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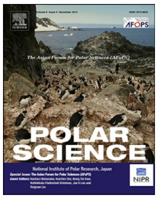

Response of Long Lake sediments to Antarctic climate: A perspective gained from sedimentary organic geochemistry and particle size analysis

Badanal Siddaiah Mahesh [a, *], Anish Kumar Warrier [a], Rahul Mohan [a], Manish Tiwari [a], Anila Babu [b], Aswathi Chandran [b], Rajesh Asthana [c, 1], Rasik Ravindra [d]

[a] *National Centre for Antarctic and Ocean Research, Earth System Science Organization (ESSO), Ministry of Earth Sciences, Govt. of India, Headland Sada, Vasco 403804, Goa, India*
[b] *Department of Post Graduate Studies and Research in Geology, Govt. College, Kasargod, Kerala 671123, India*
[c] *Geological Survey of India, NH 5P, NIT, Faridabad 121001, New Delhi, India*
[d] *ESSO, Ministry of Earth Sciences, Govt. of India, Prithvi Bhawan, Lodhi Road, New Delhi 110003, India*

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ABSTRACT

Sediments from the pristine lakes of ice-free regions of Antarctica are a great source for proxies to reconstruct the effect of past-climate on the lake evolution and its response to Antarctic climate. A 50 cm long sediment core retrieved from Long Lake, a periglacial lake of Schirmacher Oasis in Dronning Maud Land was measured for elemental (C%, N% and C/N), isotopic ($\delta^{13}C$, $\delta^{15}N$) and particle size (sand-silt-clay percent) variation. The radiocarbon dated core spanning the last 48 cal ka BP has been deciphered for the lake's response to Antarctic climate. The C/N ratio (atomic ratio) predominantly indicates that the productivity has been autochthonous for majority of the down-core while the top 0–3 cm indicates that there has been addition of terrestrial organic matter into the lake system owing to longer ice-free conditions. The organic carbon shows significantly lower values (0.2%) throughout the glacial period and major part of the Holocene while the core-top values are consistent with the presence of a microbial mat which is reflected as higher organic carbon (12%). The $\delta^{13}C$ and $\delta^{15}N$ range from −33 to −9‰ and 2 −18‰, respectively. The isotopic signals vary marginally for the entire glacial period (48–8 cal ka BP) suggesting an intense cold period. The gradual increase in C/N ratio, sand content and $\delta^{13}C$ and decrease in $\delta^{15}N$ beginning at about 6 cal ka BP suggest that the Long Lake experienced longer ice-free conditions owing to sustained warmer Holocene conditions suggesting that the ice-cover over the Long Lake persisted well through early-Holocene. The sand and silt percent shows inverse correlation likely reflecting the warmer and colder conditions. The Holocene is characterised by higher sand content owing to melting of ice due to warmer conditions. The Long Lake's response to Antarctic climate is reflected in its response to the ice-cover conditions which regulates the productivity and sedimentation in the lake system.

1. Introduction

Past-climate reconstruction in Antarctica has been a forte of ice-cores and marine sediments. However, in the recent decades, paleoclimate reconstruction using lake sediments has gained much importance due to its easy accessibility in the lakes of the ice-free regions of Antarctica and also owing to its pristine conditions. These ice-free regions (e.g., McMurdo Dry Valleys, Larsemann Hills, Schirmacher Oasis etc.), which occupies about two percent of Antarctic land mass are marked with numerous lakes and hence act as a source for paleo-archives. The lakes are well established as “sentinels of change” (Williamson et al., 2009) as they are sensitive and respond rapidly to changes in climate and integrating these information in their sediments (Adrian et al., 2009). Various techniques have been successfully used to decipher the past-climatic history from lake sediments, for example, organic geochemistry

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[*] Corresponding author.
E-mail address: mahe687@gmail.com (B.S. Mahesh).
[1] Present address: Geological Survey of India, 27, J.L. Nehru Road, Kolkata 700016, India.

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(Smith et al., 2006; Hodgson et al., 2009a,b; Verleyen et al., 2011), particle-size (Kashiwaya et al., 2001; Holz et al., 2007; Fagel et al., 2007) and environmental magnetism (Shen et al., 2008; Phartiyal, 2014; Warrier et al., 2014).

The source and accumulation of organic matter in sediments can be identified by studying the abundance and isotopic composition of carbon and nitrogen. The type and amount of sedimentary organic matter can be used to reflect the past fluctuations in lake's productivity and terrestrial inputs which are influenced by climate-induced environmental changes (Talbot and Johannessen, 1992; Meyers, 1997; Leng and Marshall, 2004). Elemental analysis (e.g., carbon, nitrogen, phosphorus) and stable isotope geochemistry ($\delta^{13}C$ and $\delta^{15}N$) are the primary archives that can be extracted from lake sedimentary organic matter. These proxies are indicators of the provenance of organic matter, the type and amount of organic matter that has been deposited in the lake over a period of time (Talbot and Johannessen, 1992; Meyers, 1997; Leng and Marshall, 2004). The C/N ratios of organic matter is also a widely used indicator of the provenance of organic matter (Talbot, 2001; Meyers, 2003). Past-changes in the lacustrine systems due to change in climate can be deciphered from the $\delta^{13}C$ and $\delta^{15}N$ of bulk sedimentary organic matter (e.g., Talbot and Johannessen, 1992; Engel and Macko, 1993). The particle size in lake sediments are principally controlled by hydraulic conditions (Sly, 1978; Håkanson and Jansson, 1983). The down-core variations in particle size reflect general trends of warming versus cooling per se in Antarctic lake sediments. Large amount of coarser particles generally indicate warmer period while higher content of fine particles indicate cooler period (Wang et al., 2001; Chen et al., 2004; Yanhong et al., 2006; Xiao et al., 2009).

Even though applications of lake sediments to past-climate is highly significant, studies on Antarctic lakes are rare. Majority of paleoclimate data generated from the ice-free regions of Antarctica are from Ross Sea region, Wilkes Land, Princes Elizabeth Land and Mac Robertson Land (e.g., Adamson and Colhoun, 1992; Cremer et al., 2003; Hodgson et al., 2006; Verleyen et al., 2011) and significant studies have been carried out in the Soya Kaigan of East Antarctica (eg., Matsumoto et al., 2010, 2013, 2014; Takano et al., 2012; Takano et al., 2015). Past-climate records for East Antarctica i.e., Schirmacher Oasis are few (Krause et al., 1997; Bera, 2004; Singh and Tiwari, 2004; Matsumoto et al., 2006; Warrier et al., 2014).

In this study, we have used multi-proxy data (e.g., C_{org}, N%, $\delta^{13}C$, $\delta^{15}N$, C/N and particle size measurements) from a sediment core of Long Lake of Schirmacher Oasis with an aim to reconstruct the past-climate variations in the Schirmacher Oasis.

2. Site description

Schirmacher Oasis is an ice-free area covering about 35 km^2, located in East Antarctica on the Princess Astrid Coast of Dronning Maud Land (Fig. 1). The oasis is about 20 km in its length and 3 km at its maximum width. Located 100 m above mean sea level, it is situated between the edge of the continental ice sheet and the Novolazarevskaya Nivl Ice Shelf. The oasis is a recent periglacial region that is unaffected by anthropogenic activity (Krause et al., 1997). Schirmacher Oasis consists of a number of low-lying hills and has 118 lakes (Ravindra et al., 2004) which can be differentiated as periglacial, proglacial and epishelf lakes. The size of the lakes vary from few hectares to a few km^2 and its maximum depth varies from a couple of meters to a few meters. All major lakes of oasis are localized along the glacial valleys (Ravindra et al., 2004). The lakes in the oases are generally under ice-cover only during winter and receive significant precipitation (Walton, 1984). The region is marked with debris cover, valley systems which are dotted with lakes which are either in glacially eroded bedrock or dammed by moraines or ice (Bormann and Fritzsche, 1995).

The general climate in Schirmacher Oasis is milder as compared to the Antarctic climate. The air temperatures range from −7.7 to +8.2 °C during mid-summer (December–January) resulting in abundant melt-water. January is the warmest month (monthly mean air temperature of 0.7 °C, maximum +8.2 °C) while August is the coldest (monthly mean air temperature of −16.3 °C, minimum −35.5 °C) with an average wind velocity of about 9.7 m/s and 264.5 mm in annual precipitation usually in the form of snow (Lal, 2006). Lichens and mosses grow on the rocky soils of Schirmacher Oasis (Verlecar et al., 1996; Lal, 2004; Rai et al., 2011). Dominant faunal group such as protozoans, nematode tuatis, turbillaria are very few which results in low organic carbon content in sediment ranging from 0.05 to 1.8%.

The Long Lake, located in Schirmacher Oasis (see Fig. 1) is a landlocked lake or a periglacial lake, primarily fed by glacier melt-water during the austral summer (Heywood, 1972). This is located towards the western side of the Priyadarshini Lake or Zub Lake. The structure of this lake is elongated and hence the name Long Lake which has a water depth of about 5 m. The periglacial lakes in the Schirmacher Oasis are ice-covered during the austral winter for a period of around eight months and become ice-free during the austral summer for a period of 3–5 months (Ravindra and Chaturvedi, 2011).

3. Materials and methods

A 50 cm long sediment core was retrieved from Long Lake from a water depth of 7 m during the 28th Indian Scientific Expedition to Antarctica. This core was raised using percussion method of coring and stored under −20 °C. The core was sub-sampled at 1 cm interval. Each 1 cm slice was labelled appropriately and stored in heavy, transparent, non-toxic, sterilized HDPE (High Density Polyethylene) whirl pack.

3.1. Radiocarbon dates

Six samples at different depths (see Table 1) were selected for radiocarbon dating. Bulk sedimentary organic matter were used for the measurement of radiocarbon dates. The AMS-^{14}C ages for the core was measured at the National Science Foundation-Accelerator Mass Spectrometer facility, University of Arizona, USA. The ^{14}C dates were converted to calendar ages by using CLAM 6 (Blaauw, 2010) program along with the age-depth model. Though a reservoir age of approximately 1000 years was reported (Schwab, 1998), due to considerable variability between lakes this was not used. We have subtracted the core-top age to account for local reservoir effect from the measured ages before calibration.

3.2. Elemental and isotope measurements

We measured bulk organic carbon (%C_{org}) and carbon isotope ($\delta^{13}C$) for both untreated and treated (with 2N HCl) samples while nitrogen ($\delta^{15}N$) isotope analysis was carried out for untreated samples. The sample aliquots were treated with excess 2N HCl acid to remove carbonate. After 24 h, the samples were rinsed in distilled water five times and dried in an oven at 40 °C. The dried samples were crushed, finely ground and homogenized using a planetary ball mill. We followed the standard procedure of rinse method (e.g., Ostle et al., 1999; Schubert and Nielsen, 2000; Galy et al., 2007) for preparing samples materials for C_{org}%, N%, $\delta^{13}C$ and $\delta^{15}N$ analysis, which involved weighing an acid-treated sample aliquot (90–95 mg) into a tin capsule. The analysis of elemental concentrations and isotopic ratios was carried out at the Marine Stable Isotope Lab (MASTIL) of National Centre for Antarctic and Ocean Research, Goa, India using an Isoprime Stable Isotope Ratio Mass

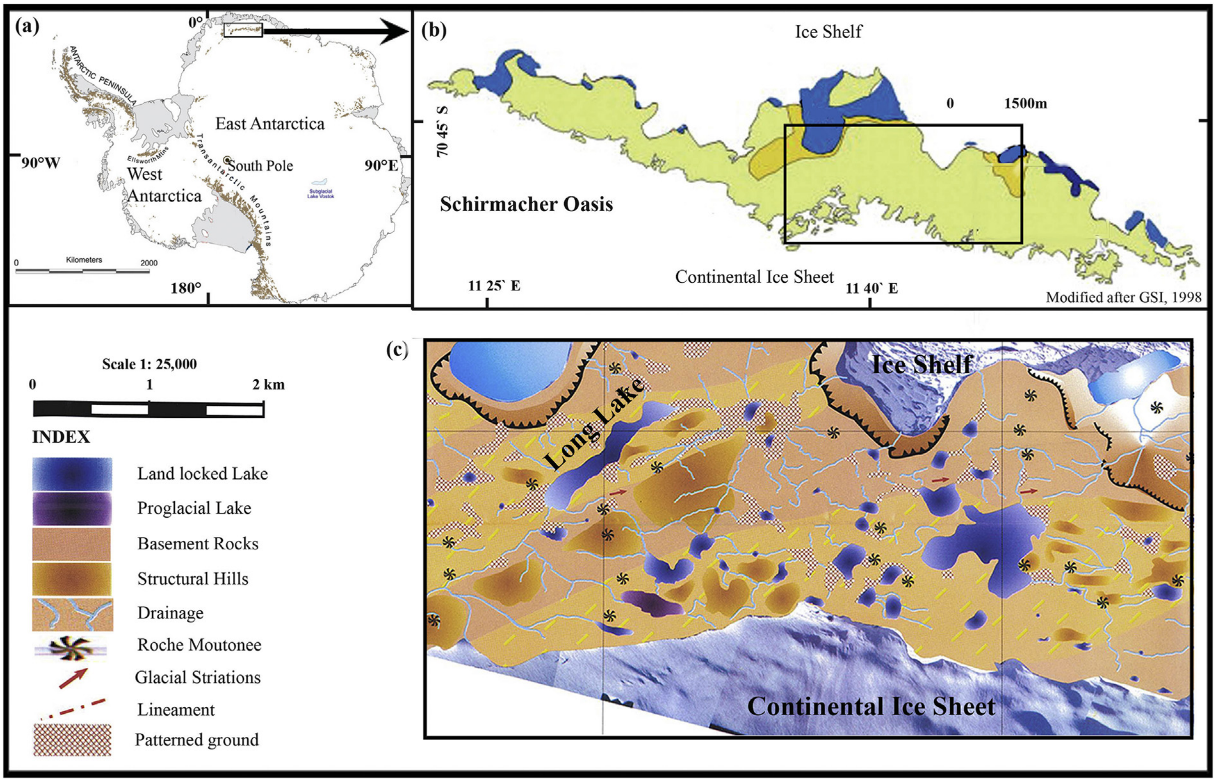

Fig. 1. (a) Map of Antarctica showing the location of Schirmacher Oasis. (b) Geomorphological map (modified after Geological Survey of India (2006)) of Schirmacher Oasis. (c) Location of Long Lake.

Table 1
Details of radiocarbon dates measured for selected depth interval. The core-top-age (524 yrs) has been applied for reservoir age correction. Calculations at 95% confidence ranges.

Lab code	Sample ID	Depth cm	$\delta^{13}C$	Conventional ^{14}C age	Error (±)	Reservoir corrected ^{14}C age	CLAM 6 ^{14}C age BP
AA97377	L27-1	0–2	−7.6	524	34	0	44
AA99547	L27-2	9–10	−9.4	1747	44	1223	2250
AA102612	L27-3	20–21	−14.2	11,943	53	11,419	14,608
AA102613	L27-4	34–35	−21	28,810	290	28,286	26,807
AA99550	L27-5	41–42	−19	30,230	350	29,706	35,417
AA97379	L27-6	46–48	−23.2	37,800	910	37,276	44,855

Spectrometer in continuous-flow mode coupled with an Elemental Analyzer (Isoprime, Vario Isotope Cube). The external precision on C_{org}% (both treated and untreated) and N% measurement are ±0.2% and ±0.3%, respectively (1σ) determined using Sulfanilamide as the standard. The external precision on $\delta^{13}C$ (both treated and untreated) and $\delta^{15}N$ is ±0.02‰ and ±0.09‰, respectively (1σ standard deviation) obtained by repeatedly running cellulose (IAEA-CH-3) and ammonium sulphate (IAEA-N-1) as the Standard. Replicate analysis of sample materials gave a precision of ±0.1% (1 σ). For carbon, all isotopic values are reported with respect to V-PDB and for nitrogen all isotopic values are reported with respect air-N_2. The reference standards used for normalizing to V-PDB and air-N_2 scale are cellulose (IAEA-CH-3) and ammonium sulphate (IAEA-N-1).

3.3. Grain-size analysis

Forty six samples from the sediment core were selected to study their particle size distribution (Carver et al., 1971). Approximately 2 g of freeze-dried sediment was taken in a pre-weighed beaker and 20 ml of 30% hydrogen peroxide (H_2O_2) and 10 ml of 10% glacial acetic acid were added to eliminate organic matter and carbonate material. The sample was washed 3–4 times with double distilled water (Millipore) to remove all traces of H_2O_2 and glacial acetic acid. Clay particle was deflocculated by adding 10 ml of 5% sodium hexametaphosphate (calgon) solution. The sample was then wet-sieved through an ASTM (American Society for Testing Materials) sieve (mesh no. 230) to separate the sand (>63 μm) and silt + clay (<63 μm) fractions. The >63 μm fraction was transferred to a pre-weighed beaker and oven-dried at 100 °C. Later 10 ml of calgon solution was added to the <63 μm fraction and the solution was stirred and poured into a 1000 ml measuring cylinder. The sample was stirred and, according to Stokes' Law, silt and clay fractions were withdrawn from the measuring cylinder with the help of a 20-ml pipette. The 20-ml solutions were transferred to pre-weighed beakers and dried in an oven at 100°C. The weight of the silt and clay fractions obtained were multiplied by 50 and a value of 1 (calgon correction factor) was subtracted from it to account for the weight of the sodium hexametaphosphate.

4. Results

4.1. Geochronology and sedimentation in Long Lake

The calibrated age-range at 95% confidence interval (2−σ) and calibrated mid-age along with the relative area under probability distribution are provided in Table 1. The age-depth model for the sediment core on calendar-year time-scale was obtained by using CLAM 6 (Blaauw, 2010). The core-top (0–2 cm) age is 40 cal y BP (Table 1) and the last dated section (46–48 cm) is 44.9 cal ka BP. Beyond this, the age has been extrapolated to the bottom of the core (49–50 cm) which extends up to 48 cal ka BP. The sedimentation rate vary between 1.1 cm/ka (minimum) to 6.2 cm/ka (maximum) with a mean rate of 2.5 cm/ka as can be seen in Fig. 2. The sedimentation rates for Long Lake are similar to that obtained in earlier studies (Warrier et al., 2014; Phartiyal et al., 2011; Bera, 2004). Generally documented sedimentation in lacustrine Antarctic sediments varies between 4 and 11 cm/ka (Shen et al., 1998). The sedimentation rates of Long Lake recorded are very low as compared with those in Soya Kaigan region (Matsumoto et al., 2010; Takano et al., 2012; Matsumoto et al., 2014).

4.2. Elemental variation and C/N ratio

The C_{org} varies between 0.1% and 12% throughout the sediment core. Interestingly, the core-top show higher C_{org} percentage (up to 12%; Fig. 3) while the lowest value is observed at 24.1cal ka BP. For most of the period between 1.0 and 48 cal ka BP, the %C_{org} variation is marginal (0.4 ± 0.2%). Similar variations were observed for untreated samples of %C_{org}. The %N also show similar variations to that of the C_{org}. The total down-core variation ranges between 1.05 and 0.04%. The highest value is recorded in the core-top (1.05%) while the lowest (0.03%) is recorded at 23.3 cal ka BP. Both the C_{org} and N% shows similar trends and are similar to that of the values recorded from a sub-glacial lake (Smith et al., 2006; Hodgson et al., 2009b) in the Antarctic Peninsula. The C/N ratios for the Long Lake sediment core is predominantly below 12 throughout the Holocene through the Last Glacial Period and exceeds values of 12 only after 6 cal ka BP (Fig. 3).

4.3. Stable isotope variations

In the present time-series, the δ^{13}C range from −33 to −9‰. The δ^{13}C shows an increase in values beginning around 10 ka BP. The lowest values (ca. −33‰) were recorded in the top 0–3 cm (Fig. 3). The last glacial period show lower value of −22‰ while the glacial average is about −20‰. The highest values were recorded during the Holocene between top 0–3 cm and 4 cal ka BP with values ranging between −16 and −9‰. The δ^{15}N for the down-core variation range from 2 to 16‰, with the highest values recorded at about 13 cal ka BP. The Holocene shows considerably lower values than the entire glacial period. The values decrease progressively from about 13 cal ka BP during the deglaciation and attain values of 2‰ for the Holocene. The glacial period shows marginal variation of 12 ± 2‰ between 8 and 48 ka BP.

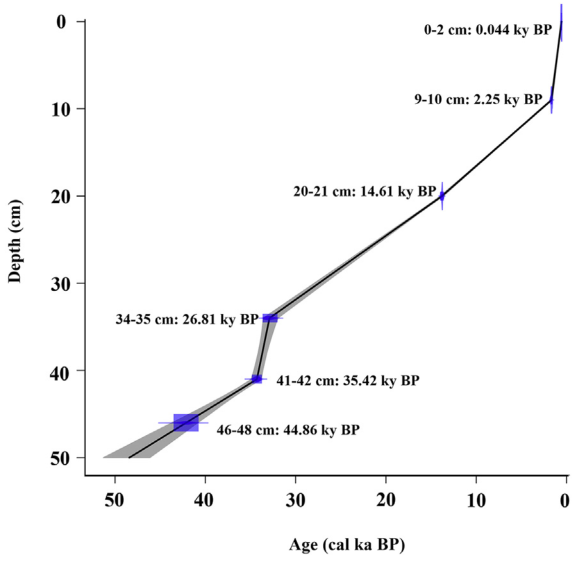

Fig. 2. Age-depth model for Long Lake sediments with error bars. Calibration for the radiocarbon dates based on CLAM6 program (Blaauw, 2010).

4.4. Grain size measurements

The sand content varies between 30 and 80% for the entire core. Low values were recorded at several intervals (0.7, 5.5, 32 and 35.4 cal ka BP) while the highest is recorded between 1 and 3.6 cal ka BP with an average of 75%. The sand content during the glacial period shows significant variation of 50 ± 10%. The highest silt content recorded for the last 48 kyr is ca. 14% (about 33 and 38 cal ka BP) while the lowest recorded is during the Holocene (ca. 2.3% at 6.6 cal ka BP). The average silt content during the glacial period (7%) is higher than the values recorded during the Holocene (4%) while the last glacial average is 5%. The clay content is high during most of the Holocene (ca. 30%) and lower during the glacial period (ca. 20%).

5. Discussion

5.1. C/N ratios and provenance

The source of organic matter to lakes in Antarctica varies largely from that of the terrestrial lakes of the low latitudes. In low latitude lakes, terrestrial vegetation forms a significant component of organic matter along with in-lake production by aquatic organisms. However, in Antarctica, where terrestrial vegetation is less (in the form of lichens and mosses), majority of the organic matter is contributed through the production of aquatic organisms such as algae and cyanobacteria (Yoon et al., 2006; Hodgson et al., 2009a,b). The C/N ratio can be used to identify the source of organic matter into the lake sediments (Talbot and Johannessen., 1992) as it provides information on relative proportion of aquatic *vs.* terrestrial organic matter as aquatic organisms (algae and cyanobacteria) exhibit C/N ratio between 4 and 10 while terrestrial derived organic matter is generally above 20 (Meyers, 1994, 2003; Meyers and Teranes, 2001). The C/N ratios for the Long Lake sediment core is less than 10 for the entire down-core variation indicating that the source of organic matter is autochthonous. However, during the late Holocene (0.04–6 cal ka BP), the C/N ratios show values higher than 10 indicating significant contribution from the terrestrial organic matter to the lake i.e., lichens and mosses. Presence of lichens and mosses have been identified during earlier studies (Lal, 2004; Rai et al., 2011) in the region. Further, the C/N ratios can be affected by diagenetic alteration. However, the scatter plots of carbon and nitrogen (Fig. 4; $r^2 = 0.98$; $n = 46$; $p < 0.0001$) show that they are organically bound and doesn't vary monotonically. Also the change in C/N ratios is not systematic which indicates that the effect of diagenesis is minimal or is absent (Talbot and Johannessen, 1992).

5.2. Treated and untreated C_{org} and δ^{13}C

We measured C_{org} content and δ^{13}C variation for both treated and untreated sediment samples for the entire down-core (Fig. 5). From the results obtained, it is very distinct that there is not much variation between the treated and untreated samples. The

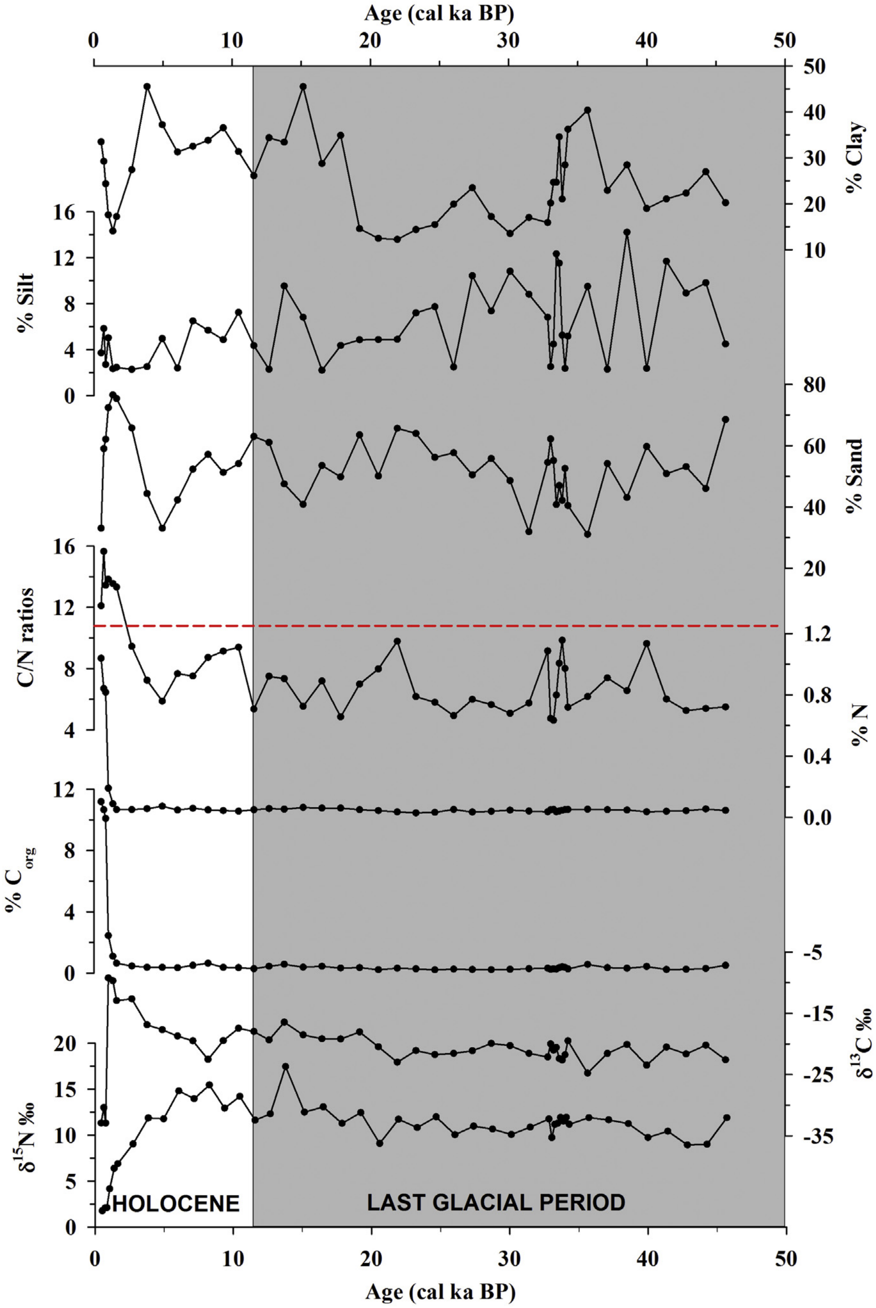

Fig. 3. Down-core variations of elemental (C_{org} and N%), isotopic ($\delta^{13}C$ and $\delta^{15}N$) and particle size (sand-silt-clay percent) variations for the Long Lake sediment core.

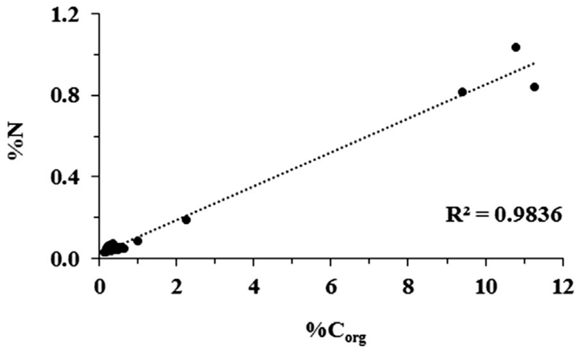

Fig. 4. Scatter-plots of $\%C_{org}$ *vs.* N% for the Long Lake sediment core.

deviation between both samples in organic carbon and carbon isotopes are minimal. The scatter plots show very strong positive correlation between the treated and untreated samples (Fig. 6a; $C_{orgtreated}$ *vs.* $C_{orguntreated}$: $R^2 = 0.91$, $p < 0.0001$; Fig. 6b: $\delta^{13}C_{treated}$ *vs.* $\delta^{13}C_{untreated}$; $R^2 = 0.97$, $p < 0.0001$) indicating absence of terrestrial source of inorganic carbon which could otherwise add significantly to the carbon pool in the lake system.

5.3. Elemental variation

From the % C_{org} and N% variations, it can be observed that the Long Lake's response to climate has been significant. The core-top has shown remarkable increase in $\%C_{org}$ which is as high as 12% and is nearly 60 times the values recorded during the Holocene i.e.,

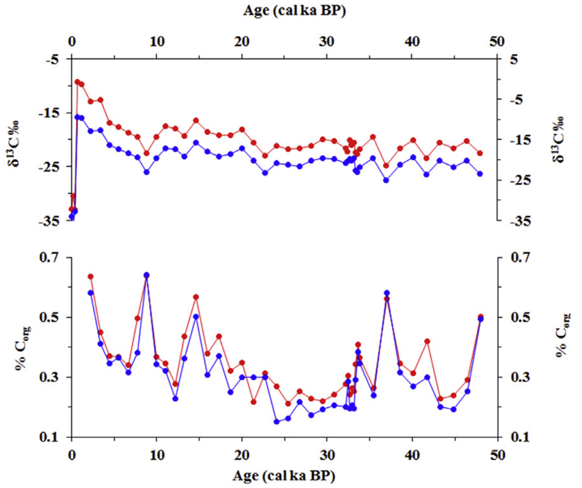

Fig. 5. Down-core variations of treated and untreated $\%C_{org}$ (from 1.5 ka BP) and treated *vs.* untreated $\delta^{13}C$.

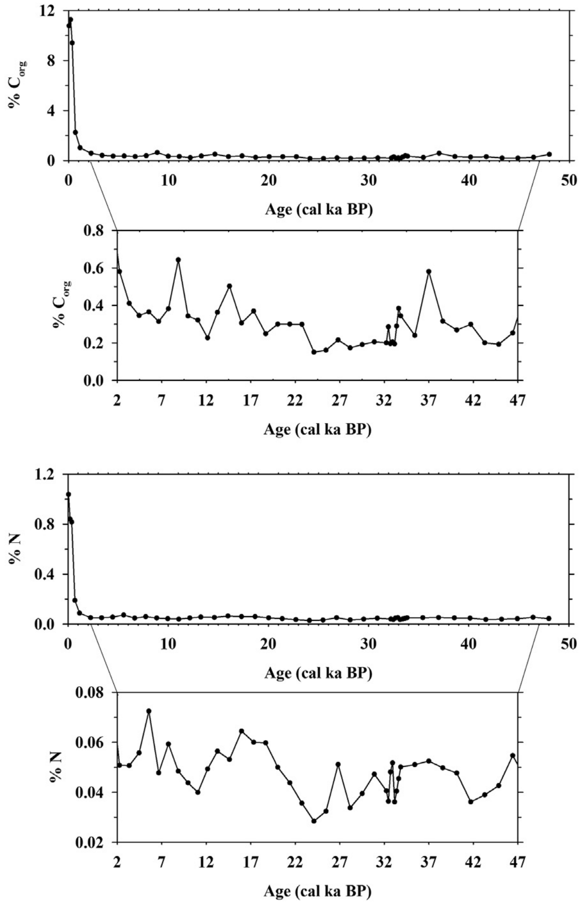

Fig. 7. Enlarged down-core variation for $\%C_{org}$ and N% from 2 ka BP to 48 ka BP.

0.2% (Figs. 3 and 7). This kind of increase can only be possible either when the productivity is very high or there is very less degradation of organic matter. Studies have shown the dominance of benthic cyanobacterial mats in Antarctic lakes (Hodgson et al., 2004; Smith et al., 2006; Verleyen et al., 2011 etc) which vary in thickness between few centimeters to couple of meters. The top few centimeters of the sediment is dominated by algal mat which would result in higher $\%C_{org}$ as evident. The presence of microbial mats is well documented in Schirmacher Oasis lakes (Komarek and Ruzicka, 1966; Vincent, 1988, 2007; Whitton and Potts, 2007 and references there in). These cyanobacterial mats forms as thick, cohesive, highly pigmented mats that coat the benthic environments (Vincent, 1988). The higher $\%C_{org}$ recorded for the top 0–3 cm would be due to the presence of such living microbial mat on the surface of the sediments (Vincent, 1988) under which black-brown decompositional layer forms (Richter and Bormann, 1995). Below these layers, monotonously developed Holocene sedimentation occurs resulting from a relatively stable climate (Schwab, 1998).

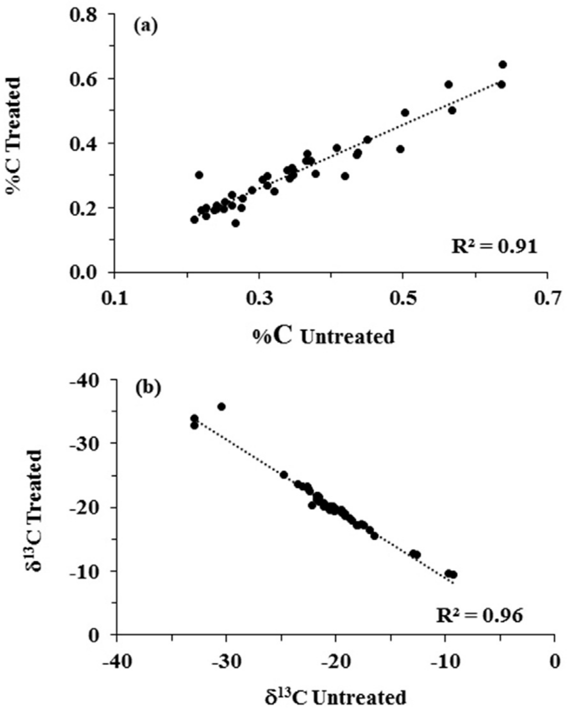

Fig. 6. Scatter-plots for treated vs. untreated $\%C_{org}$ and $\delta^{13}C$.

The lower $\%C_{org}$ during the glacial period indicates that the low productivity is probably due to ice-covered conditions wherein studies have shown that productivity sustains through cyanobacterial growth under sub-glacial conditions (Hodgson et al., 2009a). An earlier study has shown that Long Lake has undergone drying due to various processes such as – glacier recession resulting in reduced melt-water input during summer, reduced precipitation/snow accumulation, strong winds and sublimation which results in loss of ice-cover over the lake (Phartiyal et al., 2011). These factors would affect the overall sediment contribution to the lake as well as affect the productivity. Hence, this would further result in a sustained lowered productivity in the lake system as well as lowered sediment accumulation. The overall low $\%C_{org}$ during the Holocene would also be due to degradation of organic matter as the Long Lake being a shallow water lake would be well ventilated leading to oxic-rich environment. Similar to the $\% C_{org}$, the N% also shows similar variation. The N% values are the highest for the top 0–3 cm during which it reaches a maximum value of 1% (Fig. 7). From these variations, it can be observed that the N% records show increase and decrease in tandem with the $\% C_{org}$. The higher N% during the last 1000 yr BP would be due the ability of the cyanobacteria to fix nitrogen directly from the atmosphere mostly under ice-free conditions of the Long Lake.

5.4. *Stable isotope variations*

The $\delta^{13}C$ in the present time-series varies between −33 and −9‰ indicating significantly large range. Depleted values of about −33‰ are documented in the top layers (0–4 cm) while majority of the down-core vary between −16 and −24‰. The changes in $\delta^{13}C$ of sedimentary organic matter is attributed to the source i.e., allochthonous or autochthonous or both (Meyers and Lallier-Vergés, 1999; Meyers and Teranes, 2001), $\delta^{13}C$ of lake-water carbon used by phytoplankton and rate of primary productivity (Rau, 1978; Meyers and Ishiwatari, 1993; Laws et al., 1995). The values in the Long Lake is consistent with the $\delta^{13}C$ values for non-marine aquatic plants and algae (−26‰ to −12‰:Fry and Sherr, 1984; Farquhar et al., 1989). The depleted $\delta^{13}C$ recorded for the top 0–3 cm are typical of mosses (Skrzypek et al., 2007). Hence, it can be suggested that the Long Lake received terrestrial organic material during the latest Holocene due to prolonged ice-free conditions and increased melt-water which delivered terrestrial organic matter such as mosses into the lake. Though the annual productivity of Long Lake is very low, strong correlation between $\delta^{13}C$ and other proxies (C/N, % C_{org} and N %) supports the use of $\delta^{13}C$ as a proxy which can be reliably used. The records of $\delta^{13}C$ and $\delta^{15}N$ show opposite trends to each other for the majority of the down-core variation. During the glacial period, when the lake is under ice-cover conditions, the lake-to-atmosphere exchange is limited which would lead to oxygen-limited environment. Under such conditions, the aquatic organisms use dissolved nitrogen for synthesis and hence fractionate isotopically light nitrogen (^{14}N) resulting in deposition of heavy nitrogen (^{15}N) in the sediments. During the Holocene period, the aquatic organisms shift to atmospheric nitrogen which is reflected as lower $\delta^{15}N$ values (Talbot and Johannessen, 1992). Further, the bi-plot of C/N ratio *vs.* $\delta^{13}C$ shows that the organic matter analysed from the down-core variations predominantly falls in the freshwater algae zone (Fig. 8) indicating that the productivity in the lake is primarily autochthonous i.e., of aquatic origin.

5.5. *Grain size variations*

Sedimentation in Antarctic lakes is by (a) glacio-fluvial melt-water delivery of sediments during austral summer, (b) intense-wind (katabatic winds) transport coarse and fine particles which deposit on lake-ice that percolates through cracks in the lake-ice and get deposited on the lake-floor (Spaulding et al., 1997) and (c) movement of glaciers which transports rocks and soils that are lying underneath them. The sediments of Long Lake are predominantly composed of clayey sand and silty sand as seen in the ternary diagram (Fig. 9). Pearson correlation coefficient was performed on the organic matter and sedimentological data (Table 2) to understand the inter-relationship between these proxies. Sand is negatively correlated with silt ($r = -0.59$; $n = 46$; $p < 0.0001$) and clay ($r = -0.53$; $n = 46$, $p < 0.0002$). It also shows almost zero correlation with organic matter content ($r = -0.03$; $n = 46$, $p < 0.8396$). Percent silt shows a negative relationship with percent clay ($r = -0.22$; $n = 46$, $p < 0.1330$). Percent clay is positively correlated with organic matter ($r = 0.10$; $n = 46$, $p < 0.4989$), suggesting that the organic matter is residing in the clay fraction.

The variations in the sand content is marginal (50 ± 10%) from 48 to 8 cal ka BP (Fig. 3), suggesting that input velocity was low indicating that there was not much melting in the region. This perhaps gives an indication that the catchment of Long Lake had experienced colder climatic conditions during this period. The relatively higher sedimentation during the glacial period indicates deposition of coarse grained particles probably due to transportation of aeolian materials by high glacial (katabatic) wind which can move grains up to sand size (Doran et al., 2002). The wind-transported sediment gets trapped in and on the ice cover and pass through ice by a process of freezing and thawing along with gravitational settling (Squyres et al., 1991; Andersen et al., 1993). Higher silt percent along with sand percent during the glacial period indicates the contribution of wind-blown sediments into the lake system. The most likely source would be the strong westerlies during the glacial period carrying dust which was 20–50 times higher than during the Holocene and depositing over Antarctica as evident in the ice-core records (Lambert et al., 2008; Sugden et al., 2009). From 6 cal ka BP to present, there is a change in percentages of all the parameters. That is, the sand percentage increases indicating high velocity input by melt-water. This suggests warming conditions in the region due to which coarse-grained particles are transported from the catchment into the lake–basin by glacial melt-water. During this period, percent silt does not show much variations. However, percent clay shows a major change in its values indicating relatively warming conditions must have set in the Long Lake catchment after 6 cal ka BP, which continued into late-Holocene. However, the sand percent decreased from 1.5 ka BP to recent which would suggest recession of glacier and decreased input of glacial melt-water into the lake which is reflected as

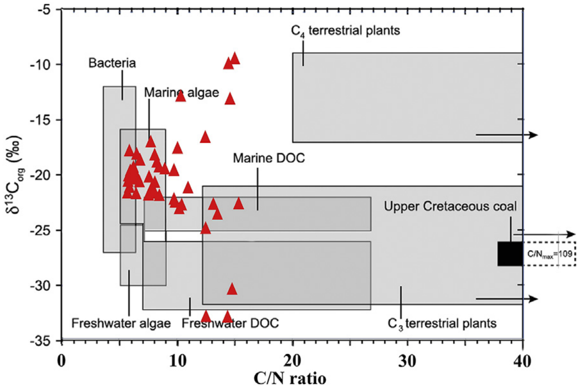

Fig. 8. Bi-plot for $\delta^{13}C$ and C/N ratios for the Long Lake sediment core. Figure modified after Hodgson et al. (2009a). The grey shaded data areas are based on data presented in Meyers and Teranes (2001); Leng and Marshall (2004): Lamb et al. (2006).

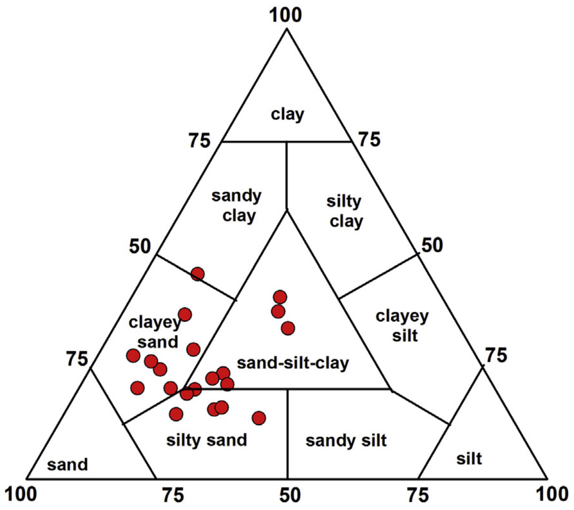

Fig. 9. Ternary diagram comparing the relative (%) sand-silt-clay grain size fractions for sediments from the Long Lake.

Table 2
Correlation coefficient matrix for organic matter and sedimentological data of Long Lake sediments given in weight percent from 1.5 ka BP ($n = 46$; statistical significant values at 95% shown in bold).

	Total organic matter	Sand	Silt	Clay
Total Organic Matter	1.00			
Sand	−0.03	1.00		
Silt	0.04	−0.59	1.00	
Clay	0.10	−0.53	−0.22	1.00

lowered sand content. The lake terraces or palaeo-shorelines (Bormann and Fritzsche, 1995; Phartiyal et al., 2011) suggests lowering of lake level which indicates the reduced delivery of fluvial load into the lake. This depositional pattern of sand is in coeval with the palaeo-shorelines (Bormann and Fritzsche, 1995) and deposition of sand and clay on the palaeo lake floor during the early Holocene (Phartiyal et al., 2011).

6. Conclusions

A detailed sedimentary organic geochemistry and particle size variation record from the Schirmacher Oasis spanning glacial-interglacial climate variations is presented in this study. The sediment core retrieved from the Long Lake of Schirmacher Oasis spans the last 48 cal ka BP reflects the lake's response to the Antarctic climate. The multi-proxy records (C_{org}, $\delta^{13}C$, C/N) give evidence that the organic carbon analysed from the lake is predominantly allochthonous. The last glacial and major part of Holocene records the lowest organic carbon indicating that the productivity has been generally lower suggesting longer ice-cover period due to extreme cold conditions. The sustained Holocene warm conditions would have resulted in the lake experiencing longer ice-free conditions beginning at 6 cal ka BP as evident in the grain size variation. The particle size variation in the lake system is primarily governed by a combination of input through ice-melt water and aeolian action. The higher sand content during the Holocene than the glacial period indicates the warming conditions.

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