper part of this large low-susceptibility interval corresponds to the St Germain I and the lower part with the Eemian (Andrieu *et al.* 1995), implying the quasi-absence of the Melisey I. An abrupt lithological change is observed at 38.7 m depth. Beige to brown silty clays

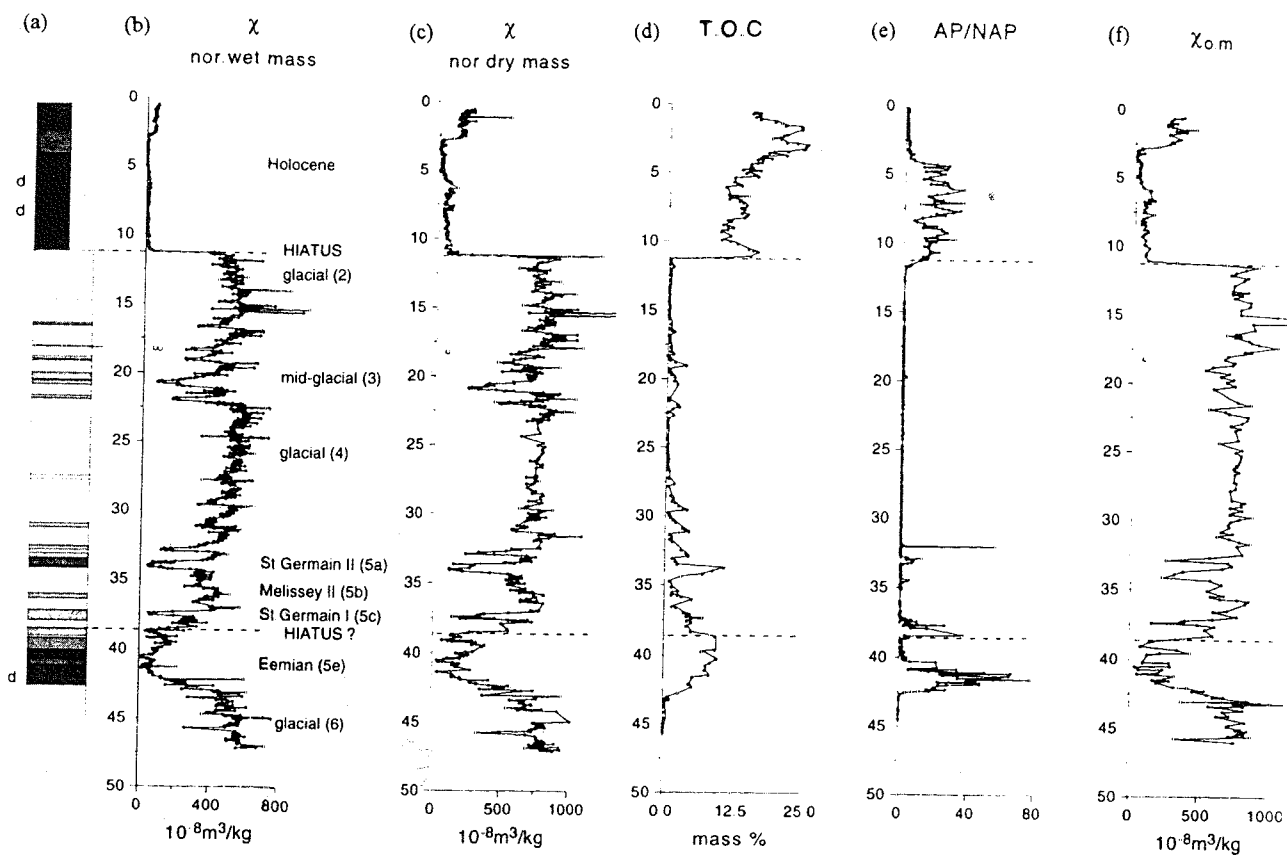


Figure 1. (a) Lithological column: narrow dark bands denote the organic gyttjas of the Holocene. Narrow less dark (mid-grey) bands denote the presence of a more clayey (silty) organic gyttja lithology. Wide pale-grey (white) bands denote a clayey (silty-clay) lithology. Wide less dark (dark) bands denote clays with some organic material (compacted organic gyttjas). 'd' before a band denotes the presence of diatom-rich layers. (b), (c) Down-core records of susceptibility normalized by (b) wet and (c) dry specimen mass, (d) mass percentage total organic carbon, (e) non-arboreal arboreal pollen percentage (corrected for *Pinus*) and (f) susceptibility corrected for the total organic mass (see text). Dotted lines indicate (possible) hiatuses (see text). The different climatic periods are marked (with their corresponding isotopic stages in parentheses)

unconformably overlie a dark brown gyttja unit. This unconformity indicates the possibility of a stratigraphic hiatus, which requires either an interruption of sedimentation or a high-energy current to remove sediments and transfer such turbiditic mud to another part of the basin. Although the extent of this possible hiatus is unknown, it might explain the quasi-absence of the Melissey I, but also implies that the youngest part of the Eemian and the oldest part of the St Germain I are absent in the Lac St Front sequence. Due to the uncertainties about the extent of this possible hiatus, it is impossible to discuss possible palaeoclimatic changes during the Eemian and St Germain I. However, it does not hamper the aim of this study, which is to compare the rock magnetic properties of sediments deposited during temperate and cold climatic periods.

After performing all rock magnetic measurements half of the total number of specimens, homogeneously divided over the entire section, were dried. For the glacial sediments, the dry mass is about 70–80 per cent of the wet mass. For the sediments in the uppermost part of the Holocene and diatom-rich layers this value is only 25–30 per cent. Susceptibilities and magnetic intensities of these samples were normalized by dry mass, because dry-mass-normalized intensities can be compared with measurements performed on instruments using dried small specimens (Table 1). Trends in wet- and dry-mass-normalized susceptibility records are similar, but the amplitude variations of the susceptibility signal differ (Fig 1). Unless otherwise

stated, only dry-mass-normalized susceptibilities and intensities are presented in this paper.

As organic material is weakly diamagnetic, susceptibility records can be corrected for the total organic mass. If the susceptibility signal is alone caused by dilution of the magnetic fraction by the organic fraction, the organic-mass-corrected susceptibility logs should be invariant with depth. Rhoujjatti (1995) showed that total organic mass, determined by the weight loss between 105° and 550°C, is about two times the total organic-carbon mass (m_{TOC}). The organic-mass-corrected susceptibility (χ_{om}) is thus defined as $\chi_{\text{om}} = (\chi_{\text{total}}) / (m_{\text{total}} - 2m_{\text{TOC}})$. Like χ , χ_{om} is much lower for the sediments deposited during temperate climatic periods than for glacial sediments (Fig 1), and the large fluctuations in χ_{om} cannot be neutralized by slightly changing the multiplication factor of the total organic carbon content (thus the estimate of the total organic mass). This indicates that susceptibility variations cannot only be explained by dilution of the magnetic fraction by the organic fraction. Hence, to explain the low susceptibilities of the sediments deposited during temperate climatic periods, one should also take into account the effects of (1) a decrease of the magnetic input fraction during temperate climatic periods, (2) dilution of the magnetic fraction by the silica of the diatoms formed in the lake and (3) changes in magnetic mineralogy and grain size. Dilution by the diatom silica is likely, as diatoms are observed in the lower part of

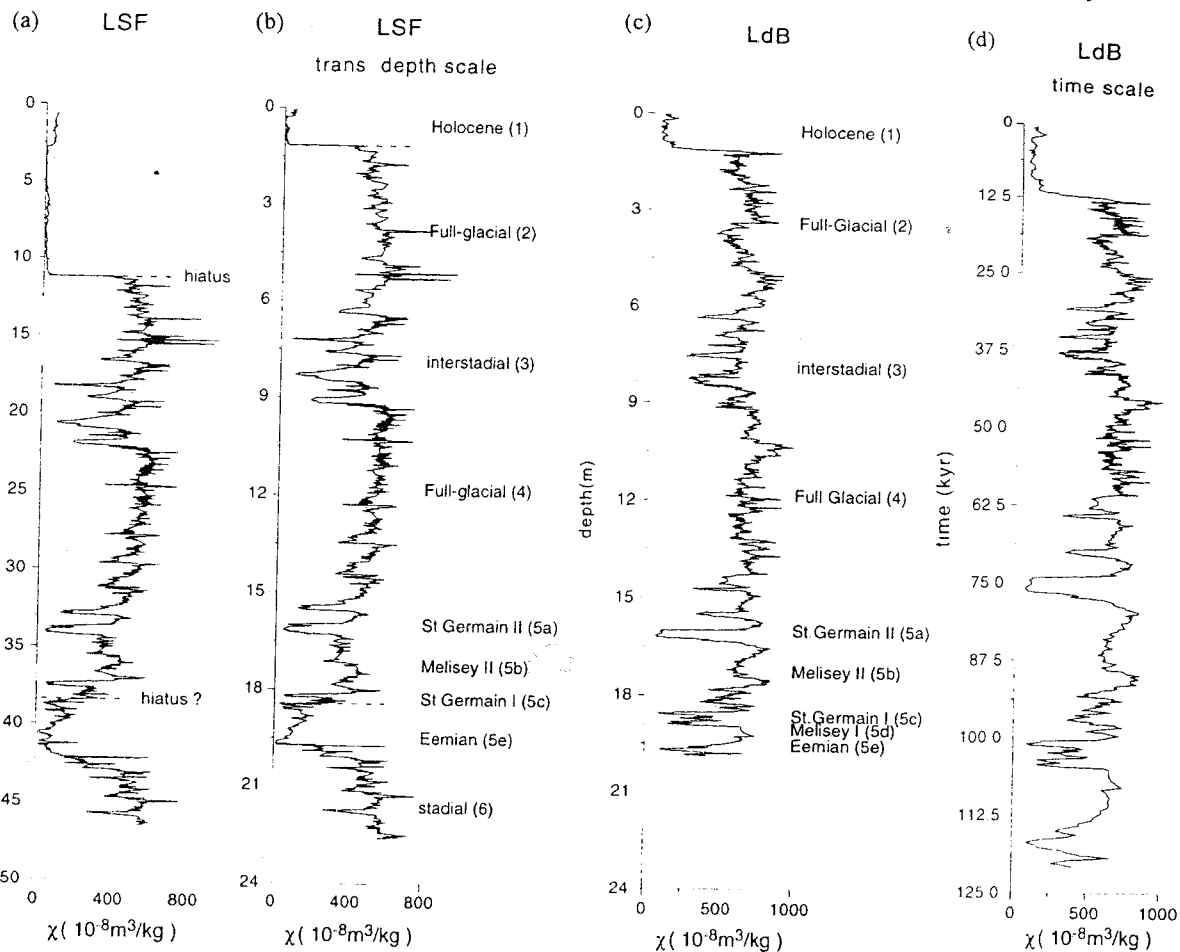


Figure 2. The Lac St Front susceptibility record on (a) the original and (b) the Lac du Bouchet depth scale. Lac du Bouchet susceptibility record plotted on (c) its depth scale and (d) its timescale. Susceptibilities in this figure are normalized by wet mass, because no dry-mass-normalized susceptibility records exist for the Lac du Bouchet sequence.

Table 1. Technical aspects of the magnetic measurements performed

measurement	section	instrument	samples	remarks	indicative for:
Low field susceptibility	3	Bartington MS-2 susceptibility bridge	wet, 8 cm ³	-	concentration, composition, dia- and paramagnetic grains, superparamagnetic (SP) grains
high-temperature M _s -T	4.1	Curie balance*	dried, 30-80 mg		magn. composition
frequency dependence of χ	4.3	Lakeshore AC Susceptometer**	dried, ~50 mg	frequency ranging from 5 to 10 000 Hz; AC field: 0.08 mT, for Holocene sed.: 0.2 mT	SP grains
hysteresis loops	4.4	Alternating Gradient Magnetometer (AGM) - 'MicroMag'	dried, ~20 mg	max. field: 500 mT; parameters: M _s , M _s , H _c , χ _{hys}	domain state (M _s /M _s , H _c /H _c), magn. concentration (M _s)
backfield demagnetization	4.5	AGM - 'MicroMag'	dried, ~20 mg	max. field 1 T; parameters: S-ratios, H _c	coercivities of minerals
IRM (isothermal rem. magn.)	4.6	DC coils	wet, 8 cm ³	IRM implanted with 1 T	IRMχ; magn. grain size
ARM (anhysteretic rem. magn.)	4.6	Schonstedt demagnetizer	wet, 8 cm ³	ARM implanted with DC: 0.1 mT, AC field 90 mT	ARMχ; see text
alternating field (AF)	4.6	Schonstedt demagnetizer	-	max AF: 90 mT	MDF _{arm} ; magn. grain size
demagnetization:IRM and ARM					MDF _{arm} ; magn. grain size
thermal demagnetization	4.6	MMTD1 furnace	-		magn. composition
IRM and ARM					
granulometric determination	4.7	Mastersizer laser granulometer	dissolved mat.		particle and grain sizes

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the Holocene (5–11.2 m) and Eemian intervals (>40 m). The other factors will be discussed in the following sections of this paper

4 ROCK MAGNETIC ANALYSIS

For the purpose of distinguishing between sediments from different climatic periods, the sediments were divided into four groups. These consist of sediments deposited during (1) the Holocene (0–11.25 m), (2) the Full-glacials and the Mid-glacial (11.25–33 m), (3) the interstadials St Germain I and II, and (4) the Eemian. These four groups are simply called Holocene, glacial, St Germain and Eemian sediments in this paper. St Germain and Eemian sediments are defined as sediments with a susceptibility lower than $400 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ which are found in the depth intervals 32.5–38.7 m and 38.7–45 m, respectively. The discrimination between the St Germain and Eemian sediments was made for two reasons. First, to check whether the magnetic properties in a small (30–50 cm) low-susceptibility interval differ from those in a larger low-susceptibility interval (1.5 m). Second, in contrast to the St Germain I and II, the lowest part of the Eemian sediments consists of diatom-rich layers. Higher susceptibilities are measured in the uppermost 2.5 m of the Holocene. Unless otherwise stated this interval is not distinguished from the underlying Holocene sediments.

4.1 Thermomagnetic runs

In thermomagnetic runs saturation magnetization versus temperature was measured up to a maximum temperature of 700 °C (Table 1). The measurements could be performed on bulk sediments because the magnetic mineral content was high enough and the balance was very sensitive. Heating and cooling rates were moderate: 6 and 10 °C min^{-1} , respectively. For the Holocene sediments, a monotonous decay in intensity is observed up to 580 °C (Fig. 3a), at which point the largest part of the magnetization is removed. Only a very small-intensity decay is observed between 580° and 680 °C. For the glacial sediments, the magnetization is completely removed at 580 °C, indicating that magnetite is the main magnetic mineral (Fig. 3b). A monotonous decay of the saturation magnetization upon heating to 630 °C is observed for the sediments of the St Germain II, indicating the presence of maghemite and/or haematite (Fig. 3c). Thermomagnetic runs of the Eemian sediments resemble those of the Holocene sediments: the largest part of the magnetization is removed at 580 °C, but a small-intensity decay is observed between 580° and 680 °C. For all sediments, the magnetization is lower during cooling than during heating, suggesting the oxidation of magnetite to haematite during heating.

4.2 Frequency dependence of susceptibility

The frequency dependence of susceptibility was measured within the frequency range 50–10 000 Hz (Table 1). The amplitude of the alternating field was set to 0.08 mT. However, the amplitude of the alternating field had to be increased to 0.2 mT to measure the weakly magnetized Holocene sediments. The frequency dependence of susceptibility is parametrized by calculating the percentage susceptibility loss between 470 (χ_{470}) and 4700 (χ_{4700}) Hz: $\chi_{fd} = [(\chi_{470} - \chi_{4700})/\chi_{470}] \times 100$ (frequencies

at which the susceptibility is measured with a Bartington susceptometer). For these measurements, χ_{fd} was calculated from a best-fitting line through the data points between 200 and 6000 Hz. Usually, χ_{fd} ranges between 1.8 and 3.0 per cent. Apart from specimens sampled in the uppermost 2.5 m (and having higher susceptibilities), lower χ_{fd} values are observed for the Holocene sediments.

The low magnetizations prevented us from measuring additional χ_{fd} values for the Holocene (and some Eemian) sediments with the Bartington MS-2 susceptometer. For the other sediments, these additional measurements confirmed the results obtained by the Lakeshore Susceptometer: χ_{fd} ranging between 1.5 and 3.0 per cent and no significant differences between χ_{fd} observed for sediments deposited during the glacials, St Germain I, II and the Eemian (Fig. 4).

4.3 Hysteresis loops

For the hysteresis experiments, a maximum field of 500 mT was used. Test runs using a maximum field of 1 T yielded similar results. Remanent coercive forces (H_{cr}) were measured by a backfield demagnetization of a remanence induced with 500 mT steady field.

Saturation magnetizations (M_s) range from 10 $\text{mA m}^2 \text{ kg}^{-1}$ for the Holocene sediments up to 1000 $\text{mA m}^2 \text{ kg}^{-1}$ for the glacial sediments. Remanent magnetizations (M_r) vary between 1 and 250 $\text{mA m}^2 \text{ kg}^{-1}$. In the case of a uniform magnetic composition of mineralogy, changes in the remanence ratio M_r/M_s and coercivity ratio H_{cr}/H_c reflect changes in magnetic domain state and grain size (Day, Fuller & Schmidt 1977). Hysteresis ratios of the Lac St Front sediments fall in the pseudo-single-domain (PSD) range. However, M_r/M_s and H_{cr}/H_c ratios of the Holocene sediments are closer to the multidomain (MD) range (Fig. 5a).

Coercive forces (H_c) are lower for the Holocene than for the glacial sediments (Fig. 5b). Remanent coercive forces (H_{cr}) are slightly lower for the Holocene than for the glacial, St Germain and Eemian sediments (Fig. 5b). Similar M_r/M_s and H_{cr} values are found for the glacial, St Germain and Eemian sediments, but the last two show a systematically lower H_c (thus a higher H_{cr}/H_c) (Fig. 5). Hysteresis parameters do not differ systematically between Eemian and St Germain sediments, but they do show large variations within these groups. Although most parameters agree with the trends described it should be noted that some Eemian samples show high coercivities, while their accompanying M_r/M_s – H_{cr}/H_c ratios suggest a trend towards the single-domain (SD) range (Fig. 5).

To study the effect of dia- and paramagnetic minerals on the low-field susceptibilities, χ should be corrected for the high-field susceptibility (χ_{hf}). However, as χ is measured on 8 cm^3 samples with a Bartington susceptibility meter and χ_{hf} on small chips with the AGM, both susceptibilities cannot be compared directly. To compare χ with χ_{hf} , the following method was used. (1) A low-field susceptibility of a small MicroMag chip was measured with a Kappa-bridge before performing the hysteresis measurements. (2) From the hysteresis loop the additional hysteresis parameter χ_{hys} , the slope of the hysteresis loop at zero field (Von Dobeneck 1996; Vlag, Rochette & Dekkers 1996b), and χ_{hf} were calculated. With this method, the commonly used low-field susceptibilities (χ) can be linked with χ_{hys} , while the latter can be directly compared with χ_{hf} . To prevent any confusion with low-field susceptibilities measured

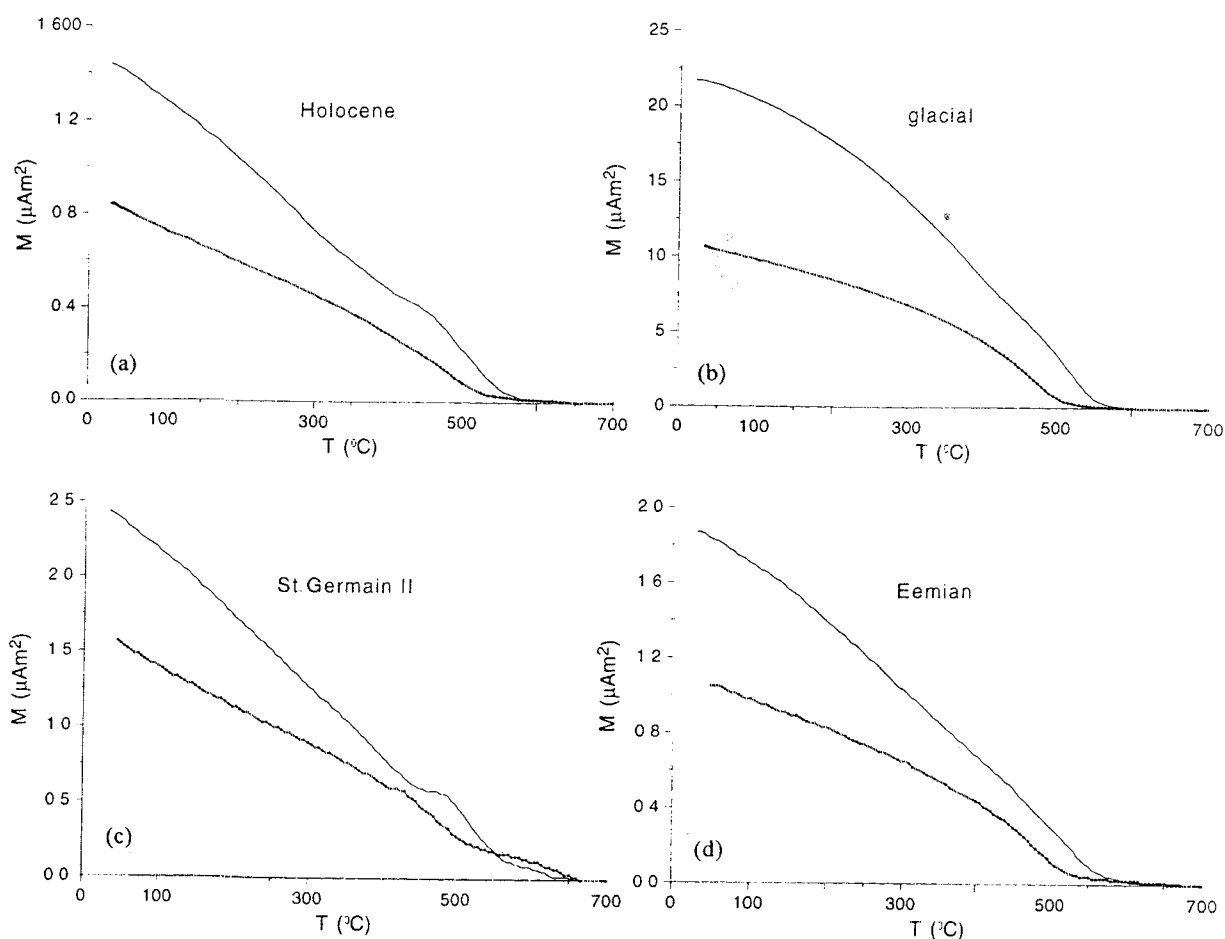


Figure 3. High-temperature M_s - T runs. Typical examples for (a) Holocene (b) glacial, (c) St Germain II and (d) Eemian specimens. Dotted-line segments denote cooling parts

on 8 cm³ samples with the Bartington susceptometer (χ), this KLY-2 low-field susceptibility is termed χ_{kly-2} in this paper. χ does not fundamentally differ from χ_{kly-2} . Cross-calibration of the KLY-2 with the MicroMag was done by measuring χ_{hys} and χ_{kly-2} of some paramagnetic schists on both instruments. Both susceptibilities are the same for these schists, indicating that differences between χ_{hys} and χ_{kly-2} are due to ferrimagnetic minerals. Vlag *et al.* (1996b) empirically found a χ_{hys}/χ_{kly-2} ratio of 1.6 for truly MD grains and an increasing χ_{hys}/χ_{kly-2} with decreasing grain size for smaller grains. For the Lac St Front sediments $(\chi_{hys}-\chi_{hf})/(\chi_{kly-2}-\chi_{hf})$ is 1.85 (Fig. 6b). Hence, like M_r/M_s and H_{cr}/H_c this ratio suggests a pseudo-single-domain state for the magnetic minerals.

For the glacial, St Germain and Eemian sediments, χ_{hf} contributes only 2–3 per cent to χ_{hys} , but for most Holocene sediments the χ_{hf} contribution to χ_{hys} is about 7 per cent. χ_{hys} is a factor of about 1.85 higher than χ and the dia- and paramagnetic contribution to these susceptibilities is the same. Hence, the dia- and paramagnetic χ_{hf} contributes about 13 per cent to χ for the Holocene sediments and cannot be neglected.

4.4 S-ratios

The commonly used S-ratio is defined by the magnetization measured with a 300 mT backfield demagnetization (M_{-300}) normalized by magnetization induced with a 1 T field (M_{1000}):

$S = -M_{-300}/M_{1000}$. For the glacial sediments S-ratios are generally higher than 0.95. This ratio is lower (0.88–0.93) for the sediments deposited under more temperate climatic periods, indicating that these intervals contain more minerals with a high coercivity.

4.5 Isothermal and anhysteretic remanent magnetization

The properties of two laboratory-induced magnetizations were studied: isothermal remanent magnetization (IRM), imparted with a DC field of 1 T, and anhysteretic remanent magnetization (ARM), imparted with a steady field of 100 μ T and a peak alternating field (AF) of 90 mT (Table 1). ARM acquisition curves show that a 90 mT AF field is sufficient to saturate the minerals.

Thermal decay curves show that IRM unblocks between 580° and 600 °C (Fig. 7a). These unblocking temperatures are slightly higher than the Curie temperature of pure magnetite (580 °C) and suggest that IRM is carried by magnetite, which is slightly oxidized (Nishitani & Kono 1983). Furthermore, it is remarkable that for the Holocene specimens about 80 per cent of the IRM unblocks below 150 °C. This IRM decay cannot be explained by goethite as a remanence carrier, because S-ratios range between 0.88 and 0.93.

For the glacial sediments, ARM also unblocks between 580° and 600 °C. For the Eemian, St Germain and Holocene

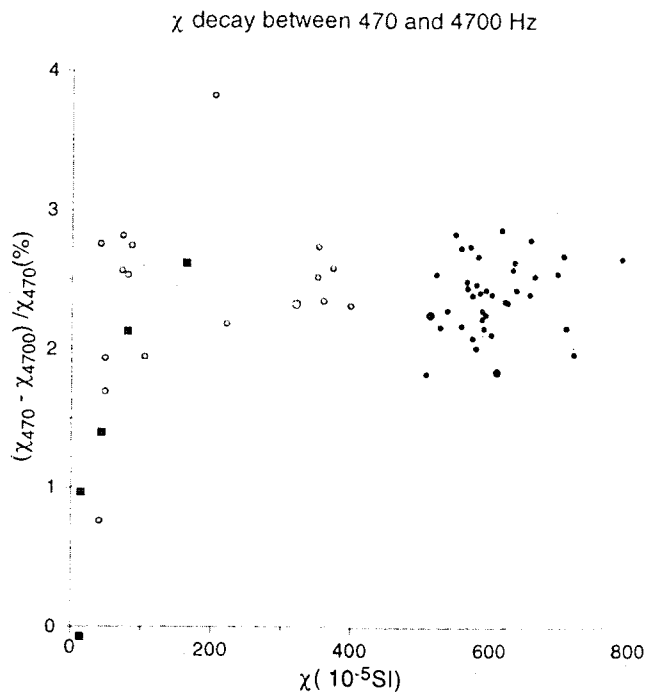


Figure 4. Frequency dependence of susceptibility χ_{fd} versus χ , large (small) symbols denote specimens measured with the AC susceptometer (Bartington susceptometer). Squares (stars) denote Holocene (glacial) sediments. Grey (open) circles denote St Germain (Eemian) sediments

sediments, however, a discontinuity in the ARM thermal decay is observed between 200° and 400 °C. Moreover, ARM is not completely removed at 580 °C, but unblocks between 620° and 680 °C (Fig. 7b). These unblocking temperatures indicate the presence of maghemite and/or haematite. As thermally stable maghemite has a maximum unblocking temperature of ≈ 630 °C (Özdemir & Banerjee 1982), the larger ARM decay between 580° and 620 °C than that between 620° and 680 °C

suggests the presence of maghemite. Maghemite is further indicated by the thermomagnetic runs of the St Germain sediments. Haematite may explain the lower S -ratios for these sediments. Its presence is also indicated by the small intensity decay between 580° and 680 °C in the thermomagnetic runs of the Holocene and Eemian sediments. In contrast to ARM, IRM unblocking temperatures of 580–600 °C indicate the presence of (oxidized) magnetite for these sediments.

IRM is removed with alternating fields (AF) up to 90 mT, which was applied in the z -axis IRM AF decay curves are similar for all sediment types. Its median destructive field (MDF_{irm}), at which half of the IRM is removed, is slightly higher for the Eemian and St Germain and slightly lower for the Holocene than for the glacial sediments (Fig. 8a). The median destructive field of ARM (MDF_{arm}) is ≈ 30 mT for glacial sediments, having an initial ARM intensity higher than 4 A m^{-1} (Fig. 8b). More weakly magnetized glacial sediments and Eemian and St Germain sediments have higher MDF_{arm} values. The lowest MDF_{arm} values are observed for the Holocene sediments.

IRM/ χ may indicate changes in ferro/ferrimagnetic grain size (Thompson & Oldfield 1986). As superparamagnetic (SP) grains contribute considerably to χ , but not to IRM, their presence might be detected by low(er) IRM/ χ ratios. Above the SP-SD threshold ($\approx 0.03 \mu\text{m}$), the grain-size dependence of χ is ambiguous: it has been generally believed that χ decreases with increasing grain size (e.g. Thompson & Oldfield 1986), but recently a grain-size independence of χ for grown magnetite grains was reported (Heider, Zitzelsberger & Fabian 1996). Nevertheless, due to the decreasing IRM intensity with increasing grain size, IRM/ χ decreases with increasing grain size above the SP-SD limit. IRM/ χ is usually lower for the Holocene than for the glacial sediments (Fig. 9a). For the Eemian and St Germain sediments, IRM/ χ fluctuates but does not significantly differ from the glacial sediments. In contrast to IRM, χ is affected by dia- and paramagnetic minerals. Hence, for the correct use of IRM/ χ as a grain-size indicator,

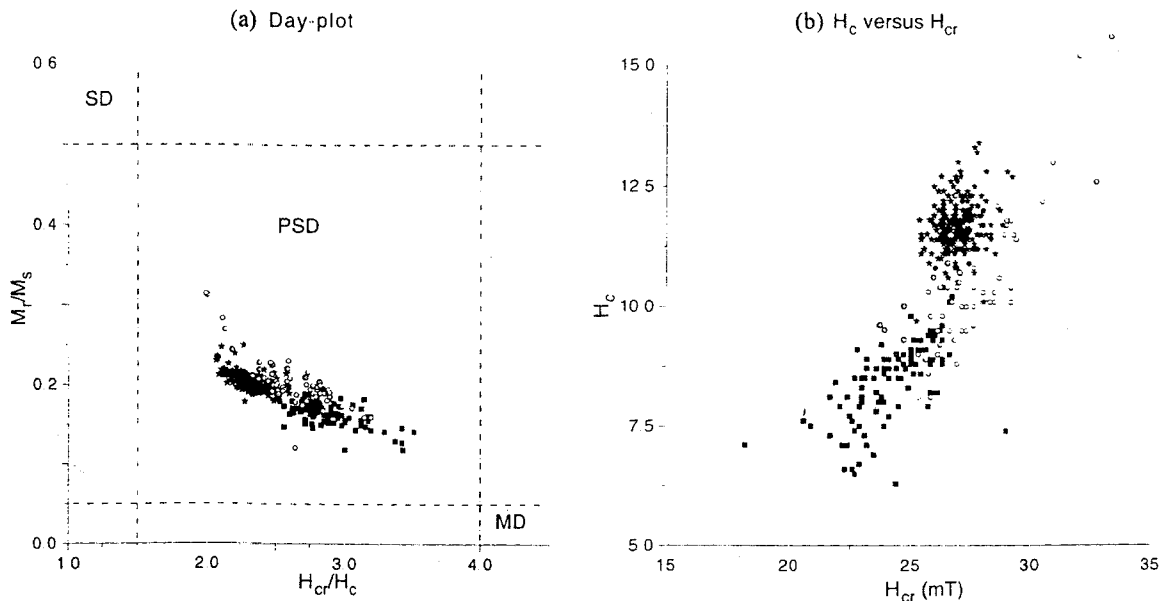


Figure 5. Hysteresis parameters. (a) M_r/M_s versus H_{cr}/H_c ; (b) H_c versus H_{cr} . Same symbols as in Fig. 4.

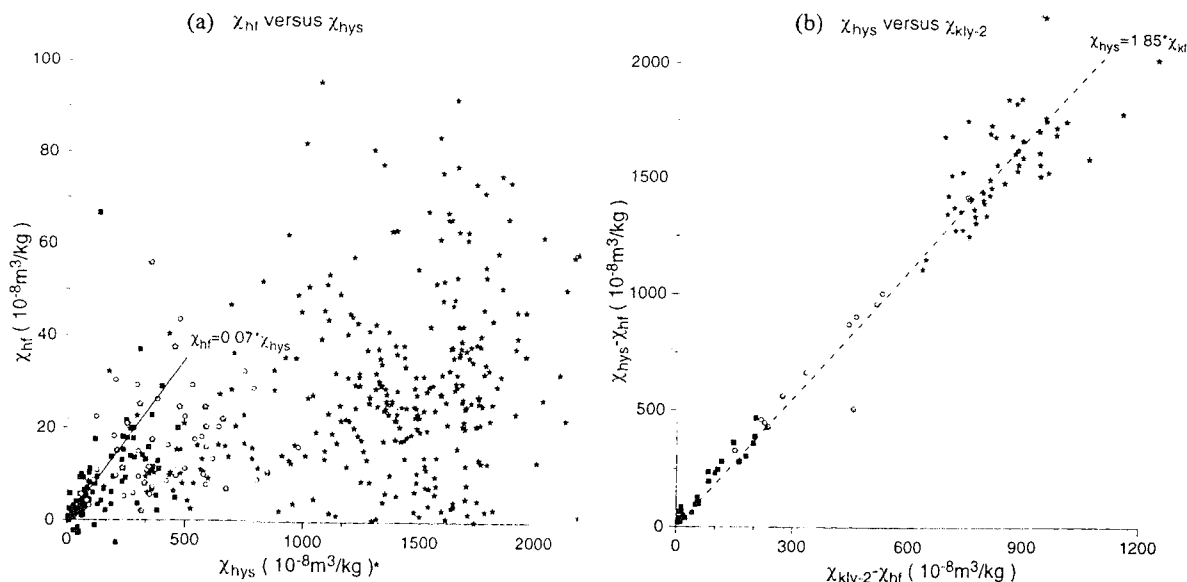


Figure 6. Hysteresis parameters (a) χ_{hf} versus χ_{hys} . The line denotes a best fit through the χ_{hf}/χ_{hys} ratios of the Holocene specimens with $\chi_{hys} < 100 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. (b) χ_{hys} versus χ_{kly-2} . The dotted line denotes the best fit through all data points. Same symbols as in Fig 4

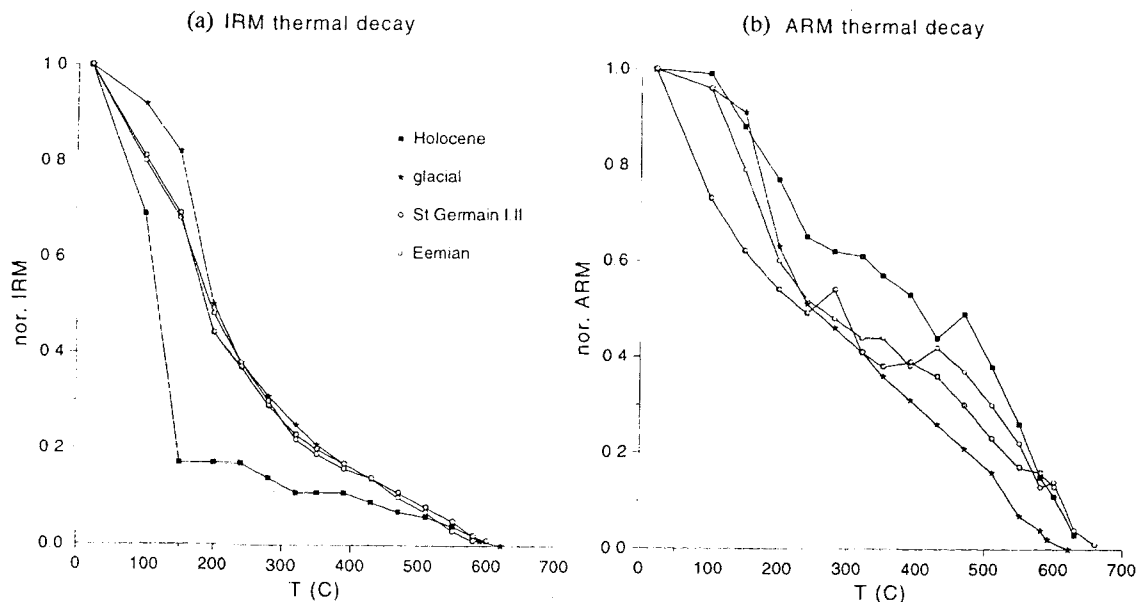


Figure 7. Normalized thermal decay curves of (a) IRM and (b) ARM. Same symbols as in Fig 4.

this parameter should be corrected for χ_{hf} : $IRM/(\chi - \chi_{hf})$. This correction is particularly important for a comparison between IRM/χ ratios of the Holocene and glacial sediments, because the χ_{hf} contribution to χ is relatively higher for the Holocene sediments. As IRM/χ was measured on 8 cm^3 cubic samples and χ_{hf} on small MicroMag chips, it is not possible to correct each individual IRM/χ ratio. Therefore, corrected ratios ($IRM/\chi_{cor} = IRM/(\chi - \chi_{hf})$) are calculated by assuming that the χ_{hf} contribution to χ is 13 per cent for all Holocene specimens and 4 per cent for all other specimens (Section 4.4). IRM/χ_{cor} is still lower for the Holocene than for the glacial sediments (Fig. 9b).

Changes in ARM/χ correlate with susceptibility variations (Figs 9c and d). For the glacial sediments and Holocene sediments with $\chi < 100 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$, ARM/χ decreases with

increasing susceptibility. This relationship is more easily visible if ARM/χ is plotted against volume susceptibilities (K) than against mass-normalized susceptibilities (χ) (Figs 9c and d). The Holocene sediments from the uppermost 2.5 m have higher susceptibilities and ARM/χ ratios than the underlying Holocene sediments. For the Eemian and St Germain sediments, ARM/χ ratios are scattered, but are generally higher than for the glacial sediments. Furthermore, it is worth noting that for the glacial and most Holocene sediments, ARM/χ and M_r/M_s correlate (Fig. 10). The higher ARM/χ ratios of specimens from the uppermost 2.5 m of the Holocene and the Eemian–St Germain, however, are not accompanied by any significant change in M_r/M_s (Figs 10a and c).

Summarizing, it can be concluded that ARM properties differ considerably from IRM: (1) ARM/χ and MDF_{arm} clearly

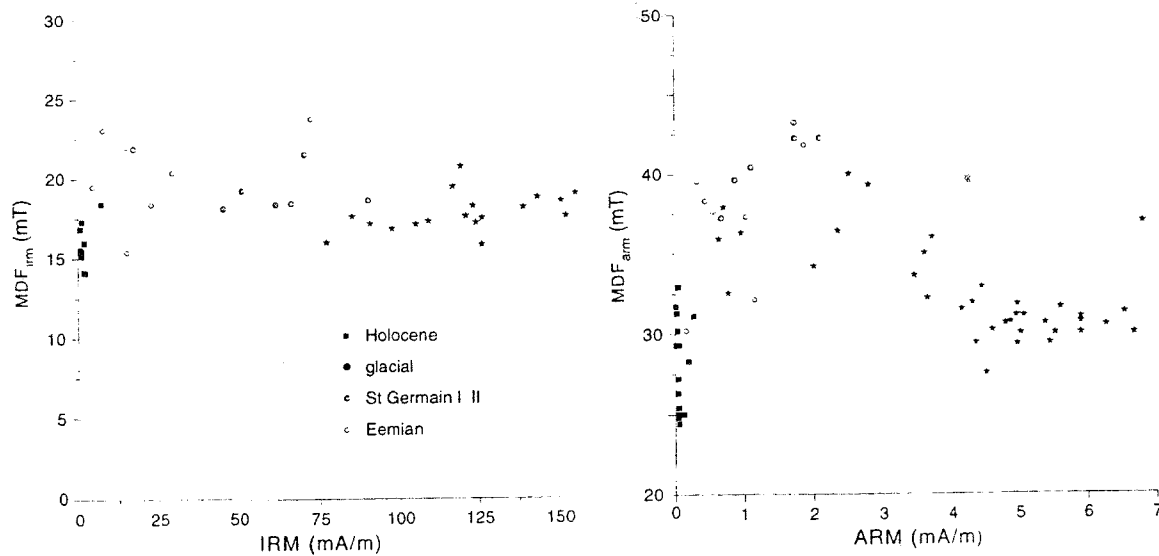


Figure 8. (a) MDF_{irm} versus IRM intensity. (b) MDF_{arm} versus ARM intensity. Same symbols as in Fig. 4.

distinguish the St Germain and Eemian from the glacial sediments, (2) variations in ARM-related parameters are much larger and (3) show a relationship with χ .

4.6 Granulometric measurements

Granulometric measurements were performed on bulk sediments and on magnetic concentrates. For these granulometric measurements (Table 1) the following experimental procedure was carried out. In a first step the studied material was dispersed in water. The dispersed material was then pumped through an optical laser granulometer and its particle-size distribution was measured 10 times before calculating an average particle-size distribution. As the volume percentage per particle diameter is determined, peak values are found at large particle diameters (Fig. 11).

For the Holocene and Eemian sediments, a bimodal particle-size distribution is found. The shoulder is found at 0.3–0.4 μm and a peak around 100 μm . Although evidence is apparently absent, the theory that the latter peak is due to aggregate formation in the dissolved organic Holocene and Eemian sediments cannot be formally excluded. Due to the quasi-absence of organic matter, aggregate formation is unlikely for the dissolved glacial sediments. These sediments also show a bimodal particle-size distribution: one peak around 0.3 μm and another around 15 μm (Fig. 11). Compared to the clayey layers, the 'large' particle mode is somewhat enhanced in the silty layers of the glacial sediments (not shown).

Magnetic concentrates were obtained by passing dissolved sediment through a ≈ 300 mT field between the poles of an electromagnet. These concentrates were then demagnetized with a 90 mT peak AF. As the grain-size distribution did not increase during the 10 consecutive grain-size determinations, it is assumed that clustering of magnetic grains did not occur during the grain-size determinations. Magnetic grain sizes range between 1 and 200 μm for the glacial and Eemian concentrates and for the Holocene concentrate from 0.8 m depth. It is worth noting that a similar particle-size distribution is found for the Holocene bulk sediments of 0.8 and 7.2 m depth, but that the magnetic concentrate of the latter shows

clearly larger grain sizes (Fig. 11). Surprisingly, the granulometric experiments on this concentrate do not reveal the presence of grains with a diameter smaller than 30 μm . As hysteresis ratios, lower IRM χ and lower MDF_{irm} values indicate an on average larger grain size for the Holocene sediments, it is suggested that this grain-size distribution is not (only) related to the magnetic extraction procedure.

In order to compare the magnetic properties of the concentrates with those of the sediments, susceptibility, hysteresis loops and ARM properties of the concentrates were measured. Samples for these measurements were prepared by dissolving the magnetic grains in a Na–Si solution with kaolin powder. ARM/χ varies between 0.3 and 0.5 kA m^{-1} , MDF_{arm} between 16 and 21 mT, M_r/M_s between 0.1 and 0.15 and H_{cr}/H_c between 4 and 5. All these parameters suggest a larger magnetic grain size for the concentrates than for the sediments. Therefore, the measurements on the concentrates have to be taken with caution. As ARM/χ and MDF_{arm} are similar for the Eemian and glacial concentrates, concentrates cannot be used to explain the different ARM behaviour between these sediments.

Scanning Electronic Microscope (SEM) images and microprobe analyses were also carried out on the concentrates. The former indicate the presence of detrital grains and the latter Ti/Fe ratios of ≈ 0.3 . The latter correspond with x -values of ≈ 0.7 in the titanomagnetite ($\text{Fe}_{3-x}\text{Ti}_x\text{O}_4$) series. Nagata (1961) showed that titanomagnetites with a composition of $\text{Fe}_{2.3}\text{Ti}_{0.7}\text{O}_4$ have Curie temperatures of $\approx 70^\circ\text{C}$. Therefore, these high Ti/Fe ratios derived from the microprobe analysis do not correspond with the unblocking temperatures derived from the thermomagnetic runs and IRM and ARM thermal demagnetization ($>580^\circ\text{C}$). It seems to us unlikely that this large discrepancy is only due to the magnetic extraction procedure. Therefore, it strongly suggests that an intergrowth of Ti-rich and Ti-poor lamellae exist in these sediments. Unfortunately, no further evidence for this hypothesis can be provided.

5 DOWN-CORE MEASUREMENTS

Hysteresis loops were measured every 10 cm and ARMs and IRMs were imparted every 5 cm. Parameters depending on

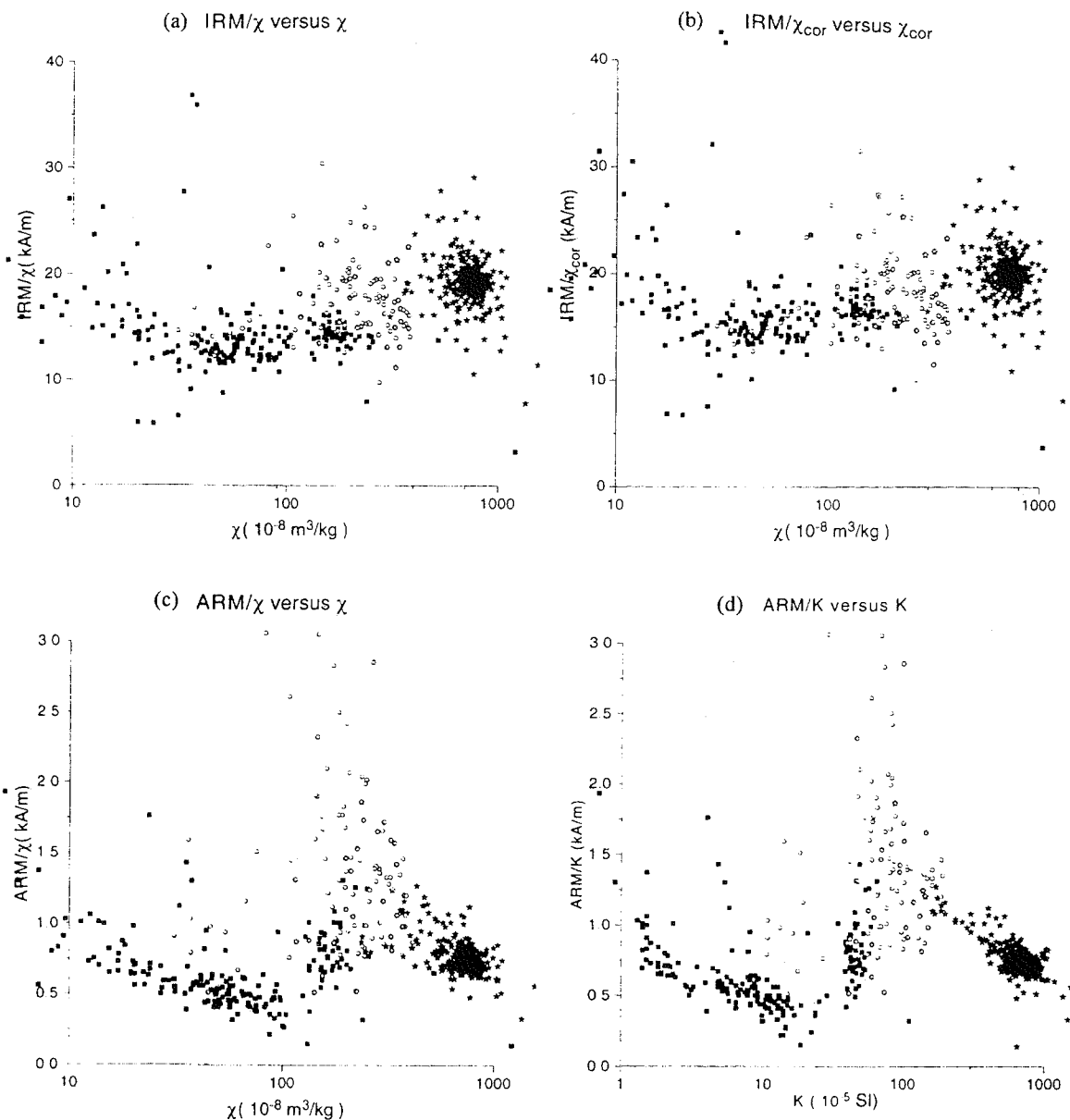


Figure 9. (a) IRM/χ versus χ. (b) IRM/χ_{cor} versus χ_{cor} [IRM/(χ-χ_{hf})/(χ-χ_{hf}); see text]. (c) ARM χ⁻¹ versus χ, using mass-normalized susceptibilities and intensities. (d) ARM/K versus K, using volume-normalized susceptibilities and intensities. Same symbols as in Fig. 4.

magnetic concentration (χ and M_s) clearly distinguish the temperate climatic periods (low magnetic concentration) from the cold climatic periods (high magnetic concentration). Small discrepancies between χ and M_s are observed in small low-concentration intervals (31.8, 32.5, 37.6–38.1 m depth). These discrepancies are probably related to a lower representativity of the small MicroMag chips in combination with a lower resolution of hysteresis measurements because for the MicroMag specimens, M_s correlates with χ_{kly-2} (not shown).

Compared to the large variations in lithology, magnetic concentration, total organic carbon content and arboreal/non-arboreal pollen ratio (Fig. 1), the changes in concentration-independent magnetic parameters are remarkably low (Fig. 12). Hysteresis parameters and IRM/χ and ARM/χ clearly distinguish the Holocene from the underlying sediments. In Section 4.5 it was shown that IRM/χ ratios corrected for the

χ_{hf} contribution are still lower for the Holocene than for the underlying sediments (Fig. 12e). Corrected ARM/χ ratios, however, do not systematically differ between the Holocene and the glacial sediments, but discontinuities can be seen within the Holocene. It should be noted that magnetic parameters fluctuate considerably within the Holocene. The increased scatter in IRM/χ and ARM/χ between 2.6 and 4.5 m depth is probably due to low susceptibilities, which are close to the sensitivity of the Bartington susceptometer. Down-core logs of hysteresis parameters, IRM/χ and ARM/χ do not clearly distinguish the 0–2.6 m depth interval (higher χ and M_s) from the underlying Holocene sediments. However, different rock magnetic properties for the 0–2.6 m depth interval are indicated by the absence of a correlation between ARM/χ and M_s (Fig. 10c) and a higher ARM/χ compared to the most weakly magnetized Holocene sediments in the 2.6–11.2 m depth interval (Figs 9c and d).

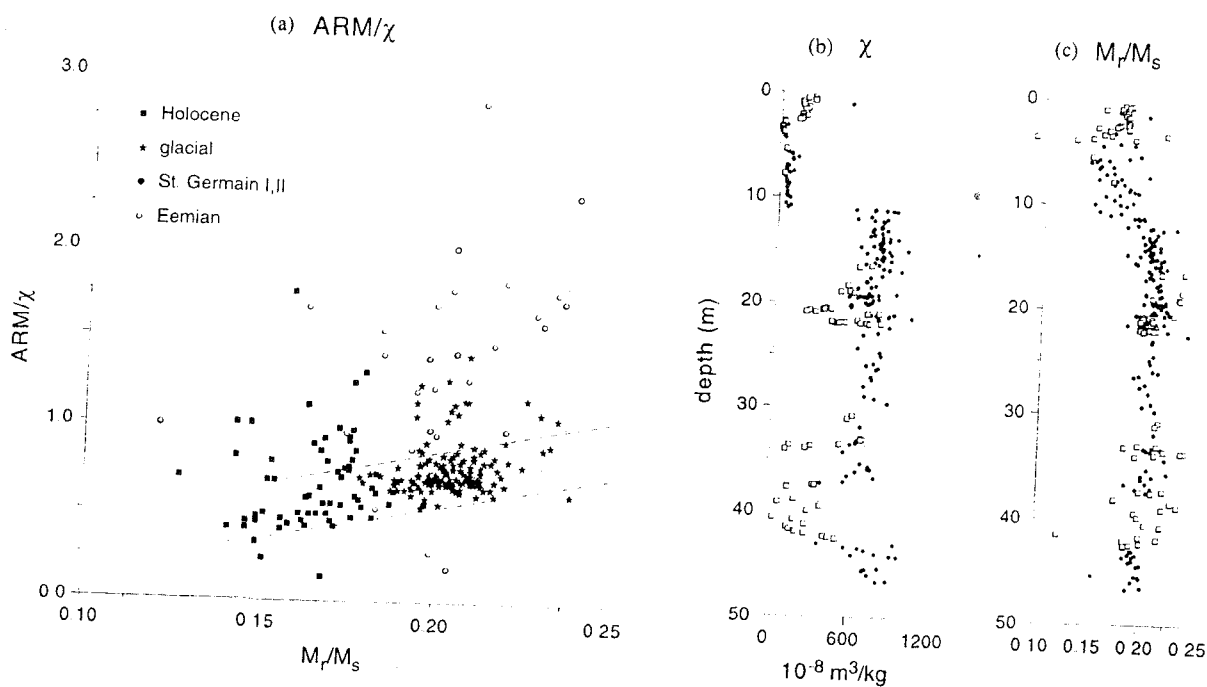


Figure 10. (a) ARM/χ versus M_r/M_s . A linear relation between ARM/χ and M_r/M_s exists for the data points between the dotted lines. These lines are arbitrarily drawn at $0.35 + 2.73 \times M_r/M_s$ and $0.52 + 2.73 \times M_r/M_s$. Same symbols as in Fig. 4. (b) χ versus depth and (c) M_r/M_s versus depth. In (b) and (c) closed circles (open squares) denote specimens for which ARM/χ versus M_r/M_s data points fall between (outside) the dotted lines of (a).

In the low-magnetic-concentration intervals, which correspond with the Eemian and interstadials St Germain I, II and Mid-glacial, hysteresis parameters and IRM/χ are similar to those of the glacial sediments, but ARM/χ is clearly higher. Below 35 m, H_{cr}/H_c is higher and most IRM/χ and M_r/M_s ratios slightly lower. These changes do not only occur in the low-magnetic-concentration intervals, but also in the high-magnetic-concentration interval of the Melisey I. Between 40.4 and 41.6 m depth of the Eemian interval, slightly lower IRM/χ and ARM/χ ratios, slightly higher susceptibilities and large variations in M_r/M_s and H_{cr}/H_c are observed.

Rock magnetic measurements show similar trends for the sediments deposited during the St Germain I, II and the Eemian (Figs 4–10 and 12). Therefore, the St Germain and Eemian sediments are considered as one magnetic group in the next sections of this paper. Apart from ARM/χ , which is higher in the lower-concentration intervals, the (small) variations in concentration-independent magnetic parameters within the glacial sediments do not show systematic trends with depth and lithology.

6 INTERPRETATION OF THE RESULTS

Magnetic susceptibility has been the main magnetic proxy used for palaeoclimatic reconstruction in maar lake sediments. This study shows similar trends in M_s , IRM and χ . Hence, all these parameters, including χ , can be used to estimate magnetic concentration. As the different climatic periods are much better reflected in concentration than in concentration-independent magnetic parameters (Fig. 12), it can be concluded that magnetic concentration is more suitable for palaeoclimatic reconstruction. On the other hand, interpreting the (smaller) differences in concentration-independent magnetic parameters leads to a better understanding of the magnetic concentration

signal (possible effects of alteration or dissolution) and can thus be used to interpret the magnetic concentration signal.

6.1 Magnetic mineralogy

Magnetic mineralogy was obtained from thermomagnetic runs and thermal demagnetization of IRM and ARM . For the glacial sediments, these indicate the presence of magnetite as a remanence carrier, but unblocking temperatures of 580 to 600 °C indicate that this magnetite is slightly oxidized (Nishitani & Kono 1983). The presence of a considerable amount of Ti, however, as suggested by the SEM images, is in contradiction with unblocking temperatures of 580 °C and higher. This suggests that an intergrowth of Ti-rich and Ti-poor lamellae exists in these sediments. Thermomagnetic runs of the St Germain sediments suggest the presence of thermally stable maghemite (Fig. 3c). These measurements suggest the presence of magnetite for the glacial, Eemian and Holocene sediments. The small intensity decay in thermomagnetic runs above 580 °C for the Eemian and Holocene sediments might be due to haematite, but the possibility of formation of haematite during heating cannot be excluded. In contrast to thermal demagnetization of the IRM , ARM thermal decay curves show that for the Eemian, St Germain and Holocene sediments 5–10 per cent of the initial ARM intensity unblocks at temperatures higher than 580 °C, indicating the presence of maghemite and possibly haematite. S -ratios are lower for these sediments, maybe due to the presence of haematite. Therefore, it was finally concluded that the remanence in the Eemian, St Germain and Holocene sediments is not only carried by magnetite, but also by maghemite and/or haematite. ARM is reported to be sensitive for magnetic grains 0.03–10 µm in size (Jackson 1991), and it appears to be sensitive for detecting the

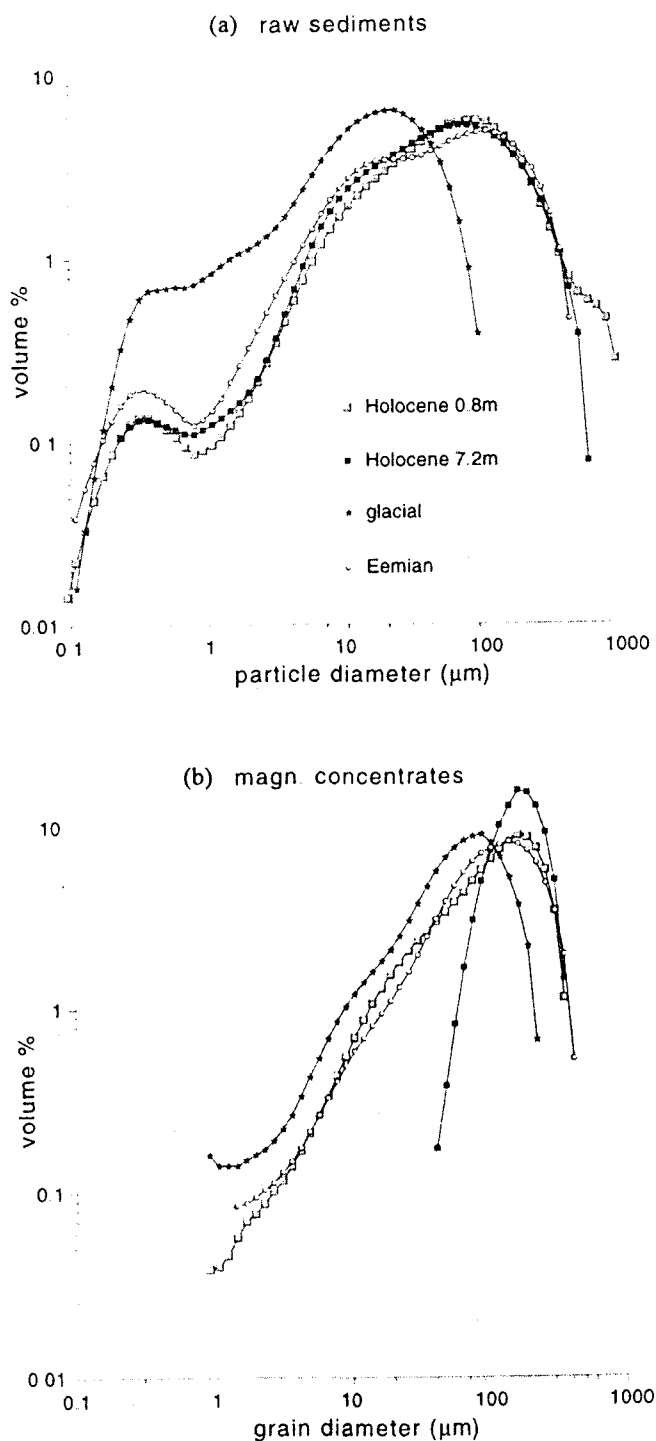


Figure 11. Granulometric experiments. Volume percentage versus particle diameter for (a) raw sediments and (b) magnetic concentrates. Same symbols as in Fig. 4.

presence of maghemite in the Lac St Front sediments. This suggests that the small grains are more oxidized to maghemite.

6.2 Grain-size variations: Eemian versus glacial

Frequency dependence of susceptibility, hysteresis parameters and ARM/χ and IRM/χ ratios are indicative of magnetic grain size. The first indicates the presence of SP grains, while the

other parameters increase with decreasing grain size above the SP-SD threshold ($0.03 \mu\text{m}$)

The Eemian and St Germain sediments are characterized by an enhancement in ARM intensities and coercivities, while hysteresis parameters and IRM/χ and MDF_{arm} hardly differ from the glacial sediments. Because differences of a factor 1.5–3 in ARM/χ (as observed between the Eemian and the glacial sediments) correspond with grain-size variations of the order of 10–15 μm (e.g. Hartstra 1983; Maher 1991) and such large variations should be reflected in hysteresis parameters, this different ARM behaviour cannot be related to grain-size variations in the PSD-MD range. In contrast to glacial sediments, thermal decay curves show that ARM is not only carried by magnetite, but also by maghemite and possibly haematite in the Eemian sediments. Although these minerals might influence the different ARM behaviour at these intervals, it might also be caused by: (1) grain interactions, and (2) the presence of fine grains just above the SP-SD limit.

Previous theoretical (Jaep 1971) and experimental (Sugiura 1979) studies showed that grain interactions, which depend on magnetic moment and concentration, result in lower ARM intensities and coercivities. Therefore, Tauxe (1993) proposed not to accept more than a factor of 10 variation in magnetic concentration to limit the interaction effect on ARM intensities. In the Lac St Front sequence, magnetic concentration is high within the glacial sediments and varies up to a factor of 1000 between all sediment types. As grain interactions predict higher ARM/χ and MDF_{arm} values for lower concentrations, their occurrence is suggested by the clearly increasing ARM/χ with decreasing χ for the glacial and most Holocene sediments. Interactions depend on the distance between the magnetic particles. Hence, the better relationship between ARM/K and volume-normalized susceptibilities K than between ARM/χ and mass-normalized susceptibilities χ reinforces this suggestion.

However, several factors do not favour explaining the changes in ARM by grain-size interactions. These are as follows: (1) ARM acquisition curves are similar to those of ARM AF demagnetization; (2) in spite of the increasing ARM/χ with decreasing χ , ARM/χ is generally lower for the Holocene than for the glacial sediments, probably due to a larger grain size (Section 6.3); (3) ARM/χ varies considerably within these St Germain and Eemian sediments and the variations within these low-susceptibility intervals do not show a linear relationship with χ (K); (4) according to the experimental data of Sugiura (1979), the difference between the highest ARM/χ and MDF_{arm} values of the Eemian sediments and those of the glacial sediments is too large to be explained by grain interactions. For these reasons, it was concluded that although interactions might well occur, they cannot on their own explain the different ARM behaviour for these rocks.

The increase in ARM/χ and MDF_{arm} and the absence of a clear change in IRM and hysteresis parameters (Fig. 10) might be caused by a varying amount of fine grains just above the SP-SD limit. This is because ARM is especially sensitive for these grains. However, in this case an increase in SP grains would also be expected. The presence of the latter can be detected by an increase in the frequency dependence of susceptibility. However, this parameter is similar for the glacial and the Eemian and St Germain specimens. This does not favour, but does not formally exclude, the option that the increase in ARM/χ and MDF_{arm} is due to the presence of small grains.

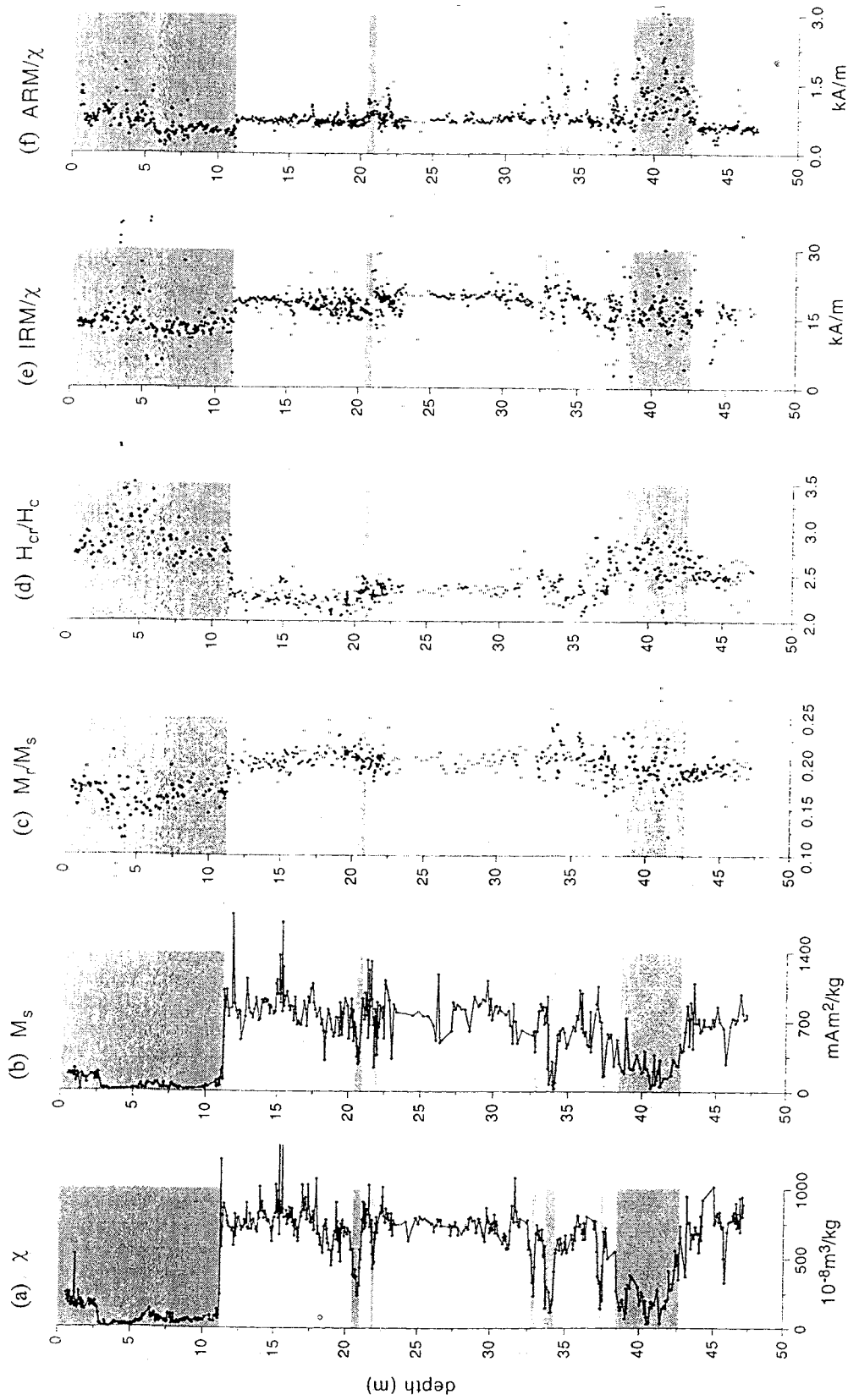


Figure 12. Down-core measurements. (a) χ , (b) M_s , (c) M_r/M_s , (d) H_{cr}/H_c , (e) IRM/χ and (f) ARM/χ versus depth. Shaded (dark shaded) areas around 21, 33, 37.5 and 40 m depth (<11.7 m depth) denote the intervals corresponding to the Eemian, St Germain II and I and the temperate climatic periods of the Mid-glacial (Holocene).

Neither interactions nor grain-size variations explain all observations in ARM behaviour, but the enhancement in ARM/χ and MDF_{arm} in the low-susceptibility intervals of the St Germain I and II and the Eemian might well be affected by a combination of these mechanisms. Taking into account that a compositional difference between the glacial and Eemian and St Germain sediments also exists (for which ARM is particularly sensitive), it is not straightforward to relate changes in ARM/χ to grain-size variations.

Slightly lower IRM/χ , H_{cr} and H_c values may indicate a larger grain size for the Eemian and St Germain sediments. This trend is, however, in contradiction with the higher MDF_{irm} values and with similar M_r/M_s ratios for glacial and Eemian sediments. The Day plot (M_r/M_s versus H_{cr}/H_c) should be interpreted with caution. The enhancement in H_{cr}/H_c suggests an apparent trend towards the MD range, but might be due to (1) the presence of superparamagnetic grains or (2) a mixture of coercivities. The latter might be indicated by slightly lower S -ratios. Furthermore, (1) taking into account the large variations in these parameters within the Eemian and St Germain I and II and (2) the compositional difference between the glacial and Eemian–St Germain sediments, it can be concluded that IRM and hysteresis parameters (and also ARM) do not clearly indicate a systematic grain-size difference for the Eemian–St Germain and glacial sediments. However, the larger variations in ARM, IRM and hysteresis parameters suggest that grain-size (and compositional) variations are larger within the Eemian–St Germain layers than within the glacial sediments.

6.3 Grain-size variations: glacial versus Holocene sediments

Although down-core logs show a magnetic variability within the Holocene, some general characteristics of the magnetic properties of these sediments can be given. Compared to glacial sediments, M_r/M_s and H_{cr}/H_c clearly indicate a trend towards the MD range, suggesting an on average larger grain size. IRM/χ , corrected for χ_{hf} , is generally lower for the Holocene sediments and also suggests a larger grain size. This trend is further confirmed by a lower frequency dependence of susceptibility and the granulometric experiments on the magnetic concentrate from the 7–7.5 m depth sediments. Correcting ARM/χ for χ_{hf} , however, shows that the corrected ARM/χ values of the Holocene sediments cannot be distinguished from the glacial sediments. However, taking into account the effect of grain interactions (Section 6.2), higher ARM/χ and MDF_{arm} values would be expected in the Holocene in the case of identical magnetic grain sizes for the Holocene and glacial sediments. Hence, similar ARM/χ and lower MDF_{arm} values, together with intensities up to a factor of 1000 lower in the Holocene, might suggest a larger grain size for these sediments. Therefore, it can be concluded that all these parameters indicate a larger magnetic grain size for the Holocene than for the glacial sediments.

In the uppermost part of the Holocene, higher magnetic concentrations are measured. This higher concentration interval has a different length in core A than in core B and is the only part of the sequence at which susceptibility profiles of the parallel cores do not match. The absence of a relationship between ARM/χ and M_r/M_s and the higher frequency dependence of susceptibility indicate different rock magnetic proper-

ties for this interval. In lake sediments, higher mineral magnetic concentrations near the sediment–water interface are often ascribed to either increased erosion of minerogenic material (Dearing *et al.* 1990) or to the input of pollutants or aerosols (Oldfield 1991), both related to anthropogenic activity in the catchment area. However, in lakes relatively unaffected by human activity these higher magnetic concentrations might also be caused by bacterial magnetite formation (Snowball 1994). As a considerable part of the Lac St Front catchment area is nowadays used as farmland, the effect of anthropogenic activity cannot be excluded. A ^{14}C dating point at 3.35 m depth, just below these ‘higher’ magnetic concentrations, reveals an age of 1440 ± 120 yr BP. This age is younger than the first period of substantial deforestation in the Massif Central, which took place during the Roman period (de Beaulieu, Pons & Reille 1988), but is older than the second period of systematic deforestation, which took place during the Middle Ages. Hence, these historical ages do not indicate that different magnetic properties in the uppermost part of the Holocene are directly related to anthropogenic activity.

7 ENVIRONMENTAL SIGNAL

7.1 Holocene versus Eemian

This study reveals a larger magnetic grain size for the Holocene than for the glacial sediments. This larger grain size is not observed for the Eemian and St Germain sediments. Taking into account that the trends in magnetic composition (maghemite, haematite) and concentration are similar for the Eemian and Holocene sediments, this contradiction in grain size is intriguing. Furthermore, for interpretation of the susceptibility records of the Eemian and the Holocene sediments in terms of climatic changes, it is especially important to solve this question. For two reasons it is unlikely that this contradiction is directly related to a climatic signal. First, temperature variations, reconstructed from pollen assemblages of the nearby Lac du Bouchet (Guiot 1990), suggest a similar annual temperature during the Eemian and Holocene. Second, similar magnetic properties are observed for sediments deposited during the temperate climatic periods of the St Germain I and II and the Eemian.

Due to a shorter erosion time, the crater wall was steeper and higher during the Eemian than during the Holocene and the sediments were deposited with a higher energy. This results in a larger grain size for the Eemian sediments, which is in contrast with the observed trend. Therefore, another mechanism must have occurred.

Nowadays, a small outlet is situated at the southwestern shore of the lake. Due to a higher crater wall, it is likely that this outlet did not exist during the Eemian and glacial periods. Due to this outlet part of the fine particles might have been directly carried off during the Holocene, while all fine particles were deposited in the lake during older periods. In this case both magnetic and non-magnetic grain size should be larger for the Holocene sediments. This is, however, in contrast with the results of the granulometric experiments, which show the presence of a small-particle-size mode for both the Holocene and the Eemian bulk sediments. Furthermore, these measurements indicate a similar non-magnetic particle-size distribution for the Holocene sediments from the upper 2.5 m and between 7 and 7.5 m depth, but an on average larger magnetic grain

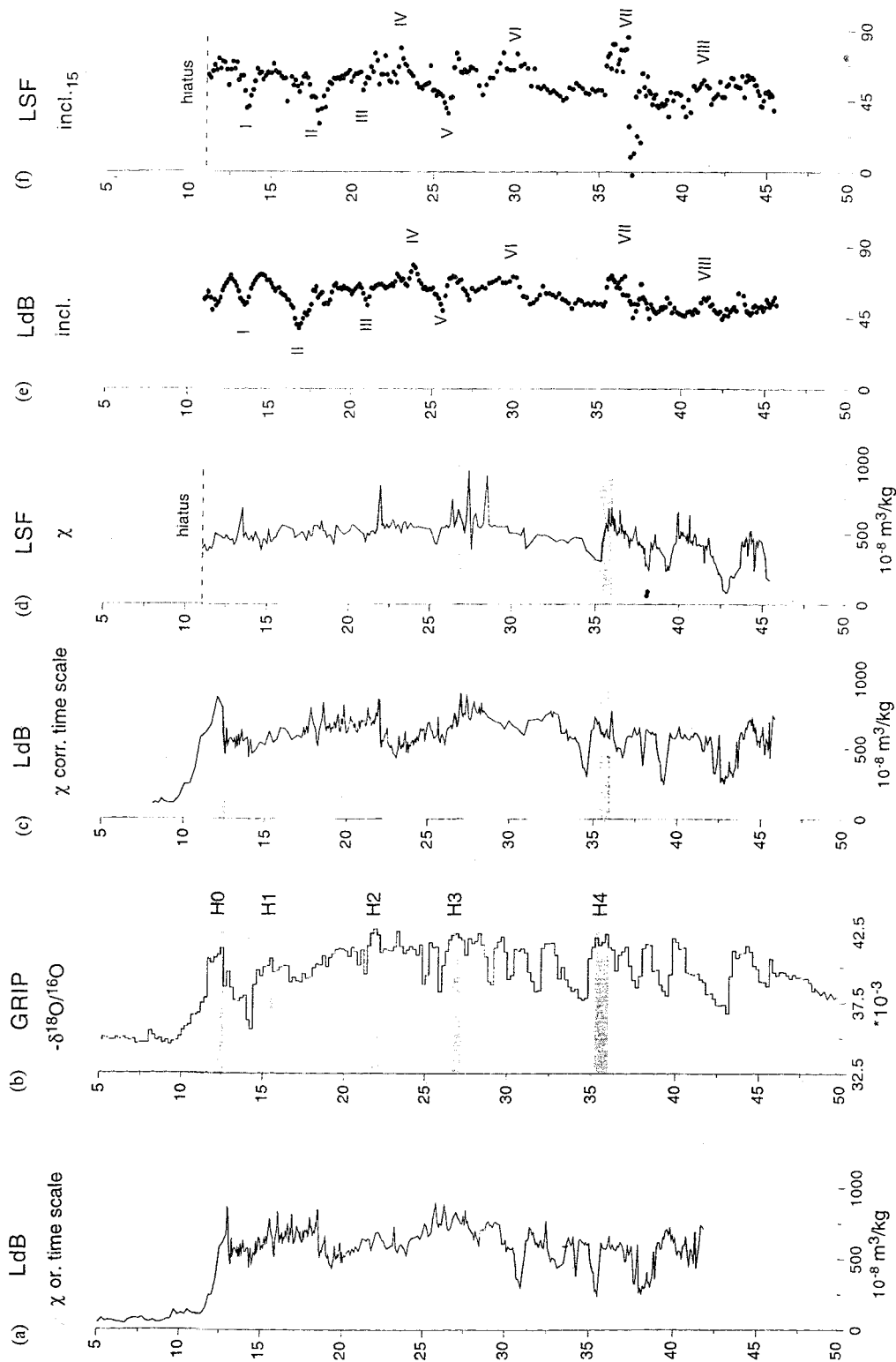


Figure 13. (a) The susceptibility record of Lac du Bouchet on its original timescale (10–45 kyr). (b) $\delta^{18}\text{O}/^{16}\text{O}$ record of the GRIP ice cores. Susceptibility and inclination records (Thouveny *et al.* 1993) of (c) and (e) Lac du Bouchet and (d) and (f) Lac St. Front on the revised timescale of Lac du Bouchet (after Thouveny *et al.* 1994). Shaded areas labelled H0, ..., H4 denote the Heinrich events as identified in the GRIP ice cores. Roman numerals denote correlation points between the inclination records of Lac du Bouchet and Lac St. Front. The excursion in Lac St. Front (correlation point VII) is smoothed out in Lac du Bouchet (Thouveny *et al.* 1994).

size for the latter. This may suggest that the larger magnetic grain size for the Holocene sediments is specific for the magnetic minerals.

Another mechanism which might have occurred is dissolution. In anoxic, organic-rich, freshwater sediment, iron oxides are dissolved by bacterial reduction. As fine iron-oxide grains are likely to be the first to be resolved, dissolution might be indicated by an increasing magnetic grain size. Assuming that dissolution was less effective (or did not occur) in the Eemian, it may explain the larger magnetic grain size for the Holocene sediments. Products of sulphide reduction, such as pyrite, mackinawite and greigite (e.g. Karlin & Levi 1983; Canfield & Berner 1987; Roberts & Turner 1993) are not observed. In rapidly deposited organic-rich sediments, manganese oxides are precipitated and biogenetic magnetites can be formed above the iron reduction zone (Karlin, Lyle & Heath 1987; Petermann & Bleil 1993). Below the iron reduction zone, these and also small detrital magnetite grains are dissolved. If this process occurred in Lac St Front, the higher magnetic concentrations in the uppermost 2.5 m of the Holocene sediments do not result from anthropogenic activity and bacterial magnetite should be present in this interval. As no rock-magnetic indication for bacterial magnetite exists, the latter hypothesis cannot be confirmed. Nevertheless, in spite of the fact that no positive identification of dissolution exists, it seems to us the most probable mechanism to explain the larger grain size of the Holocene sediments.

7.2 Environmental signal during the last glacial period

The rock magnetic analysis showed that variations in concentration-independent magnetic parameters within the glacial sediments are limited. Changes in ARM χ correlate with susceptibility changes and might be the result of grain interactions. This implies that changes in magnetic grain size and composition are extremely limited and that dilution is the dominant factor in the magnetic concentration variations within the glacial sediments. By slightly modifying the Lac du Bouchet depth-time transformation, Thouveny *et al.* (1994) showed that the major susceptibility minima in Lac du Bouchet correlate with major $\delta^{18}\text{O}$ maxima in the GRIP ice cores (Fig. 13) (Dansgaard *et al.* 1993). These authors also suggested that the susceptibility maxima in the glacial sediments of Lac du Bouchet may correlate with $\delta^{18}\text{O}$ minima of the ice cores. According to Thouveny *et al.* (1994), this indicates that these susceptibility maxima in Lac du Bouchet may reflect Heinrich events, short colder climatic periods within the glacials which are attributed to a discharge of large icebergs from the ice sheets (Heinrich 1988; Bond *et al.* 1993). If this hypothesis is true, susceptibility maxima in the glacial sediments of Lac St Front should also correlate with $\delta^{18}\text{O}$ minima of the GRIP ice cores.

After comparison of the Lac St Front palaeomagnetic and susceptibility records with those of Lac du Bouchet (Dansgaard *et al.* 1993), a more detailed chronology of the 11–22 m depth interval in Lac St Front sequence could be established. Transformation of the Lac St Front susceptibility and inclination records on the modified Lac du Bouchet timescale shows that inclination records correlate better between 12 and 30 kyr (11.5–16 m Lac St Front depth) (Fig. 13). This observation shows that local effects from the catchment area also influence the susceptibility records and that a combination of

susceptibility and palaeomagnetic records is required to establish a more detailed chronology. Between 30 and 45 kyr, representing the Mid-glacial, susceptibilities correlate better. As the validity of the susceptibility correlation between Lac du Bouchet and Lac St Front is verified by the inclination records, it can be shown that the susceptibility maxima at 14, 15.6 and 16.8 m depth (22, 27.5 and 35.5 kyr) reflect regional environmental episodes of eastern central France and not a local signal from the catchment area. According to the modified Lac du Bouchet timescale (Thouveny *et al.* 1994), these susceptibility maxima correlate with those $\delta^{18}\text{O}$ minima in the GRIP ice core that are associated with the Heinrich events H2, H3 and H4. If this is true, H3 is best reflected in Lac St Front. In contrast to the susceptibility maxima, which may correspond to H4 and H2, this susceptibility peak is recorded in a more silty layer (Fig. 2). Higher H_{cr}/H_c and lower IRM/χ ratios indicate a slightly different magnetic behaviour at this interval (Fig. 13). As in Lac du Bouchet, the Heinrich event H1 is not well expressed in Lac St Front. The absence of the Heinrich event H0 is explained by the hiatus at the Full-Glacial–Holocene limit.

8 CONCLUSIONS

A detailed rock magnetic approach reveals that magnetites are the magnetic carriers in the sediments of Lac St Front. ARM, however, shows the presence of maghemite and haematite in the sediments deposited under more temperate climatic periods. Environmental changes are much better reflected in magnetic concentration than in parameters independent of magnetic concentration. Due to the large variations in magnetic concentration ARM might be affected by grain interactions. All other parameters indicate a larger magnetic grain size for the Holocene than for the glacial sediments. This trend is not observed for the sediments deposited during the Eemian and the interstadials St Germain I and II. The most likely explanation for this discrepancy is the occurrence of dissolution in the Holocene sediments. For the glacial sediments, variations in concentration-independent magnetic parameters are limited. Three susceptibility peaks in the glacial sediments of stage 2, which are also found in the nearby Lac du Bouchet, may correspond with Heinrich events.

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