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Glacial–interglacial climatic variations at the Schirmacher Oasis, East Antarctica: The first report from environmental magnetism

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ABSTRACT

We discuss in this paper the first detailed environmental magnetic record of glacial–interglacial climatic variations in the Schirmacher Oasis, East Antarctica. We determined environmental magnetic properties and inter-parametric ratios (χ_{lf}, χ_{fd} %, χ_{ARM}, SIRM, χ_{ARM}/SIRM, χ_{ARM}/χ_{lf}, χ_{ARM}/χ_{fd}, SIRM/χ_{lf}, S-ratio and HIRM) for sediment samples of a core from the Sandy Lake. Accelerator mass spectrometer (AMS) ^{14}C dates were obtained on the organic matter from bulk sediment samples. The sediment core spans the past ~42.5 cal. ka B.P. The magnetic minerals are mainly detrital and catchment-derived, as there is no evidence for the presence of authigenic greigite, bacterial magnetite or diagenetic dissolution. The last glacial period is characterized by a high concentration of ferrimagnetic minerals such as titanomagnetite (high values of χ_{lf}, SIRM etc.) and coarse magnetic grain size (low χ_{ARM}/SIRM and χ_{ARM}/χ_{lf} values and high S-ratio values). Deglaciation in the Schirmacher Oasis began around 21 cal. ka B.P. as suggested by the low magnetic mineral concentration. The Holocene period is characterized by relatively warm climatic events as seen in the low values of magnetic susceptibility which is primarily contributed by fine-grained titanomagnetite resulting from pedogenesis (high χ_{fd} % values). Several of the relatively warm and cold events that we deciphered from the environmental magnetic data are correlatable with lake sediments from the Schirmacher Oasis and other ice-free areas in East Antarctica and from ice-core records on the Antarctic Plateau.

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1. Introduction

Paleoarchives such as marine and lake sediments, ice-cores, tree-rings, corals and speleothems have been successfully used to determine past variations in climate on different time-scales. These archives are abundant in tropical and temperate regions. However, polar regions, especially Antarctica, offer ice cores and marine sediments apart from lake sediments for paleoclimatic reconstruction. Lacustrine sediments are most widely used for paleoclimatic reconstruction as they are ideal repositories of air-borne and especially stream-borne materials (Peck et al., 2004; Foster et al., 2008; Mügler et al., 2010; Warrier et al., 2014a). They bear a strong signal of catchment soils via the inputs of minerogenic and chemical weathering products. They are more sensitive than ocean sediments to climatic and environmental changes because of their smaller size and higher sedimentation rates. Lake sediment records, therefore, allow a finer temporal resolution and a direct comparison with known historical and instrumental climatic records of the surrounding area.

Environmental magnetism (also known as rock magnetism or mineral magnetism) concerns the application of rock magnetic methods to environmental studies. The technique has been successfully used to identify the link between environmental processes and the magnetic minerals present in rocks, soils, sediments etc. Magnetic minerals such as magnetite, maghemite, hematite, goethite and greigite occur as accessory minerals in natural samples and are useful proxies for determining changes in past climate. Being omnipresent in the environment, the aforementioned minerals are produced, transported, and deposited in lacustrine or marine systems. It is well established that the magnetic mineral content of sediments provides a sensitive medium for recording environmental change (Evans and Heller, 2003). For a given climatic regime, magnetic minerals are characterized by a particular concentration, grain size and mineralogy. Any change in climate would then modify one or more of the above-mentioned attributes of magnetic minerals. Lake sediments record this change through temporal and spatial variations in the mineralogy, concentration and grain size of magnetic carriers. Due to the easy, rapid, non-destructive and sensitive

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nature of the measurements, environmental magnetism has found varied applications (Shankar et al., 2006; Sandeep et al., 2010, 2012; Tudryn et al., 2010; Warrier et al., 2011, 2014b). However, in Antarctica only a few detailed studies on paleoenvironmental reconstruction using environmental magnetism are reported (Sagnotti et al., 2001; Bloemendal et al., 2003; Phartiyal et al., 2011; Brachfeld et al., 2013, 2002; Phartiyal, in press).

The continent of Antarctica is bestowed with several ice-free areas such as the Schirmacher Oasis, the Larsemann Hills, the Amery Oasis, the Bunger Hills, the Windmill Islands and the Vestfold Hills. The ice-free areas have plenty of fresh-water lakes that are potential archives of past climatic variations. Although lake sediments in most ice-free regions are well studied (see Verleyen et al., 2011 and Hall, 2009 for review), Schirmacher Oasis is one region from which a limited number of paleoclimate records have been reported (Bera, 2004; Sharma et al., 2007; Phartiyal et al., 2011; Phartiyal, in press). In this study, we have attempted to reconstruct the paleoenvironmental/paleoclimatic changes in the Schirmacher Oasis (hereafter referred to as SO) based on the environmental magnetic properties of a sediment core from the Sandy Lake.

2. Study area

Situated in the Queen Maud Land (East Antarctica), the Schirmacher Oasis is a 35 km^2 ice-free area and lies between the margins of the continental ice sheet and the ice-shelf (Fig. 1). It consists of several hills of low elevation (~200 m; Srivastava and Khare, 2009) and about 120 lakes which may be classified as epishelf, proglacial and landlocked, depending on their geomorphic evolution (Ravindra, 2001). Sandy Lake (70°45′45.9″S; 11°47′34.7″E) is one of the small, land-locked lakes (Fig. 1c) situated ~2.5 km from the Indian Research Station — *Maitri*. It is a shallow, fresh water lake with a water depth of 1–2 m. It receives water from a few streams in the catchment. The Lake is covered with ice for almost 7–8 months in a year but ice-free for the remaining period. The thickness of the ice cover is 0.5 to 1 m. There is very little vegetation in the catchment in the form of mosses etc. The Lake is surrounded by *roche moutonnées* (erosional forms created by the passage of a glacier on an underlying rock; Benn and Evans, 1998). The terrain is predominantly gneissic with the felsic variety (belonging to the Precambrian age; Sengupta, 1986) constituting >85% of the exposed bed-rocks (Rao, 2000). Other rock types found are alaskite, garnet-biotite gneiss, pyroxene granulites, enderbites, calc-granulites, khondalites, migmatites and streaky gneiss, intruded by basalt, lamprophyre, pegmatite, dolerite and ophiolite rock types (Sengupta, 1986; Bose and Sengupta, 2003). The general weather conditions in the Schirmacher Oasis are harsh with dry and extremely low temperatures and strong winds. The summer season is from November to February when the maximum temperature varies from 0.4 to −2.6 °C and the minimum temperature from −2.7 to −8.8 °C. During winter (March to October), the maximum temperature dips to between −4.5 and −12.9 °C and the minimum temperature plummets to −10.4 to −20.9 °C (Lal, 2006). July and August are the coldest months whereas December and January record the warmest temperatures. The annual average wind speed is 17.5 knots; winds blow mainly from the southeast (Lal, 2006). Precipitation is scanty and is mainly received in the form of snowfall. It is more frequent between April and September.

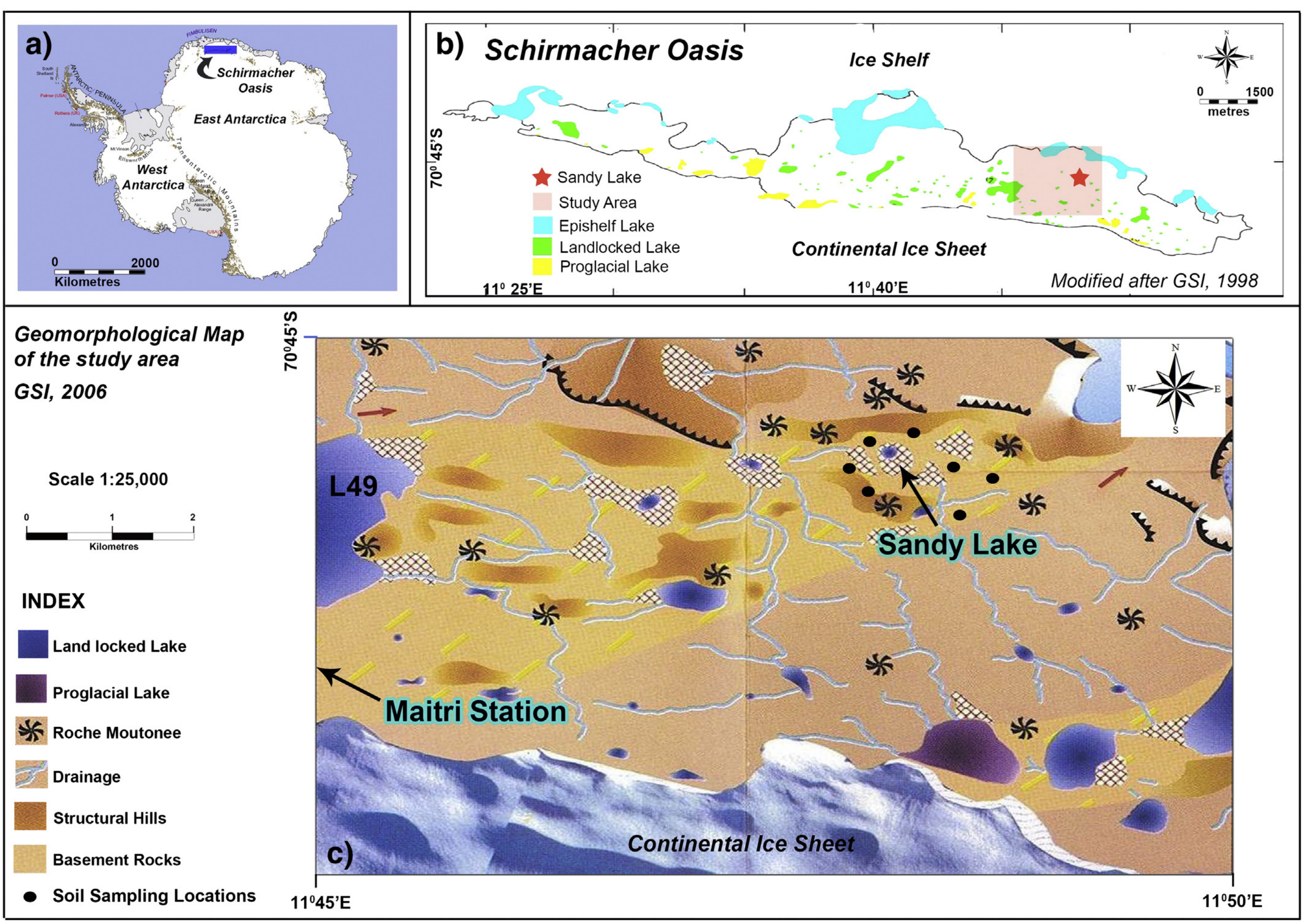

Fig. 1. (a) Map of Antarctica showing the location of Schirmacher Oasis; (b) Map of Schirmacher Oasis (modified after Ravindra, 2001) showing the location of Sandy Lake (indicated by a "*"); (c) Geomorphological map of the area around Sandy Lake (modified after Geological Survey of India, 2006); Locations of soil samples are also shown.

3. Materials and methods

3.1. Sampling

During the 28th Indian Scientific Expedition to Antarctica, a 68-cm long sediment core was retrieved from the periphery of the lake when it was ice-free. The core was retrieved by manually hammering an acrylic pipe into the lake-bed. After raising the core, it was labelled, packed and stored in a deep-freeze at <4 °C. The core was transported to the laboratory and sub-sampled at 1 cm interval to obtain high-resolution paleoenvironmental data. The sub-samples were packed in labelled polythene covers, stored in a deep-freeze and used for laboratory studies. Surface soil samples were also collected from seven locations (Fig. 1c) in the catchment during the 32nd Indian Scientific Expedition to Antarctica. The soil samples were collected with the help of a plastic spatula after scraping the top-layer to remove gravelly materials. The samples were neatly packed and brought to the laboratory. Detailed environmental magnetic measurements were carried out on these seven samples.

3.2. Geochronology

Carbon-14 dating by accelerator mass spectrometry (AMS) was carried out at the AMS Dating Facility, University of Arizona, USA, on the organic matter of bulk sediment samples from different depths in the sediment core. The radiocarbon dates were calibrated to calendar years (B.P.) by using the CALIB 6.0 (Stuiver and Reimer, 1993) software. Two calibration curves, i.e., SHCal04.14C (for ages up to 11,000 cal. years B.P.; McCormac et al., 2004) and IntCal09.14C (for ages beyond 11,000 cal. years B.P.; Reimer et al., 2009) were used for calibration. As there are no reservoir corrections available for the region, no such corrections were applied. The details of the ^{14}C dates are provided in Table 1. Based on the dates obtained, an age-depth model (Fig. 2) was constructed and the age for each sample depth was calculated using the linear interpolation model. The sedimentation rates were calculated from the age-depth model.

3.3. Environmental magnetism

Standard rock magnetic methods (Thompson and Oldfield, 1986; Oldfield, 1991; Walden et al., 1999) were used to study the magnetic properties of sediment and soil samples.

Magnetic susceptibility was measured at low- (0.47 kHz; χ_{lf}) and high- (4.7 kHz; χ_{hf}) frequencies on a Bartington Susceptibility Meter (Model MS2B) with a dual-frequency sensor. The sensor was calibrated by using the Fe_3O_4 (1%) standard supplied by the instrument manufacturer. Percentage frequency-dependent susceptibility (χ_{fd} %) was calculated by using the formula, $\chi_{fd}\,\% = ((\chi_{lf} - \chi_{hf}) / \chi_{lf}) \times 100$ (Dearing, 1999a). Anhysteretic remanent magnetisation (ARM) was induced in the samples using a Molspin AF demagnetiser (with an ARM attachment) set with a peak alternating field of 100 mT (millitesla) and a DC biasing field of 0.04 mT. The ARM induced was measured on a Molspin spinner fluxgate magnetometer. The susceptibility of ARM (χ_{ARM}) was calculated by dividing the mass-specific ARM by the size of the biasing field (0.04 mT = 31.84 Am^{-1}; Walden, 1999). Isothermal remanent magnetisation (IRM) was induced in the samples at increasing field strengths (20, 60, 100, 300, 500 and 1000 mT) using a Molspin pulse magnetiser. The isothermal remanence induced at 1 Tesla field (the maximum field attainable in the Environmental Magnetism Laboratory at Mangalore University) was considered as the saturation isothermal remanent magnetisation (SIRM). The remanence acquired was measured using the Molspin spinner fluxgate magnetometer. The sediment and soil samples were oven-dried at 35 °C and the dry sample weight was used to calculate the magnetic parameter values on a mass-specific basis. To determine the magnetic grain size and mineralogy of magnetic minerals, inter-parametric ratios like χ_{ARM}/SIRM, χ_{ARM}/χ_{lf}, χ_{ARM}/χ_{fd}, SIRM/χ_{lf}, IRM_{20mT}/ARM and S-ratio, and HIRM were calculated (Maher et al., 1999; Walden, 1999; Evans and Heller, 2003). The magnetic measurements, their units and interpretation are given in Table 2 (after Thompson and Oldfield, 1986; Oldfield, 1991).

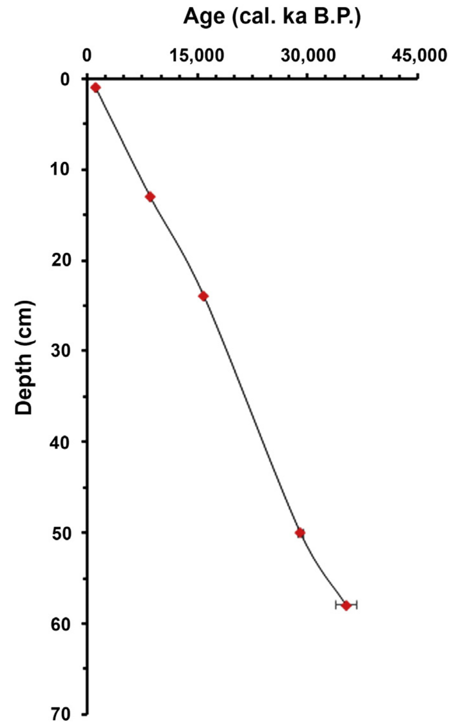

Fig. 2. Age-depth model for the Sandy Lake sediment core. *Note:* The radiocarbon dates were calibrated using the CALIB 6.0 software (Stuiver and Reimer, 1993); two calibration curves (SHCal04.14C, McCormac et al., 2004 and IntCal09.14C, Reimer et al., 2009) were used. Error bars for the ages are also marked.

Table 1
Radiocarbon dates for sediment samples from Sandy Lake core.

Sample ID	Depth (cm)	Lab code	Material	AMS ^{14}C yr BP	$\delta^{13}C$ (‰)	2-sigma range	Mid-calibrated age (cal. ka BP)	Relative area under probability distribution
Sl-1	0–2	AA97380	Bulk sediment	1245 ± 35	−12.8	1049–1183	1116	0.855
SL-A	12–13	AA99557	Bulk sediment	7847 ± 36	−16.6	8447–8644	8546	1.00
SL-B	23–24	AA99558	Bulk sediment	13,144 ± 58	−18.4	15,270–16,519	15895	1.00
SL-C	35–36*	AA99559	Bulk sediment	23,700 ± 150	−19.7	27,970–28,939	28455	1.00
SL-2	40–42*	AA97381	Bulk sediment	24,150 ± 200	−18.5	28,475–29,442	28959	1.00
SL-D	49–50	AA99560	Bulk sediment	24,260 ± 350	−19.1	28,220–29,830	29025	1.00
SL-E	57–58	AA99561	Bulk sediment	30,800 ± 1500	−19.5	31,934–38,664	35299	1.00
SL-3	64–66*	AA97382	Bulk sediment	22,580 ± 280	−20.0			

NOTE: The dates were calibrated with the help of Calib 6.0 software (Stuiver and Reimer, 1993) using the SHCal04.14C (McCormac et al., 2004) and IntCal09.14C (Reimer et al., 2009) calibration curves. The dates marked with a * were not used in the age-depth model.

Table 2
Details of rock magnetic parameters and inter-parametric ratios, their units and interpretation (after Thompson and Oldfield, 1986; Oldfield, 1991; Walden et al., 1999).

Parameter	Units	Interpretation
χ_{lf}	10^{-8} m^3 kg^{-1}	Concentration of magnetic minerals
χ_{fd}	%	Proportion of superparamagnetic (SP) grains
χ_{ARM}	10^{-5} m^3 kg^{-1}	Concentration of SSD grains (~0.02–0.04 um)
SIRM	10^{-5} Am^2 kg^{-1}	Concentration of all remanence-carrying magnetic minerals
χ_{ARM}/SIRM	10^{-5} mA^{-1}	Magnetic grain size indicator; higher (lower) values suggest a finer (coarser) magnetic grain size; Values greater than 200 × 10^{-5} mA^{-1} are an indicator of bacterial magnetite
χ_{ARM}/χ_{lf}	10^3	Magnetic grain size indicator; higher (lower) values suggest a finer (coarser) magnetic grain size; Values greater than 40 suggest the influence of bacterial magnetite
χ_{ARM}/χ_{fd}	10^3	Indicator of magnetic concentration (SSD and SP grains) and magnetic grain size; higher (lower) values suggest a finer (coarser) magnetic grain size; Values greater than 1000 indicate bacterial magnetite
SIRM/χ_{lf}	10^3 Am^{-1}	Magnetic grain size indicator; higher (lower) values suggest a coarser (finer) magnetic grain size; Values grater than 30 or 40 × 10^3 Am^{-1} indicate the presence of authigenic greigite
S-ratio (IRM$_{300mT}$/SIRM)	Dimensionless	Indicates the relative proportions of ferromagnetic and canted antiferromagnetic minerals; values close to 1 indicate a higher proportion of magnetite and values close to 0 a higher proportion of hematite
HIRM (SIRM–IRM$_{300mT}$)	10^{-5} Am^2 kg^{-1}	Concentration of canted antiferromagnetic minerals

3.4. SEM-EDS analysis

Magnetic minerals were extracted from a few samples from the sediment core. For this, the sample was dispersed and suspended in 500 ml deionized water using a magnetic stirrer. A small rare-earth magnet sealed in a zip-lock polythene cover was suspended in the beaker. The magnetic minerals that stuck to the polythene cover were collected in a small beaker and dried before SEM-EDS studies (Hounslow and Maher, 1999). The magnetic extracts was sputter-coated with platinum (~2 nm thickness) and examined at 150× using a JEOL-JSM-6360 LV SEM operated at 15–20 keV. Elemental analysis of the magnetic extract was performed using an OXFORD INCA 200 Energy Dispersive Spectrometer (EDS).

4. Results and discussion

4.1. Geochronology

The calibrated age range at 95% confidence interval (2-σ) and the calibrated mid-age along with the relative area under probability distribution are provided in Table 2. The age-depth model (Fig. 2) shows that the Sandy Lake sediment core spans the past ~42,360 cal. years B.P. The youngest age is 1116 cal. years B.P. (0–2 cm depth; Table 1); the oldest age of 42,357 cal. years B.P. was obtained by extrapolation. The sediment layer corresponding to zero age is absent in the sediment core, probably because of its loss during core recovery or compaction of sediments due to hammering. Carbon-14 dates with a * symbol in Fig. 3 were excluded from the age-depth model as they have unrealistic ages. Initially, we included these two dates in the age-depth model but the sample resolution for this section of the core came down to 7 years/cm (i.e., 1 cm thick sediment sample gave a time span of 7 years) when compared with the 600 years/cm for the other part of the core. Hence, we decided to omit these two dates and termed it as unrealistic. Based on the dates obtained, sedimentation rates were calculated for the different sample intervals and ages assigned to them. The mean sedimentation rate is 0.015 mm/year with a minimum of 0.013 mm/year during MIS 3 and a maximum of 0.019 mm/year during MIS 2. Similar rates of sedimentation have known to occur in the lakes of Schirmacher Oasis. For example, Phartiyal et al. (2011) reported sedimentation rates of 0.069 mm/year, 0.132 mm/year and 0.019 mm/year for three sediment profiles from the Schirmacher Oasis. Bera (2004) also documented a sedimentation rate of 0.124 mm/year for sediments from L-49 Lake, Schirmacher Oasis. According to Shen et al. (1998), a sedimentation rate of 0.004–1.1 mm/year is generally documented for lacustrine sediments of Antarctica.

4.2. Sediment lithology

The lithology of the Sandy Lake sediment core is shown in Fig. 3. The sediment is greyish black and no profound changes in lithology were found. The sediments are devoid of fossils and predominantly made up of clastic particles. On visual examination, the core appears to consist mainly of sand (0–8 cm, 13–23), silty sand (8–10 and 26–30 cm) and silty clay (30–46 and 50–68 cm). These layers are interspersed with clayey silt, silty clay and sandy silt with rock debris (Fig. 3). Magnetic susceptibility (χ_{lf}) values show significant variations with the changing lithology in the sediment core. The values are high in the silty clay unit but decrease when rock pieces are present in such sections. The values of χ_{lf} decrease towards the core-top as the sediment core is principally made up of silty sand and sandy silt layers with a few rock pieces. The top 25 cm of the sediment core is predominantly made up of sandy particles, which is mimicked by the low χ_{lf} values. A moderate increase in χ_{lf} values is documented for 8–15 cm depth as this section is composed of silty sand and clayey silt. The peak in χ_{ARM} (0.41 × 10^{-5} m^3 kg^{-1}) at 23–26 cm depth coincides with a change in lithology, as the sediment composition changes from sandy silt with rock pieces to sand-sized particles (Fig. 3). These changes in the rock magnetic parameters and sediment lithology are a reflection of the changes in local climate and catchment disturbances (Haltia-Hovi et al., 2010).

4.3. Environmental magnetic properties of Sandy Lake sediments

4.3.1. Magnetic concentration

The profiles of concentration-dependent parameters for the Sandy Lake core are plotted against age in Fig. 3. Magnetic susceptibility (χ_{lf}) is a measure of the degree to which a sample can be magnetised whilst exposed to a weak magnetic field. It is a concentration-dependent parameter and a measure of the sum of the magnetic susceptibilities of a range of magnetic minerals, including ferrimagnets (e.g., magnetite), canted antiferromagnets (e.g., haematite), paramagnets (e.g. pyrite and biotite) and diamagnets (e.g., water and organic matter) (Thompson and Oldfield, 1986; Walden et al., 1999). Ferrimagnetic minerals are strongly magnetic whereas para- and dia-magnetic minerals are weakly so (Thompson and Oldfield, 1986). Magnetic susceptibility values for the Sandy Lake sediments during the Holocene vary between 20.96 × 10^{-8} m^3 kg^{-1} (15–16 cm; 10.55 cal. ka B.P.) and 66.19 × 10^{-8} m^3 kg^{-1} (8–9 cm; 6.07 cal. ka B.P.) with an average of 48.56 × 10^{-8} m^3 kg^{-1}. Compared to the Holocene sediments, glacial sediments display higher values, ranging between 27.87 × 10^{-8} m^3 kg^{-1} (18–19 cm; 12.55 cal. ka B.P.) and 135.89 × 10^{-8} m^3 kg^{-1} (57–58 cm; 34.51 cal. ka B.P.) with an average of 83.84 × 10^{-8} m^3 kg^{-1}. The high χ_{lf} values throughout the core suggest that ferrimagnetic minerals

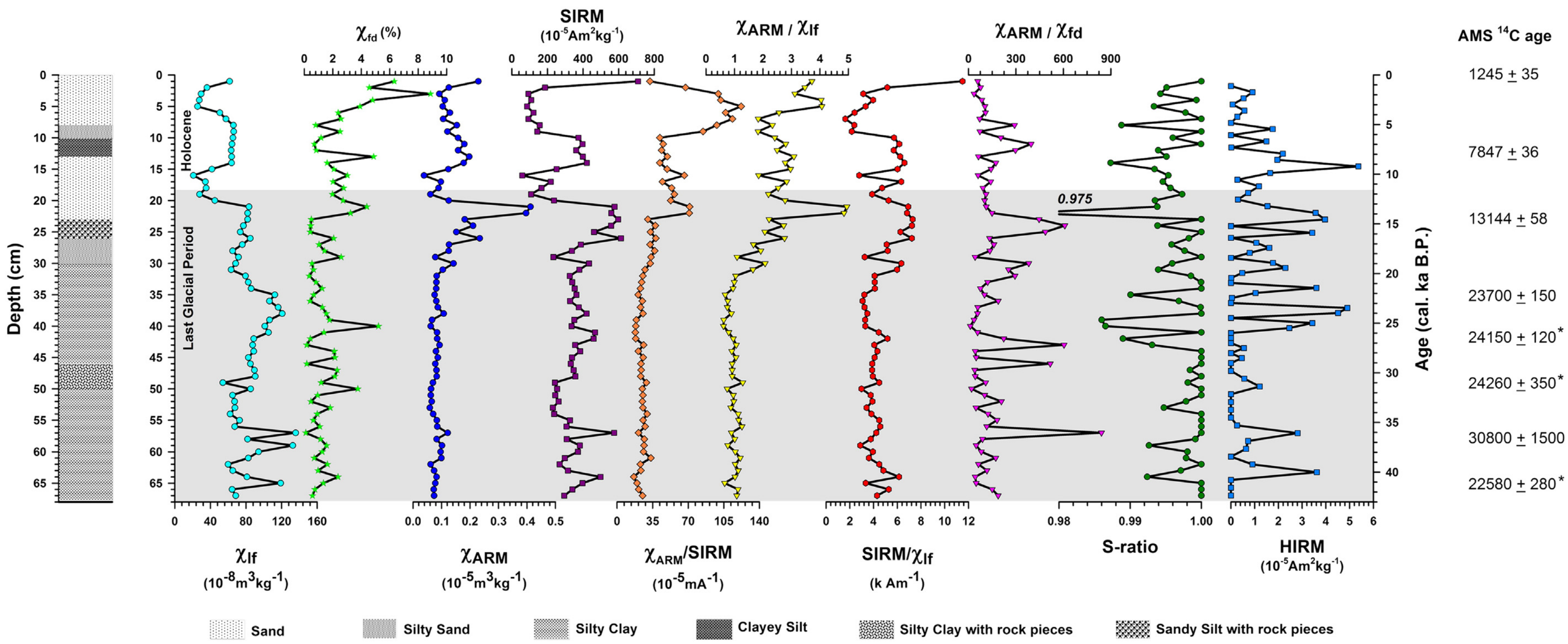

Fig. 3. Lithology and down-core variations of rock magnetic parameters for the Sandy Lake sediment core. The Holocene and the last glacial period are demarcated. Also shown are the measured AMS ^{14}C ages. The ages indicated by a '*' were not used in the age-depth model.

determine the magnetic susceptibility signal of the sediments (Thompson and Oldfield, 1986; Oldfield, 1991).

Percent frequency-dependent susceptibility (χ_{fd} %) is a measure of the concentration of superparamagnetic (SP) grains (Dearing, 1999a; Evans and Heller, 2003). Values of χ_{fd} % < 2% indicate the absence of SP grains whereas values of 2–10% suggest an admixture of SP and coarser magnetic grains. A sample contains all of SP grains when χ_{fd} % is in the range of 10 to 14% (Dearing, 1999a). Superparamagnetic grains may form in nature due to pedogenesis or fire activity (Evans and Heller, 2003). The χ_{fd} % values for the Holocene sediments are low, varying from 0.71% (10–11 cm; 7.31 cal. ka B.P.) to 8.87% (2–3 cm; 2.35 cal. ka B.P.; Fig. 3). The average χ_{fd} % value is 3.10%. Such low values suggest that the samples have an admixture of SP and magnetically coarse grains (Dearing, 1999a). Sediments deposited during the glacial period have even lower values of χ_{fd} %, ranging between 0.11% (56–57 cm; 34. 51 cal. ka B.P.) and 5.21% (39–40 cm; 23.98 cal. ka B.P.) with a mean of 1.49%, suggesting the absence of SP grains (Dearing, 1999a).

Susceptibility of anhysteretic remanent magnetization (χ_{ARM}) is a concentration-dependent parameter and is biased towards the stable single domain (SSD) grain size (Maher, 1988). Values of χ_{ARM} during the glacial regime vary between 0.06×10^{-5} m^3 kg^{-1} (61–62 cm; 38.44 cal. ka B.P.) and 0.41×10^{-5} m^3 kg^{-1} (20–21 cm; 13.89 cal. ka B.P.) with an average of 0.11×10^{-5} m^3 kg^{-1}. The Holocene samples have slightly lower values of $\chi_{ARM;}$ they display a low of 0.04×10^{-5} m^3 kg^{-1} (15–16 cm; 10.54 cal. ka B.P.) and a high of 0.23×10^{-5} m^3 kg^{-1} (0–1 cm; 1.12 cal. ka B.P.). Saturation isothermal remanent magnetization (SIRM) is generally influenced by the concentrations of all remanence-carrying magnetic minerals (Walden, 1999) and hence reflects the total magnetic mineral content (Oldfield, 1991). Values of SIRM are high during the glacial period (average = 369.52×10^{-5} Am^2 kg^{-1}) compared to the Holocene period (average = 241.41×10^{-5} Am^2 kg^{-1}), suggesting a higher concentration of magnetic minerals in the former period.

4.3.2. Magnetic mineralogy

The magnetic mineralogy of lake sediments is controlled mainly by catchment lithology and climatic factors (Shankar et al., 2006). S-ratio, hard isothermal remanent magnetization (HIRM) and IRM acquisition curves are the primary indicators of magnetic mineralogy in natural samples. Although, S-ratio and HIRM values give a fair indication of the magnetic mineral assemblage, semi-quantitative methods like X-ray powder diffraction, Mössbauer spectroscopy, diffuse reflectance spectroscopy, and low-temperature magnetic measurements are needed for confirmation (Liu et al., 2007). As such measurements are beyond the scope of this investigation, we relied on the simple rock magnetic parameters and inter-parametric ratios to determine the magnetic mineralogy of Sandy Lake sediments with corroboration from SEM-EDS studies. S-ratio (IRM_{300mT}/IRM_{1000mT}) is indicative of the relative proportions of ferrimagnetic and antiferromagnetic minerals in the sample (Walden et al., 1999; Evans and Heller, 2003). A higher proportion of magnetically "soft" minerals like magnetite, titanomagnetite and maghemite is indicated if the S-ratio value is close to 1. In the Sandy Lake sediment core, S-ratio values are extremely high and fluctuate between 0.97 and 1.00 (Fig. 3), indicating the dominance of low-coercivity magnetic minerals. Incremental IRM acquisition curves (Fig. 5) for selected samples representing χ_{lf} peaks and troughs show that a majority of the samples saturate in a magnetic field strength of <300 mT. This corroborates the fact that magnetic mineralogy of Sandy Lake sediments is dominated by ferrimagnetic minerals like magnetite, titanomagnetite etc. However, being natural samples, the presence of canted antiferromagnetic minerals like hematite in the samples is also evident from the HIRM parameter values (Fig. 3). The HIRM values are high during the last glacial period (average = 2.12×10^{-5} Am^2 kg^{-1}) compared to the Holocene period (average = 1.05×10^{-5} Am^2 kg^{-1}), suggesting a higher content of high-coercivity minerals like hematite during the former period.

4.3.3. Magnetic grain-size

Inter-parametric ratios, χ_{ARM}/SIRM and $\chi_{ARM}/\chi_{lf,}$ are used to determine magnetic grain size. High ratio values generally indicate a fine magnetic grain size and vice versa (Oldfield, 1991). Both the ratio values exhibit similar down-core variations as also evident from a statistically

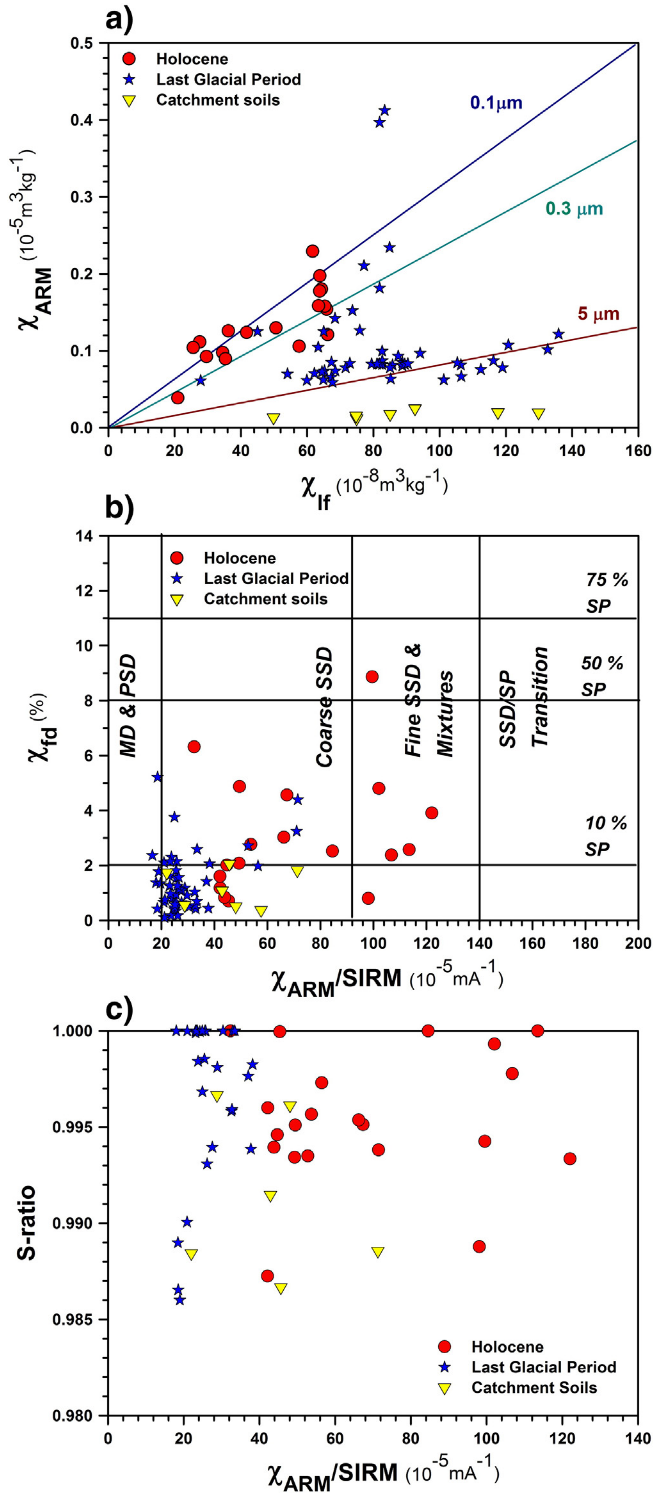

Fig. 4. Bi-plots of magnetic parameters and inter-parametric ratios indicating the magnetic grain size for Sandy Lake sediments and catchment soils. (a) Bi-plot of χ_{lf} vs. χ_{ARM} (also known as the King's plot; King et al., 1982). Dashed lines suggest the magnetic grain size; (b) Scatter plot of χ_{ARM}/SIRM vs. χ_{fd} % (Dearing et al., 1997; Maher, 1988); and (c) Scatter plot of χ_{ARM}/SIRM vs. S-ratio values indicate the magnetic grain size of titanomagnetite. Note: Several of the Holocene samples plot away from the cluster of glacial samples, suggesting that they have a finer magnetic grain size than the glacial samples.

significant correlation between them ($r^2 = 0.49$; n = 67; p < 0.0001). Their values are low from ~43 to ~19 cal. ka B.P., suggesting the dominance of coarse magnetic grains. The ratio values begin to increase after this period and show pronounced fluctuations during the Holocene. This indicates the presence of fine magnetic grains.

Fig. 4a and b provides a fair idea of the magnetic grain size. The biplot of χ_{fd}% vs. χ_{ARM}/SIRM (Fig. 4a) gives an indication of the magnetic grain size and also the contribution from SP grains (Maher, 1988; Dearing et al., 1997). The samples representing the glacial period plot on the boundary between "multi-domain & pseudo single domain (MD & PSD)" and "Coarse SSD" with ~10% contribution from SP grains. The Holocene samples are scattered in the "Coarse SSD" and "Fine SSD & mixtures" fields and the contribution from SP grains is ~15–30%. The χ_{ARM} vs. χ_{lf} biplot, also known as the King's plot (Fig. 4b; King et al., 1982), is used to decipher both the concentration and grain size of magnetic minerals and has also been previously used on lacustrine (Bloemendal et al., 2003) and marine sediments (Sagnotti et al., 2001) from Antarctica. The former is represented by the distance of each sample from the origin and the latter by the slope of the line joining each sample point with the origin (Bloemendal et al., 2003). For the Sandy Lake sediments, the Holocene samples have a low concentration of magnetic minerals but at the same time they are generally fine-grained (grain size varying between 0.1 and 0.3 μm). Glacial samples have a relatively high concentration of magnetic minerals and they are magnetically coarse grained (~5 μm). Fig. 4c is a scatter plot of χ_{ARM}/SIRM vs. S-ratio for the last glacial and Holocene samples. It is evident that the last glacial period samples have coarse-grained, and the Holocene samples fine-grained, magnetic minerals although a few Holocene samples do plot within the cluster of glacial samples.

4.4. Environmental magnetic properties of catchment soils

Detailed magnetic measurements were made on seven soil samples collected from the Sandy Lake catchment and the data are presented in Table 3. The χ_{lf} values vary from 49.85×10^{-8} m^3 kg^{-1} to 129.84×10^{-8} m^3 kg^{-1} with a mean value of 89.22×10^{-8} m^3 kg^{-1}. The percent frequency-dependent susceptibility is also low with values ranging from 0.28 to 1.68%. This indicates weak pedogenesis as polar soils are covered with snow and ice for a major part of the year, which does not allow any soil–atmosphere interaction that is necessary for the formation of pedogenic fine-grained magnetic minerals. The magnetic minerals present in the soil samples are 'soft' ferrimagnetic minerals like magnetite, titanomagnetite etc. as evident from the high S-ratio values (Table 3). Isothermal remanence magnetisation (IRM) acquisition curves also confirm the presence of 'soft' ferrimagnetic minerals (Fig. 5).

4.5. Sources of magnetic minerals

Magnetic minerals present in lacustrine sediments are principally terrigenous. They may also be influenced by factors such as magnetic mineral dissolution (Anderson and Rippey, 1988), and the presence of bacterial magnetite (Petersen et al., 1989; Paasche et al., 2004; Kim et al., 2005), anthropogenic magnetite (Jordanova et al., 2004) and authigenic greigite (Roberts, 1995). If dissolution ever occurs, fine grains with a large surface area-to-volume ratio are selectively removed, leading to coarsening of the magnetic grain size. Therefore, dissolution may be identified by a sharp decrease in the concentration-dependent magnetic parameter values, associated with parallel declines in the values of χ_{ARM}/SIRM and χ_{ARM}/χ_{lf} (Foster et al., 2008). The profiles of these parameter and ratio values do not show any evidence of magnetic mineral dissolution in Sandy Lake sediments. Bacterial magnetite is formed by magnetotactic bacteria (e.g. *Magnetospirillum* spp.) which are aquatic organisms. They synthesise SD magnetite crystals which help them navigate along geomagnetic field lines in search of anaerobic conditions (Bazylinski and Williams, 2007). Bacterial magnetite is said to be present if the ratio values are >40 for χ_{ARM}/χ_{lf}, >1000 for χ_{ARM}/χ_{fd} (Dearing, 1999b), and $>200 \times 10^{-5}$ mA^{-1} for χ_{ARM}/SIRM (Foster et al., 2008). However, the ratio values for the Sandy Lake sediments and the catchment soils are less than the threshold values mentioned above (Fig. 3). Oldfield (1994) proposed a biplot of χ_{ARM}/χ_{lf} vs. χ_{ARM}/χ_{fd} to distinguish between fine-grained magnetic minerals of detrital and bacterial origins. Sandy Lake sediment and soil data plotted on this biplot (Fig. 6) indicate that the magnetic minerals are primarily catchment-derived and there is no significant contribution from bacterial magnetite. Authigenic greigite (Fe_3S_4) forms under anoxic conditions (Roberts, 1995). An SIRM/χ_{lf} value $>30 \times$ k Am^{-1} (Walden et al., 1999) is an indicator of greigite. The value of this ratio is $<5 \times$ k Am^{-1} (Fig. 3) for samples representing both the last glacial and Holocene periods. Hence, greigite is most likely absent. The data discussed above suggest that the magnetic minerals in the Sandy Lake sediment core are primarily derived from the catchment and the effect of dissolution or the presence of bacterial magnetite and greigite may be discounted. Scanning electron microscopic (SEM) and energy dispersive spectrometric (EDS) data show that the magnetic minerals are made up of Fe and Ti oxides (titanomagnetite) with small amounts of Mn, Al and Si (Fig. 7). As Al and Si are usually associated with the terrigenous fraction of sediments, it may be inferred that the magnetic minerals present in Sandy Lake sediments are detrital (Jelinowska et al., 1997; Williamson et al., 1998).

4.6. Interpretation of the magnetic data for Sandy Lake sediment samples

Magnetic susceptibility of lake sediments has been used as an indicator of terrigenous fraction (including magnetic minerals; Thompson and Oldfield, 1986; Murdock et al., 2013) and hence of paleoclimate. Two models have been used by workers to interpret environmental magnetic data.

In the first model, which applies to soils and sediments from *tropical* regions and not related to polar regions, high (low) χ_{lf} values correspond to warm and wet (cold and dry) climate (Maher and Thompson, 1995; Shankar et al., 2006). This is because the intensity of chemical weathering is high, leading to strong pedogenesis. During this process, iron in non-magnetic forms is transformed into magnetic forms (Maher, 2009). Soil-formation is accompanied by the production of ultrafine-grained superparamagnetic magnetite (pedogenic magnetite) due to in situ inorganic processes (Maher and Taylor, 1988). The presence of organic matter, Fe and suitable Eh-pH conditions in soils

Table 3
Rock magnetic data for catchment soils of Sandy Lake (* = 10^{-8} m^3 kg^{-1}; # = 10^{-5} m^3 kg^{-1}; $ = 10^{-5} Am^2 kg^{-1}; & = 10^3Am^{-1}; @ = 10^{-5} mA^{-1}).

Sample no.	χ_{lf}*	χ_{fd} %	χ_{ARM}#	$IRM_{300mT}$$	SIRM$	SIRM/χ_{lf}&	χ_{ARM}/χ_{lf}	χ_{ARM}/χ_{fd}	χ_{ARM}/SIRM@	S-ratio	HIRM$
Soil 1	92.55	1.82	0.02	34.56	34.96	0.38	0.27	14.77	71.28	0.99	0.40
Soil 2	74.93	1.74	0.01	53.36	53.98	0.72	0.16	9.12	22.00	0.99	0.62
Soil 3	74.78	0.37	0.02	26.21	26.76	0.36	0.21	55.03	57.61	0.98	0.54
Soil 4	49.85	2.05	0.01	28.56	28.94	0.58	0.27	12.90	45.66	0.99	0.39
Soil 5	85.04	0.51	0.02	36.43	36.57	0.43	0.21	40.72	48.06	1.00	0.14
Soil 6	117.61	0.56	0.02	69.02	69.25	0.59	0.17	30.25	28.77	1.00	0.23
Soil 7	129.84	1.09	0.02	45.20	45.59	0.35	0.15	13.87	42.89	0.99	0.39
Average	89.23	1.16	0.02	41.90	42.29	0.49	0.20	25.24	45.18	0.99	0.39

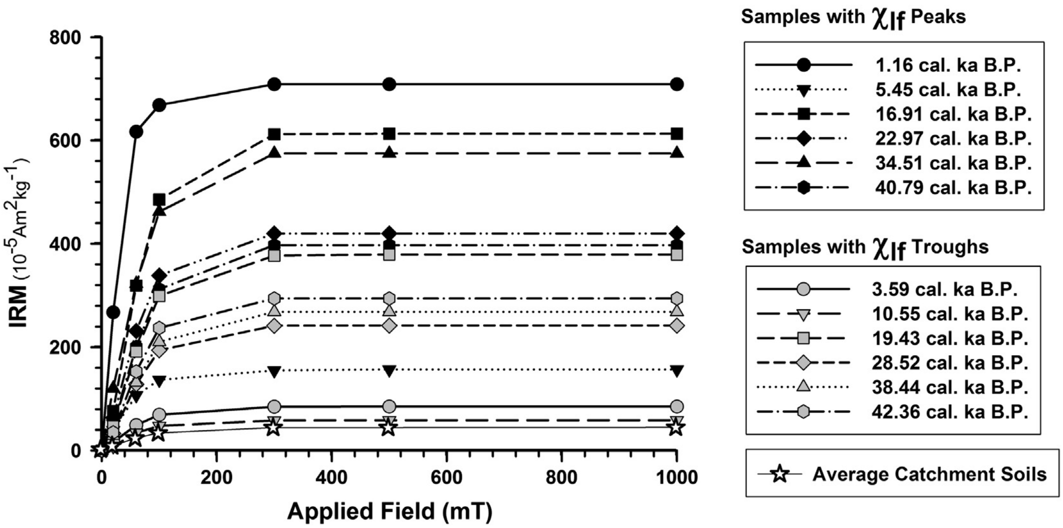

Fig. 5. IRM acquisition curves for selected samples of Sandy Lake sediments representing peaks and troughs in magnetic susceptibility data. Also plotted is the acquisition curve for the average IRM value of catchment soils (n = 7). Note: All the samples saturate at ~300 mT, indicating the dominance of ferrimagnetic minerals.

favour the production of pedogenic magnetite. Hence, high amounts of rainfall and large number of wetting/drying cycles in soils produce large amounts of pedogenic magnetite. This pedogenic magnetite is responsible for the enhancement of χ_{lf} values in soils and, therefore, in sediments as well.

In the second model, however, high values of χ_{lf} represent cold (glacial) periods and low values relatively warm (interglacial) periods (Thouveny et al., 1994; Evans and Heller, 2003; Peck et al., 2004; Wang et al., 2010). During cold climatic conditions, frost (mechanical) weathering dominates, leading to the release of primary, coarse grained ferrimagnetic minerals from catchment rocks (Reynolds and King, 1995). These will be abundantly available on slopes and hence easily

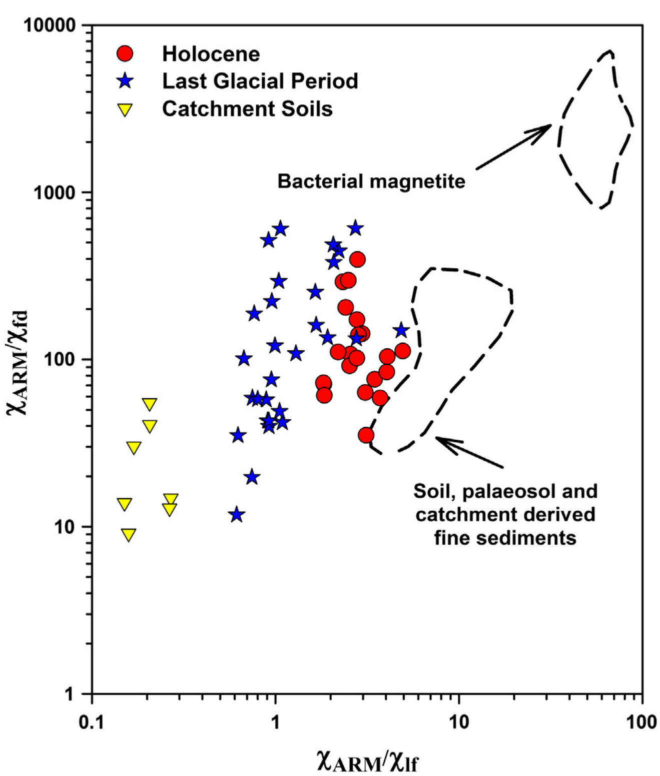

Fig. 6. Bi-logarithmic plot of χ_{ARM}/χ_{lf} vs. χ_{ARM}/χ_{fd} (Oldfield, 1994) for Sandy Lake sediments and catchment soils.

transported to the depositional basin by erosional agents. The sediments resulting from such weathering will have a high χ_{lf} value but low values of χ_{fd} %, χ_{ARM}, χ_{ARM}/SIRM and χ_{ARM}/χ_{lf} (Wang et al., 2010). During relatively warmer conditions, however, chemical weathering and pedogenesis predominate, resulting in the production of fine-grained magnetic minerals (SP and SD size range). Hence, sediments deposited during relatively warm climatic conditions exhibit low values of χ_{lf} (Peck et al., 1994; Thouveny et al., 1994; Reynolds and King, 1995; Phartiyal et al., 2011; Phartiyal, in press) but high values of χ_{fd} %, χ_{ARM}/SIRM and χ_{ARM}/χ_{lf} (Wang et al., 2010). Apart from melt-water streams and glacier movements, sediments (containing magnetic minerals) may also be transported by wind (Li et al., 2006). Strong winds pick up and carry dust particles (including magnetic minerals) and deposit them on the lake-ice when wind energy drops. The dust load gets trapped in cracks present in the lake-ice. During glacial summer, melting or fracturing of ice sheets would allow dust particles to penetrate through vertical conduits and reach the lake floor (Spaulding et al., 1997). However, Sagnotti et al. (1998) suggested low values of magnetic susceptibility to be indicative of cold climate and vice versa as seen in the CIROS-I marine sediment core of Ross Sea, West Antarctica.

4.7. Paleoenvironmental reconstruction from the environmental magnetic data of Sandy Lake sediment core and comparison with other records

Based on the rock magnetic properties discussed above, we have reconstructed the paleoenvironmental conditions for the Schirmacher Oasis (SO) during the past 42.5 cal. ka B.P.

4.7.1. The last glacial period (~42.35–11.86 cal. ka B.P.)

Low values of χ_{lf} indicate relatively warm climatic conditions and vice versa (Evans and Heller, 2003; Peck at el., 2004). This relation is seen in the glacial/interglacial records of marine (Manoj et al., 2012) and lake (Thouveny et al., 1994) sediments too. The Sandy Lake sediment magnetic record agrees with this observation as concentration-dependent magnetic parameter (χ_{lf} and SIRM) values are high during the last glacial period and low during the Holocene (the present interglacial; Fig. 3). Several peaks in the χ_{lf} record (during 40.78, 36.08, 34.51, 29.03, 28.02–21.45 cal. ka B.P.) suggest cold climatic conditions in the Schirmacher Oasis. These periods are also characterized by coarse magnetic grain size (low χ_{ARM}/SIRM and χ_{ARM}/χ_{lf}). Values of χ_{fd} % are also low, indicating the absence of pedogenesis due to ice-cover. The extent of ice-cover over the soils would not allow any soil–atmosphere

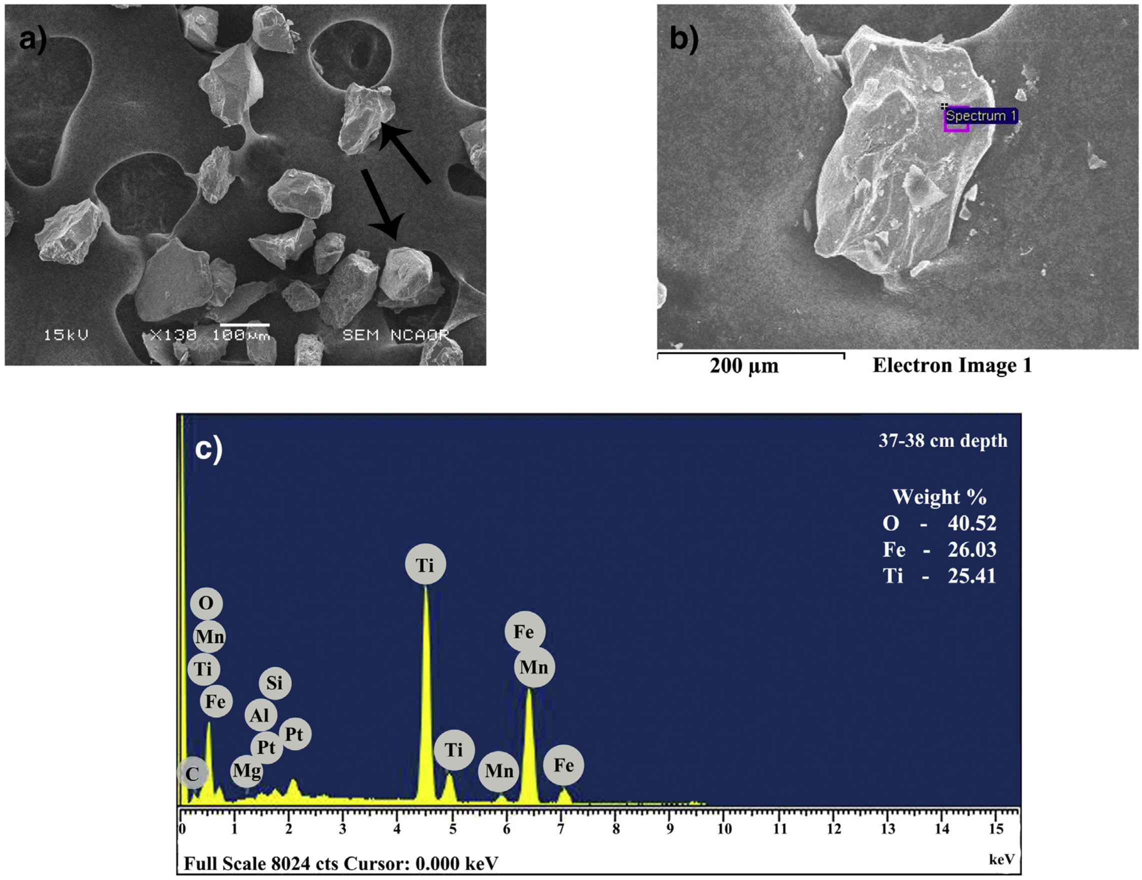

Fig. 7. Data on magnetic extracts. (a) and (b) SEM images of magnetic mineral grains extracted from Sandy Lake sediment core (37–38 cm); and (c) EDS spectrum, indicating that the magnetic mineral is titanomagnetite.

interaction which is essential for pedogenic formation of fine-grained magnetic minerals. The period between 20.94 and 24.47 cal. ka B.P. also exhibits high magnetic mineral concentration and coarse magnetic grain size. It is demarcated as the Last Glacial Maximum (LGM) when ice-cover was widespread. Relatively warmer periods in the SO are documented during 38.44–39.22, 33.73–29.81, and 28.52 cal. ka B.P. Deglaciation in the SO began around 21 cal. ka B.P. (after the LGM) as evident from the decreasing values of χ_{lf} and SIRM (Fig. 3), which continued until the advent of the Holocene. Achyuthan et al. (2008) deciphered the climatic conditions by calculating the sedimentation rates for two long sediment cores from L-49 Lake situated near the Indian Research Station — *Maitri* — and ~2.5 km away from the Sandy Lake. According to them, cold climate existed in the SO between 30.64 and 21.69 cal. ka B.P. and relatively warm conditions between 32.66 and 30.64 cal. ka B.P. Further, we compared our χ_{lf} data with the $\delta^{18}O$ data for ice-cores from Byrd (Blunier and Brook, 2001) and EPICA Dronning Maud Land (EDML; EPICA Community Members, 2006; Fig. 8) situated in the Central Dronning Maud Land to determine if the relatively warm and cold events indicated by our environmental magnetic data matched with the oxygen isotopic data. Several of the Antarctic Isotopic Maximum (AIM) events seem to be present in our χ_{lf} data as well (Fig. 8). The trough in χ_{lf} recorded during 38.44–39.22 cal. ka B.P. coincides with the Antarctic Warming Event — A1 (one of the seven warming events reported from Antarctica during the past 90 cal. ka B.P.; Blunier and Brook, 2001; Fig. 8). It is interesting to note that the 28–33 cal ka B.P. interval also has registered low χ_{lf} values which are similar to the A1 warming event (Fig. 8), indicating that SO experienced relatively warmer periods during this time period. This is supported by other proxy data available from Schirmacher Oasis (Achyuthan et al., 2008) and the ice-core data which show relatively warm periods during this time interval (Events 4, 4.1 and 5; Fig. 8c).

Infra-red stimulated luminescence (IRSL) dates (53.7 ± 8.2 and 51.2 ± 9.4 ka B.P.) obtained by Krause et al. (1997) from two lakes in the SO suggest that the region must have been ice-free. Our rock magnetic data also support the findings of Krause et al. (1997). Like other ice-free oases in East Antarctica, SO also escaped full glaciation during the past 40 cal. ka B.P. (Hodgson et al., 2001; Gibson et al., 2009; Colhoun et al., 2010). The data suggest that χ_{lf} of terrestrial sediments is a suitable proxy to demarcate relatively warm and cold events in Antarctica.

4.7.2. The Holocene period (~11.86 cal. ka B.P.–present)

The low values of χ_{lf} and high values of χ_{ARM}/SIRM and χ_{ARM}/χ_{lf} (Fig. 3) from 12.55 to 9.88 cal. ka B.P. (Pleistocene–Holocene boundary) suggest a low concentration of magnetic minerals and a fine magnetic grain size. The data indicate the onset of relatively warm climatic conditions at the Pleistocene–Holocene boundary. Values of χ_{fd} % also register a slight increase during this period, indicating that the retreating ice-cover facilitated soil-atmosphere interaction and the formation of ultra-fine superparamagnetic grains in catchment soils. This deglaciation event in the Schirmacher Oasis is also indicated by a grounding line retreat in the Lazarev Sea (Gingele et al., 1997). According to Phartiyal et al. (2011), the SO was dominated by several glacial lakes; due to the Early Holocene warming, the glaciers retreated which led to the formation of a few pro-glacial lakes. The Early Holocene warming conditions have also been deciphered from ice-cores (Steig et al., 2000; Mayewski et al., 2009) and lake sediments (Hodgson et al., 2001; White et al., 2009) of coastal and continental Antarctica. After the Early Holocene warm conditions as seen in our χ_{lf} record, colder climatic conditions prevailed from 9.21 to 4.21 cal. ka B.P. This is evident from the high χ_{lf} and SIRM values; besides, the magnetic minerals have a coarse magnetic grain size (low values of χ_{fd} %, χ_{ARM}/SIRM

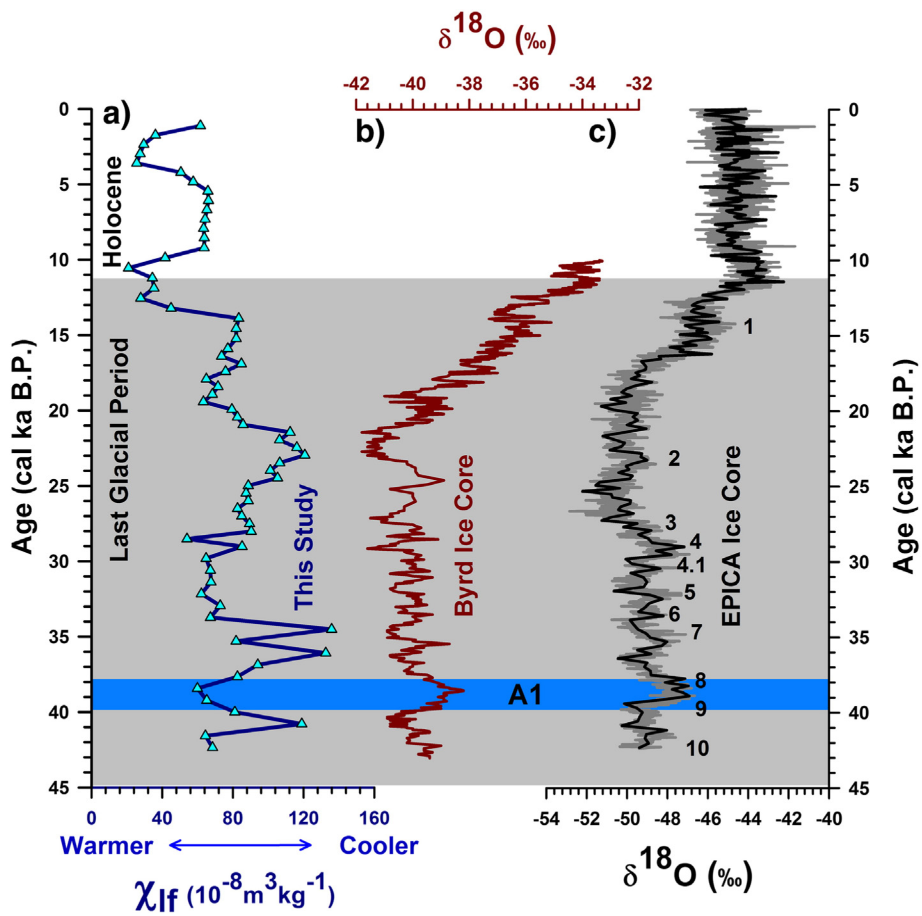

Fig. 8. Comparison of (a) χ_{lf} data of Sandy Lake sediments with the oxygen isotopic data of ice-cores from (b) Byrd (Blunier and Brook, 2001) and (c) EDML (EPICA Community Members, 2006) stations in the Dronning Maud Land, East Antarctica. A1 is one of the seven warming events reported in Antarctica during the past 90 cal. ka B.P. (Blunier and Brook, 2001).

and χ_{ARM}/χ_{lf}). Phartiyal et al. (2011) too documented cold climatic conditions between 9.5 and 5 cal. ka B.P. from a study of the magnetic susceptibility and loss-on-ignition (LOI) properties of sediment profiles from the Schirmacher Oasis. However, the climatic patterns across other ice-free areas of East Antarctica during this period are not similar, as one of the lakes in the Vestfold Hills recorded relatively warm climatic conditions between 8.5 and 5.5 cal. ka B.P. (Verleyen et al., 2011) whereas in the Larsemann Hills, cold and dry conditions prevailed from 9.5 to 7.4 cal. ka B.P. as suggested by the low lake levels (Verleyen et al., 2004). Lakes in the Bunger Hills were also covered by ice for an extended period, indicating cold and dry conditions with reduced melt-water input from 9 to 5.5 cal. ka B.P. (Verkeulich et al., 2002). Schirmacher Oasis experienced relatively warm climatic conditions from 4.21 to ~2 cal. ka B.P. as evident from the low magnetic mineral concentrations and fine magnetic grain size. Values of χ_{fd} % too are high during this period, indicating strong pedogenesis during which fine-grained magnetic minerals (fine SSD and SP) formed in the catchment and were transported to the lake by melt-water streams (Wang et al., 2010). The relatively warm conditions during this period are recorded in other ice-free regions of East Antarctica too. Verleyen et al. (2004) documented a relatively warm period in the Larsemann Hills as indicated by a rise in the lake level and by the flourishing of open water marine diatoms. Wagner et al. (2004) reported abundant organic matter in the sediments of Lake Terrasovoje from the Amery Oasis during this period and suggested that the high organic matter content is due to relatively warm climatic conditions. Other ice-free areas like the Vestfold Hills, the Lutzow-Holm Bay and the Bunger Hills also witnessed warming events during this time interval (Bjorck et al., 1996; Melles et al., 1997; Roberts and McMinn, 1999; Okuno et al., 2007). After ~2.35 cal. ka B.P., magnetic values, especially the magnetic concentration-dependent parameters such as χ_{lf} and SIRM, increase and magnetic grain size indicators like χ_{ARM}/SIRM decrease, suggesting a high concentration of coarse-grained magnetic minerals. Therefore, cold and dry climatic conditions must have set in in the Schirmacher Oasis, leading to an extensive ice-cover over the region. This cooling event may be related to the neoglacial cooling (Verleyen et al., 2011), which is also evident in proxy records from the Schirmacher Oasis (Phartiyal et al., 2011) and other ice-free regions of East Antarctica (McMinn, 2000; Wagner et al., 2004; Hodgson et al., 2005). The χ_{lf} variations during the Holocene as documented by our study do not have a one-to-one correlation with the ice-core data (Fig. 8), which is due to the coarse temporal resolution of our data. However, the general climatic trend is similar in both the proxy records. Global climatic signals such as the Little Ice Age and the Medieval Warm Period are not documented.

5. Conclusions

The environmental magnetic data of Sandy Lake sediments of Schirmacher Oasis, East Antarctica, enable us to draw the following conclusions:

1. The dominant magnetic mineral in the sediments is titanomagnetite, which is detrital and catchment-derived; the magnetic mineralogy is not influenced by either the presence of authigenic greigite and bacterial magnetite or diagenetic dissolution.
2. Scanning electron microscopy and energy dispersive spectrometry studies confirm the presence of titanomagnetite as the magnetic mineral.
3. Glacial periods are characterized by high magnetic mineral concentrations (high values of χ_{lf} and SIRM) and coarse SSD titanomagnetite

(low χ_{ARM}/SIRM, χ_{ARM}/χ_{lf} and high S-ratio values). Extremely cold periods in the Schirmacher Oasis are recorded during 40.78, 36.08, 34.51, 29.03 and, 28.02–21.45 cal. ka B.P. Relatively warm periods are documented during 38.44–39.22 cal. ka B.P., 33.73–29.81 cal. ka B.P. and 28.52 cal. ka B.P. The LGM has documented the highest concentration of magnetic minerals, indicating widespread glaciation in the Schirmacher Oasis.

4. The Holocene period is characterized by alternating phases of relatively warm (12.55–9.88 cal. ka B.P. and 4.21–~2 cal. ka B.P.) and cold (9.21–4.21 cal. ka B.P. and from ~2 cal. ka B.P. onwards) events.
5. Many of the relatively warm and cold events discerned in this study are correlatable with other lake sediment and ice-core records from the Schirmacher Oasis and other ice-free areas in East Antarctica.
6. This study provides environmental magnetic evidence for the Schirmacher Oasis escaping full glaciation during the past 40,000 years.
7. This is the first report of a detailed environmental magnetic record of glacial–interglacial climatic variations from the Schirmacher Oasis.

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