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Review Article

Lake Sediment Studies in Ice-Free Regions of East Antarctica – An Indian Perspective

ANISH KUMAR WARRIER[1,#,*], B S MAHESH[1] and RAHUL MOHAN[1]

[1]*National Centre for Antarctic and Ocean Research, Earth System Science Organisation, Headland Sada, Vasco-da-Gama, Goa 403 804, India*

[#]*Present address: Department of Civil Engineering, Manipal Institute of Technology, Manipal University, Manipal 576 104, Karnataka, India*

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Antarctica plays a vital role in controlling Earth's climate. Recent data indicates that there are widespread changes in Antarctica, especially the Antarctic Peninsula due to global warming. Therefore collecting past climatic information from ice-cores, marine and lake sediments are extremely important as the data can be utilized in the available models to plausibly model the future climate for the region. Lake sediments are widely found in Schirmacher Oasis, Larsemann Hills and Vestfold Hills in East Antarctica. During the period 2010-2015, considerable amount of work has been done on surficial sediments, water samples from the sediment-water interface and sediment cores from lakes of these regions for different environmental applications, such as provenance, bacterial diversity and paleoclimatic studies. Techniques such as environmental magnetism, geochemistry (organic and inorganic), sedimentology, clay mineralogy, scanning electron microscopy and geochronology have been employed on these sediments to decipher the past climate and environmental changes on different time-scales and to understand the provenance of these sediments. Few paleoclimatic studies are limited to the Holocene whereas a couple of studies document glacial-interglacial climatic variations in Schirmacher Oasis. These studies have a much better chronological framework when compared to the earlier studies. However, there are still issues with the temporal resolution of the data when compared with ice-cores which offers much better sample resolution. It is therefore crucial that future studies on lake sediments from these regions be made on a high-resolution interval which will allow the researchers to have a good correlation with other archives such as ice-cores, etc.

Keywords: Lake Sediments; Ice-free Regions; Paleoclimate; Schirmacher Oasis; Larsemann Hills; Vestfold Hills; East Antarctica

Introduction

The continent of Antarctica plays a crucial role in controlling the Earth's climatic system. Hence, it is equally important to study how climate has evolved in Antarctica during the geological past. The past climatic data can be used to predict the climatic patterns in the future. Recent studies have shown that the western part of Antarctica has warmed up considerably during the last 50 years, especially the Antarctic Peninsula, when compared with its eastern counterpart (Steig *et al.*, 2009; Vaughan *et al.*, 2003). In order to place observed and predicted 21st century climate change in perspective, reliable and highly resolved paleoclimatic data from Antarctica is essential (Kaplan and Wolfe, 2006). Unlike the *tropical* and *temperate* regions, past climate reconstruction in Antarctica is restricted to ice-cores, marine and lake sediments.

It is well established that lakes are "*sentinels of change*". They are sensitive and respond rapidly to changes in climate, integrating information about these changes in their sediments. Lakes, which record a host of paleoenvironmental conditions in their sediments not only serve as archives for their past-history but also record past environmental conditions of its surrounding region (Smeltzer and Swain, 1985)

*Author for Correspondence: E-mail: akwarrier@gmail.com

and mechanisms of climate change. Lakes respond well to changes in environmental conditions such as seasonal temperature shifts, period of ice-free conditions, catchment runoff and input of glacial melt-water. These responses are reflected in the variation of sediment composition and associated proxy variables. The continent of Antarctica is bestowed with several ice-free regions namely, Larsemann Hills, Schirmacher Oasis, Bunger Hills, Vestfold Hills, etc. There are more than 100 lakes in Schirmacher Oasis and 150 lakes in Larsemann Hills which are classified into epishelf, pro-glacial and land-locked depending on their geomorphic characteristics (Ravindra, 2001). Similarly, Vestfold Hills contains more than 300 lakes which are either fresh or brackish depending on its proximity to the marine shoreline (Swadling *et al.*, 2001) According to Smol and Cumming (2000), the climatic information recorded in the sediments of these polar lakes offers tremendous potential in reconstructing the past climate and environmental changes.

India's early attempt on freshwater lakes in East Antarctica was in the austral summer of 1984-85 to describe the microfaunal component of freshwater habitats in Schirmacher Oasis (Ingole and Parulekar, 1993). Since then quite a few studies have been made on lake sediments from Schirmacher Oasis (Sharma *et al.*, 2007; Sharma *et al.*, 2000; Sinha *et al.*, 2000a; Sinha and Chatterjee, 2000) to decipher the past climate, long-distance transport of palynodebris and pollen (Bera, 2004; Sharma *et al.*, 2002) and presence of freshwater protozoans – *Arcellaceans* (Mathur *et al.*, 2006); Water samples from the lakes of Schirmacher Oasis have been utilized too for hydrogen and oxygen isotopic studies (Sinha *et al.*, 2000b); and quartz grains from surficial sediments of lakes in Larsemann Hills (Narayana *et al.*, 2010) and Schirmacher Oasis (Asthana and Chaturvedi, 1998) have also been studied to understand their provenance. In this paper, we have provided a review of work carried out in the three ice-free regions of East Antarctica (Fig. 1), namely Schirmacher Oasis, Larsemann Hills and Vestfold Hills since 2010-2011. The review is broadly based on work carried out on surficial sediments and sediment cores from the three regions.

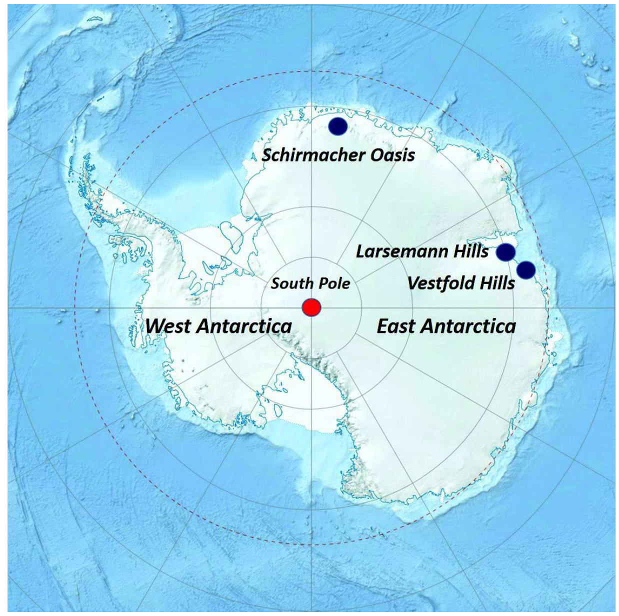

Fig. 1: General map of Antarctica showing the locations of Schirmacher Oasis, Larsemann Hills and Vestfold Hills

Studies on Surface Sediments and Sediment-Water Interface From Lakes

Table 1 provides a brief indication of the type of studies carried out on lake-bed sediments and water samples from sediment-water interface from lakes of Schirmacher Oasis and Larsemann Hills over the past few years. The techniques that have been employed on the surface sediments are sedimentology, geochemistry, scanning electron microscopic observations and clay mineralogy to understand the provenance of these sediments as well as the geological processes.

Srivastava *et al.* (2011) studied the clay mineralogical properties of glacial sediments found near the lakes of Schirmacher Oasis. The main aim of the study was to understand the origin of clay minerals in the sediments and decipher the paleoclimate. The clay content was separated from the sediment and studied for mineral identification using differential thermal analysis, thermogravimetric analysis and X-ray diffraction analysis. The results showed well-developed peaks of chlorite, illite, kaolinite, smectite and vermiculite. Most of the aforementioned clay minerals were formed due to weathering and alteration of igneous and metamorphic rocks of Schirmacher Oasis under cold climatic

Table 1. Details of studies made on surficial sediments from lakes of Schirmacher Oasis and Larsemann Hills

Sl.No.	Location	Studies made	Reference
1.	Schirmacher Oasis	Sedimentology, Mineralogy and Scanning Electron Microscopic observations of Quartz grains	Shrivastava *et al.* (2012)
2.	Schirmacher Oasis	Differential thermal analysis, Thermogravimetric analysis and X-ray diffraction analysis	Srivastava *et al.* (2011)
3.	Schirmacher Oasis	Geochemistry and Mineralogy	Srivastava *et al.* (2013)
4.	Schirmacher Oasis	Sedimentology	Srivastava *at al.* (2012)
5.	Schirmacher Oasis and Larsemann Hills	Sedimentology	Asthana *et al.* (2013)

conditions. Chlorite was formed due to the physical weathering of igneous and metamorphic rocks, whereas kaolinite - a product of chemical weathering of feldspar, was formed during relatively warmer climatic conditions. Smectite was interpreted to be of authigenic origin formed due to transformation of pyroxene, basalt and dolerite, whereas vermiculite was derived from the primary micas. The study provides good baseline data of clay minerals from the sediments of Schirmacher Oasis and can be ably used in studying the past climate.

In another study on surficial sediments, Shrivastava *et al.* (2012) investigated the sedimentological and mineralogical properties of surficial sediments from two epi-shelf lakes in Schirmacher Oasis. In addition, scanning electron microscopy observations were made on quartz grains from these sediments to evaluate the sedimentary provenance, modes of transport and weathering features. The study revealed that the quartz grains underwent different modes of physical weathering and chemical precipitation before they were deposited in these epi-shelf lakes as sediments. The sediments were mainly gneissic in composition as revealed by chemical analysis and saltation and suspension were believed to be the two dominant modes of transportation of the poorly sorted glaciofluvial sediments.

Srivastava e*t al*. (2012) made a detailed sedimentological investigation on sediment samples from different regions (polar ice, ice-free lakes, lakes and the coastal shelf area) in the Schirmacher Oasis. Basic stati-stical particle-size parameters like graphic mean, standard deviation, skewness and kurtosis were calculated for samples from the four locations. The results indicated that the Schirmacher Oasis is mainly characterized by glacial processes, including deposition and erosion of the sediments by glaciers, melt-water channels and winds, thus influencing the sediments in various ways. All the sediment samples were all poorly to very poorly sorted, fine-skewed to near-symmetrical and platykurtic to leptokurtic in nature.

Srivastava *et al.* (2013) also performed mineralogical and geochemical studies on glacial sediments collected from different locations in Schirmacher Oasis. Mineralogically, the sediments are predominantly made up of quartz and feldspar in higher proportion, and a large variety of heavy minerals: zircon, tourmaline, rutile, garnet, hornblende, hypersthene, enstatite, kyanite, sillimanite, andalusite, zoisite, lawsonite, chlorite, spinel, topaz, and opaques. The rare earth and trace elemental data relative enrichment in the coarse fraction as against fine fraction, indicating enrichment of heavy minerals in the coarse fraction. The sediments were mainly transported by melt-water streams and wind. However, transport under the influence of gravity and glacier action was also evident. The sediments underwent low degrees of chemical weathering (incipient to moderate) and the overall conclusion made through this study was that although there were minor differences amongst the sediments collected from different locations, they represented similar geochemical and mineralogical characteristics.

Asthana *et al.* (2013) studied the sedimentological properties of surface sediments from Schirmacher Oasis and Bharati Promontory, Larsemann Hills with an aim to understand the sedimentary and glacial processes taking place in the two regions. In addition to sedimentological data, scanning electron microscopic (SEM) observations on quartz grains were also made to strengthen the data. Field observations, sedimentological data and SEM of quartz grains from both the regions showed similar results. However, the extent and strength of glacial and glaciofluvial processes varied between the two regions. The field observations and SEM studies indicated that the effect of glaciers were quite prominent on quartz grains from Larsemann Hills, whereas, glaciofluvial activity played a dominant role in leaving its imprints on quartz grains from Schirmacher Oasis. The sedimentological data suggested that the sediments in both areas were poorly sorted and made up of pebble, sand, silt and minor clay fractions. Higher content of % sand was reported from both the regions. The silt + clay weight percentage was much less than that of sand in both the areas, which could have been removed by localized melting and fluvial action. A change in energy conditions was evident from the bimodal and polymodal distribution of sediments from both the study areas. The authors concluded that the periglacial environment of Schirmacher Oasis and Bharati Promontory, Larsemann Hills are characterized by a wide range of sedimentary and glacial processes, resulting in different combinations of erosional and depositional features.

In another study, Huang *et al.* (2013; 2010) characterised the bacterial diversity of water samples close to the sediment-water interface from Lake Tawani and Lake Untersee in Schirmacher Oasis. The objective of the study was to investigate the variety of bacteria present in the lakes of Schirmacher Oasis, especially those connected through surface channels and encompassed by valleys. The study would help in unraveling the dynamic nature of these unique seasonal, freshwater lakes, which potentially harbors highly adapted bacterial taxa with defined ecological functions. To this effect, the authors used culture-independent Bacterial Tag Encoded FLX Amplicon Pyrosequencing (bTEFAP), clone library construction, and culture-based analysis to target the eubacterial 16S rRNA gene. The results show the presence of around thirteen bacterial phyla and one-hundred and twelve genera. Bioinformatics analysis on the bTEFAP exhibited higher coverage of the bacterial composition in the waters of the Lake. When compared to other available methods, this method was able to detect different members of the phyla: *Chloroflexi*, *Gemmatimonadetes, Planctomycetes, Nitrospira*, and *Candidate Division TM7* due to the method's higher sensitivity. The authors finally propose the use of multiple approaches to identify more complete bacterial community rather than relying on any single technique.

Paleoclimate Reconstruction Using Lake Sediments and Paleo-Lake Deposits

Since 2010-2011, a number of studies have been made on lake sediments and paleo-lake deposits from Schirmacher Oasis, Larsemann Hills and Vestfold Hills to decipher the paleoclimate/paleoenvironment. A variety of techniques have been used for this purpose. For example, environmental magnetism, sedimentology, geochemistry, biogenic silica, diatoms etc. Table 2 provides details of paleoclimate studies (using various proxies) that have been carried out on sediment cores and paleo-lake deposits from the three regions.

Phartiyal *et al.* (2011) reconstructed the evolution history of Schirmacher Oasis from 13 cal ka B.P. to the Present by analyzing the magnetic susceptibility (MS) and loss-on-ignition (LOI) data for seven sediment profiles from five paleo-lake deposits. The LOI data suggested a very low organic content, whereas MS data helped in the reconstruction of changing detrital input. The presence of longer sediment profile (> 1 m thick) indicated the presence of five large lakes in the Schirmacher Oasis during the Holocene, which shrunk over a period of time leading to the occurrence of smaller lakes. The authors inferred that from 13 to 12.5 cal ka B.P., the whole of Schirmacher Oasis was dominated by glaciers with the present day land-locked lakes being the glacial lakes. The onset of Holocene warming at 11.5 cal ka B.P. led to the retreating of glaciers giving rise to five large proglacial lakes which occupied the low-lying valleys of Schirmacher Oasis. The drying of the landlocked lakes was attributed to several factors such as lack of water supply during summer months due to the recession of glaciers, reduced precipitation or snow accumulation, less melt-water streams, strong winds and sublimation of the lake due to prolonged ice-cover. On the other hand, the proglacial and the epishelf lakes continue to have a regular source of melt water from the continental ice sheet and the ice shelf, respectively. The authors inferred that although the clear cause of

Table 2. Details of paleoclimate studies made on sediment cores from lakes of Schirmacher Oasis, Larsemann Hills and Vestfold Hills

Sl.No.	Area of Study	Name of the Lake	Techniques used	Time-span	Reference
1.	Schirmacher Oasis	Paleo-lake deposits	Magnetic susceptibility, loss-on-ignition and geochronology	13 cal ka B.P. to the Present	Phartiyal *et al.*, 2011
2.		Paleo-lake deposits	Environmental magnetism, geochemistry and geochronology	13 cal ka B.P. to the Present	Phartiyal, 2014
3.		Sandy Lake	Environmental magnetism, geochronology, sedimentology and scanning electron microscopy of quartz grains	42.5 to 1.16 cal ka B.P.	Warrier *et al.*, 2014; Warrier *et al.*, 2016
4.		Long Lake (L-27)	Organic geochemistry, sedimentology and geochronology	48 cal ka B.P. to the Present	Mahesh *et al.*, 2015
5.		Lake L-6	Plant fossil	10.65 cal ka B.P.	Singh *et al.*, 2012
6.	Larsemann Hills	Lake L-2	Sedimentology, biogenic silica, total organic carbon and geochronology	8.3 cal ka B.P. to the Present	Govil *et al.*, 2011; Govil *et al.*, 2012
7	Vestfold Hills	CD-01 Lat: 68°37' 26.7''S; Long: 77°58'14.6''E	Diatoms and geochronology	6.5 to 2.5 cal ka B.P	Mazumder *et al.* 2013a; Mazumder *et al.* 2013b; Mazumder and Govil, 2013

the lowering of water levels for these palaeolakes was not known, they could still serve as an important source of information for Quaternary researchers.

There are very few studies from Schirmacher Oasis wherein lake sediments have shown the potential of recording climatic variations on glacial-interglacial timescales. By analyzing the environmental magnetic and geochemical properties of sedimentary deposits of Schirmacher Oasis, Phartiyal (2014) reconstructed the climatic conditions during the past 13 cal ka B.P. Higher values of magnetic concentration-dependent parameters correspond to colder periods and low values reflect comparatively warmer lacustrine phases. Multivariate cluster analysis of the paleoclimatic data enabled the author to trace six phases of climatic fluctuations between 13 and 3 cal ka B.P. According to the author, Schirmacher Oasis experienced a short phase of relatively warmer climatic conditions during 12.5 cal ka B.P. (Late Pleistocene), 11-8.7 cal ka B.P. (Early Holocene Optimum) and 4.4-3 cal ka B.P. (Mid-Holocene Hypsithermal). This observation was made due to the decreased values of magnetic concentration-dependent parameters. Several major elements (Fe, Rb, Zn, Mo, Co, Pb, Mn, Cu and As) were observed in the sediments in order of decreasing abundance.

Based on the environmental magnetic properties of sediments deposited in Sandy Lake, glacial-interglacial climatic variation was reconstructed for the past 42.5 cal. ka B.P. (Fig. 2; Warrier *et al.*, 2014). The magnetic minerals present in the sediments were not affected by the presence of authigenic greigite, bacterial and anthropogenic magnetite. The magnetic mineralogy was dominated by the presence of titanomagnetite as evident by scanning electron microscopic observations. Glacial periods were 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 were recorded during 40.78, 36.08, 34.51, 29.03 and, 28.02–21.45 cal. ka B.P. Relatively warm periods were 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. The Holocene period was 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. Many of the relatively warm and cold events discerned in this study were correlatable with other lake sediment and ice-core records from the Schirmacher Oasis and other ice-free areas in East Antarctica. This study

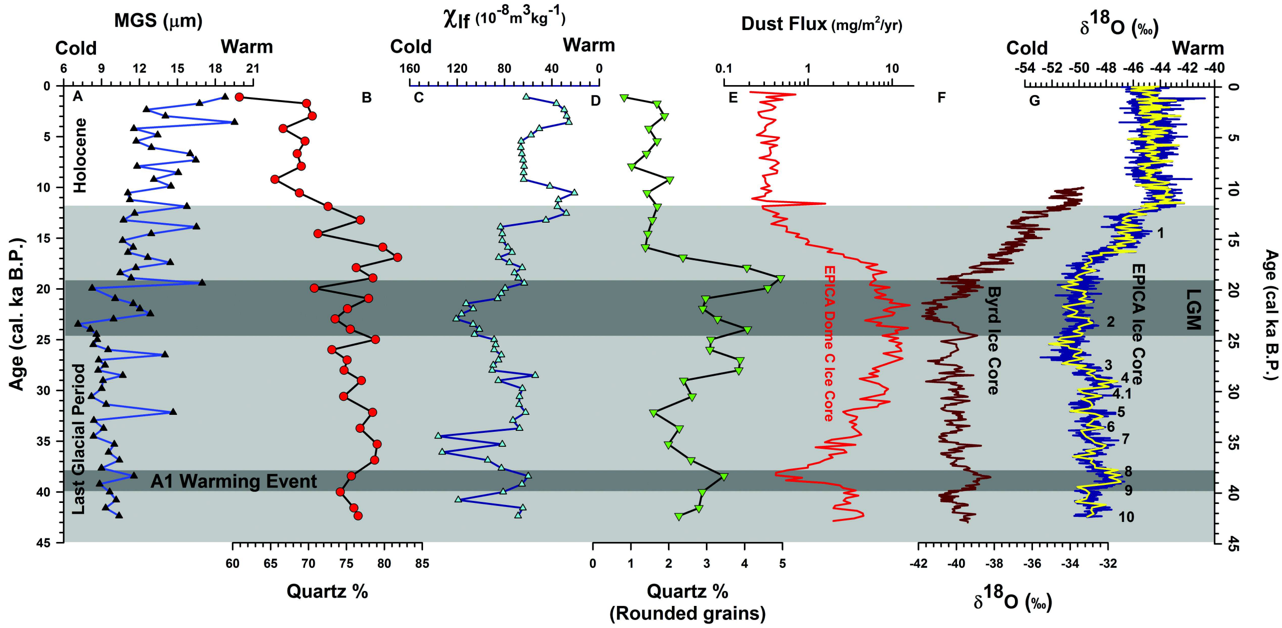

Fig. 2: Comparison of (A) mean grain size, (B) % quartz, (C) magnetic susceptibility $(\div_{lf})$, (D) % rounded quartz grains data of Sandy Lake sediments in Schirmacher Oasis (modified after Warrier *et al.*, 2014, 2016) with (E) dust flux (Lambert *et al.*, 2012) and oxygen isotopic data of ice-cores from (F) Byrd (Blunier and Brook, 2001) and (G) EDML (EPICA Community Members, 2006) station 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)

provided environmental magnetic evidence for the Schirmacher Oasis escaping full glaciation during the past 40,000 years. This was the first report of a detailed environmental magnetic record of glacial–interglacial climatic variations from the Schirmacher Oasis.

Sediment particle size and quartz grains deposited in the sediments of Sandy Lake were used to understand their provenance and also the strength of the transporting medium during the past 42.5 cal ka B.P. (Warrier *et al.*, 2016). The poorly sorted and finely skewed sediments showed different modes of grain size distribution throughout the last 43 cal ka B.P. The statistical parameters of grain size data (sorting, skewness, kurtosis, mean grain size, D_{10}, D_{50}, D_{90} and SPAN index) indicated that the sediments were primarily transported by melt-water streams and glaciers. During the last glacial period, wind activity was strong as evident by the good correlation between rounded quartz data and dust flux data from EPICA ice-core data. The mean grain size values were low during the last glacial period indicating colder climatic conditions and the values increased after the last glacial maximum (LGM) which suggested an increase in the energy of the transporting medium, i.e., melt-water streams. Scanning electron microscopic (SEM) studies of selected quartz grains and analyses of various surface textures indicated that glacigenic conditions must have prevailed at the time of their transport. Semi-quantitative analyses of mineral (quartz, feldspar, mica, garnet and rock fragments & other minerals) counts suggested a mixed population of minerals with quartz being the dominant mineral. Higher concentration of quartz grains over other minerals indicated that the sediments were compositionally mature. The study revealed the different types of physical weathering, erosive signatures, and chemical precipitation most of them characteristic of glacial environment which affected these quartz grains before final deposition as lake sediments.

Organic geochemical and sedimentological data from sediments deposited in Long Lake (L-27), Schirmacher Oasis, provide a history of glacial-interglacial climatic variations during the last 48 cal ka B.P. (Mahesh *et al.*, 2015). The multi-proxy record (C_{org}, $\delta^{13}C$, C/N) gives evidence that the organic carbon analyzed from the lake is predominantly allochthonous. The lowest values of organic carbon during the last glacial and major part of Holocene indicated that the productivity was 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 B.P. 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. The results show that 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.

Singh *et al.* (2012) reported the presence of *Pohlia nutans* – moss species in a sediment core from Lake L6 in Schirmacher Oasis. The authors reported a radiocarbon date of 10.65 cal ka B.P. for the sediment layer (160-162 cm) from where the moss species was obtained. The preserved Holocene sub-fossil moss included delicate leaves, axes and rhizoids and perfectly matched the extant specimen of *P. nutans.* This was the first record of this sub-fossil from the central Dronning Maud Land (cDML), although the species is one of the most commonly found as part of the present-day flora in other parts of Antarctica. The current moss distribution data will be useful in monitoring the changes in its population and diversity in the Schirmacher Oasis region and also be helpful in reconstructing the past climate and environmental changes.

Govil *et al.* (2011) reconstructed the Holocene paleoenvironmental conditions by analysing the biogenic silica, sand and organic carbon concentrations in a sediment core from Lake L2 situated in the Grovnes, Larsemann Hills. The 78 cm sediment core represented a time-span of ~8.3 cal ka BP. The sediment core showed higher productivity values from ~8.3 to ~6 cal. ka B.P. High % sand suggested that sediments were deposited due to glacio-fluvial activity during ~8.3 to ~5 cal. ka B.P. Total organic carbon showed little variation throughout the sediment core, except in the upper ~10 cm (~4 cal. ka B.P.) part wherein it is comparatively high. The increased TOC in the upper part of the core possibly indicated the presence of algal mats due to exposure of the lake to the ice-free conditions. The BSi showed positive correlation with sand content during ~8.3 to ~5 cal ka BP and negative correlation from ~ 5 cal ka B.P. to the Present which was attributed to the high and low ratio of $Al:SiO_2$ (Govil *et al.*, 2012).

Detailed study on diatom assemblage was carried out on sediments from an inland lake situated in Vestfold Hills, East Antarctica. AMS ^{14}C dates of the sediments of the lake extrapolate the time span of ~6500 to 2500 years BP. A total of thirteen diatom species were identified up to species level from the 47 cm length of the core. Eleven pennate forms (namely, *Achnanthes* aff. *Achnanthes groenlandica*, *A. taylorensis*, *Amphora ovalis*, *Cocconeis costata*, *Diploneis crabro*, *D. smithii*, *Fragilariopsis curta*, *F. ritscheri*, *Navicula directa*, *Navicula* sp. A and *Trachyneis aspera*) and two centric forms (namely, *Paralia sulcata* and *Thalassiosira anguste-lineata*) were identified. The variation of total diatom population and the abundance of salt crystal present in sediments suggest that the constant seawater influence (which was predominated in early Holocene) got weakened after ~5000 yrs BP till date (Mazumder *et al.* 2013a). Based on the abundance of icier condition indicator species *Fragilariopsis curta* along with other diatom assemblages (using unweighted pair group averaging method of Q-mode Cluster Analysis), it also can be concluded that Late Holocene experienced relative warmer climatic condition than its previous period (Mazumder *et al.* 2013b; Mazumder and Govil, 2013).

Scope for Future Work

A number of studies have been made on surface sediments and sediment cores from the three regions in East Antarctica. It can be seen that paleoclimate data obtained from sediment cores are quite little and also have a coarser temporal resolution with only a couple of studies extending back to glacial-interglacial timescale (~ 42.5 and ~ 48 cal ka B.P.; Warrier *et al.*, 2014, 2016; Mahesh *et al.*, 2015). It is therefore necessary that future studies on lake sediments from Schirmacher Oasis, Larsemann Hills and Vestfold Hills be carried out with a clear aim of obtaining the longest possible sediment cores from the different types of lakes i.e., epishelf, pro-glacial and land-locked lakes. Closer interval sampling must be carried out to obtain high-resolution paleoclimate/paleoenvironment data. The high-resolution data will allow the researchers to have a good correlation with other archives such as ice-cores etc. Apart from closer interval sampling, newer proxies such as biomarkers, fossil pigments, glycerol dialkyl glycerol tetraether (GDGT) lipids etc. may also be used for getting quantitative estimates of past temperature variations.

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