A Synthesis of Glacial-Interglacial Paleoenvironmental Records from Lake Sediments of Schirmacher Oasis, East Antarctica

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Abstract Antarctica plays a significant role in regulating the global climate, mainly due to its geographic position, characterized by the freezing climate and high albedo. Antarctica attributes this attribute amid several paleoclimatic questions ranging from global warming to Antarctic ice sheet melting associated with sea-level rise. Thus, reconstructing the Antarctic past-climate is of prime importance in understanding and modelling future climatic changes. Many lakes in Antarctica remained free from the continental ice sheet's influence during the last glacial maxima. Hence, their sedimentary archives are a repository of paleoclimatic evidence for the Late Quaternary. Paleoclimatic studies using lake sediments drew scientific attention due to their efficiency to record long, high-resolution climate records. Recent studies have employed multiple proxies like environmental magnetism, isotope geochemistry, petrography, sedimentology, and geochronology on lake sediments of Schirmacher Oasis to decipher the past climate and the prevailing ecological conditions. The existing studies poorly record climatic events such as the Mid-Holocene Hypsithermal and neoglacial cooling. Despite better chronometric control in these studies, coarse temporal resolution and sparsely documented finer-scale climatic variations place the need for future high resolution works in the East Antarctic region.

Keywords Lake sediments · Environment · Organic matter · Magnetic minerals · Late quaternary · East Antarctica

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1 Introduction

Antarctica's lakes, which dote the ice-free regions along the continental margin, are significant archives of past-climate records and the best source to monitor changes in modern climate that respond to the increasing global temperature. The Polar Regions are the first respondents of climate change. Due to their limited spatial entity, the lakes respond to subtle changes in the global weather system and act as good thermometers to measure human-induced climate change.

During recent decades, the global mean temperatures around the world have registered an increase. During the period January–October 2019, the global mean temperature was around 1.1 ± 0.1 °C above pre-industrial levels (1850–1900) (WMO Provisional Statement of the State of the Climate 2019). To forecast the future climatic scenario, we must have a fair understanding of the modern-day weather and study the past climate. This way, one can explore the interconnections that exist between these changes. The Southern Hemisphere, especially the Antarctic continent, plays a vital role in modulating the global climate during the present and the past. Antarctica is particularly crucial to the worldwide climate system due to its high albedo, low thermal conductivity, and contribution to deep ocean water circulation. Most of the global climatic signatures are also found pronounced in this continent due to its pristine conditions. Many important questions regarding the paleoclimate and environment of Antarctica are yet to be answered even though research in this area has flourished well in the last couple of decades (Verleyen et al. 2011).

A novel finding that many existing ice-free regions of Antarctica escaped the last glaciation (Gore et al. 2001) awaken paleoclimatologists' enthusiasm. These ice-free regions have numerous pristine lakes, the repository to sedimentary archives that offer high-resolution climate records and environmental changes. The Antarctic summer in these ice-free regions is generally warmer (above freezing point). The lakes become ice-free, responding well to local and regional climatic changes. These changes are preserved as additional biochemical and physical evidence (Govil et al. 2016). A varied number of techniques are used in past-climate reconstruction using lake sediments, viz. environmental magnetism, organic and inorganic geochemistry, quartz petrography, sedimentology, geochronology.

Schirmacher Oasis, one of the many ice-free regions, is a 25 km long and up to 3 km wide ice-free region on the Princess Astrid Coast in Queen Maud Land in East Antarctica is on average 100 m above sea level (Fig. 1). It has close to 118 lakes (proglacial, epi-shelf and periglacial lakes; Ravindra 2001). The majority of the lakes' surface remain ice-free during austral summer, and the ice cover rarely exceeds 2 m thickness (Hermichen et al. 1985). The lakes receive melt-water contributed by the snow and continental ice sheet. The sediments deposit into these lakes via fluvioglacial, in-situ productivity and aeolian activities ((Warrier et al. 2021a, b; Govil et al. 2016). Several of these lakes are found in rocks eroded by glaciers, and some are closed by moraines or ice (Bormann and Fritzsche 1995). The plant life of Schirmacher Oasis is limited to lichens and mosses, which thrive in rocky soils.

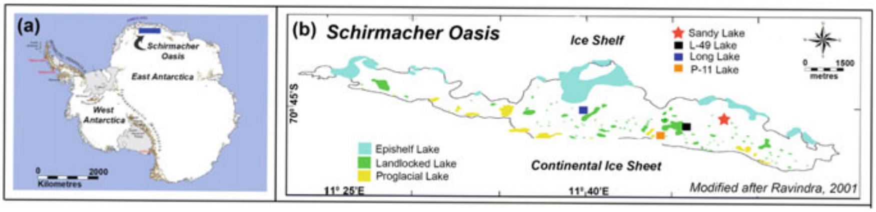

Fig. 1 **a** General map of Antarctica showing the location of Schirmacher Oasis. **b** Map of Schirmacher Oasis showing the distribution of epi-shelf lakes, periglacial (land-locked) lakes and proglacial lakes (modified after Ravindra 2001)

Over the last couple of decades, several paleoclimate records have been reconstructed using lacustrine sedimentary archives from various Antarctic lakes to understand local and regional climate. These records were often correlated with global climatic events and probed for their linkages and their processes. This chapter summarizes a review of past-climate records reconstructed from sediment cores from Schirmacher Oasis using different proxies.

2 Organic Geochemistry and Variations in Productivity

The sedimentary organic matter (OM) deposited in lakes acts as a source for elemental analysis (e.g. carbon, nitrogen, phosphorous) and stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) along with C/N ratios to understand the provenance of organic matter (Meyers 2003; Talbot 2001). These multi-proxy records help understand long-term climatic changes and evolution during the last glacial stage through deglaciation and Holocene. This approach will also help minimize bias in interpreting the measured data and ascertain OM's source and possible variations concerning climate-induced environmental changes.

The type and amount of sedimentary OM can be used to reflect past fluctuations in lake productivity and organic matter source perhaps linked to climate-forced environmental changes (Leng and Marshall 2004; Meyers 1997; Talbot and Johannessen 1992). The utility of the C/N ratio is well-studied to identify the source of organic matter in sediments (Meyers 2003; Talbot 2001). The relative proportion of aquatic versus terrestrial OM where phytoplankton and aquatic macrophytes exhibit C/N ratio between 6 and 12 while terrestrial derived OM, between 14 and 20 (Meyers 1994, 2003; Meyers and Teranes 2001). The $\delta^{13}C$ and $\delta^{15}N$ of bulk sedimentary OM is a good indicator of past environmental changes in lacustrine systems (e.g. Talbot and Johannessen 1992; Engel and Macko 1993), which forges a basis for further studies. When used in conjunction, they (C_{org}, C/N, $\delta^{13}C$ and $\delta^{15}N$) provide information on past-changes in (a) productivity (e.g. Hodell and Schelske 1998), (b) nutrients (Meyers 1997, 2003), (c) environmental variation (e.g., Meyers 2003; Talbot and Johannessen 1992) and supply of organic material (Hedges and Keil 1995).

Records based on sedimentary organic geochemical proxies have been published (Mahesh et al. 2015, 2017, 2019) for Schirmacher Oasis from three different lakes viz., Sandy Lake, Long Lake and Zub Lake, respectively. The sediment cores (<1 m in length) span the last 36–43 kyr spanning the Last Glacial Maxima. These records provide overall productivity and provenance patterns over glacial-interglacial timescale and the lakes' response to the local and regional climate (Fig. 2). The organic matter in high-latitude (Antarctic) lakes widely varies from that of low-latitude lakes, wherein the former is dominated by aquatic macrophytes (autochthonous: cyanobacterial algal mats) and terrestrial bryophytes (allochthonous: lichens and moss). In the modern period, i.e., Holocene, algae flourish (diminish) during periods of ice-free (ice-cover) conditions, i.e., during Austral summer (winter) owing to sustained warm (cold) conditions. During the Holocene summer, the temperature is warm enough to melt the lake cover rendering them ice-free for 3–5 months. The melting facilitates increased productivity in the lake through algae production. However, productivity is hindered when the lake surface is covered with ice as there is no exchange of gases with the atmosphere and the limitation of sunlight. The sedimentary organic matter in Schirmacher Oasis shows, in general, less than 1% during the glacial stage, indicating prolonged and intense winter and mild summer, which would have led to the existence of ice-cover for a more extended period. This would have hindered any exchange of gases between the lake and the atmosphere limiting sunlight and extremely low productivity within the lake. The ice-cover would also have restricted the influx of sediments either from melt-water or wind-blown.

Interestingly, SO does not record higher productivity at the beginning of Antarctic deglaciation (~ 17 cal ka BP: Petit et al. 1999). The ice-cover conditions continued

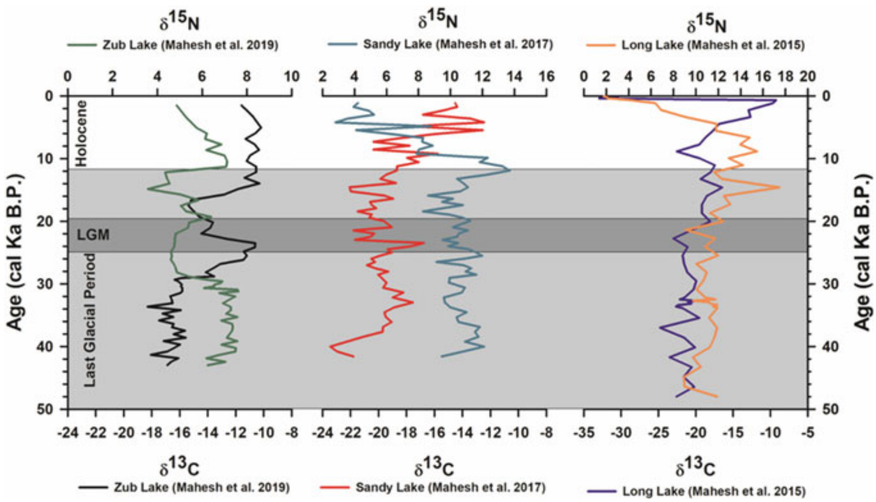

Fig. 2 A comparison of down-core variations of $\delta^{13}C$ and $\delta^{15}N$ for Zub (L-49) Lake, Sandy Lake and Long Lake sediment cores from Schirmacher Oasis

to persist through deglaciation in all three lakes indicating cold summer conditions, i.e., sub-zero conditions. The $\delta^{13}C$ values for non-marine aquatic plants and algae are between −26‰ to −12‰ (Fry and Sherr 1989; Farquhar et al. 1989), while for terrestrial plants, it varies between −24 and −32‰ (Trumbore and Druffel 1995). The $\delta^{15}N$ values of terrestrial plants which use atmospheric N_2 are lower (0‰) as compared to the nitrate incorporating algae ($\delta^{15}N$ values of 7–10‰: Peters et al. 1978).

However, the Holocene's productivity in these three lakes widely varies even though they are spatially within the same oasis. The Long Lake records an increase in C_{org}% (1.2%) only in the core-top (0–3 cm). In comparison, Sandy Lake shows an increase in C_{org}% at the beginning of the Holocene. The Zub Lake offers increasing productivity (C_{org}%: 1–7%) beginning at 18 cal ka BP and attains Holocene optimum conditions at ~11 cal ka BP. Such contrasting variation in C_{org}% suggests the response of these lakes to climate. Under current conditions, it can be noted that the Sandy Lake and Long Lake (periglacial lakes) are located significantly farther from the continental ice sheet and are very unlikely to receive melt-water from the ice-sheet. At the same time, Zub Lake is connected with numerous lakes along the continental ice-sheet edge and gets a significantly large amount of melt-water from the other lakes fed by the melting ice-sheets. Hence, factors such as the lake's proximity to the ice-sheet or the ice-shelf play a significant role in the lake ecosystem. The nitrogen content (N%) also shows similar variations to that of the C_{org}%, suggesting no selective loss of both carbon and nitrogen with time (Talbot and Johannessen 1992).

The C/N ratios (<10) for all the three sedimentary records indicate that the source of organic matter during the glacial stage is autochthonous. In contrast, the Holocene records higher C/N ratios (>10), suggesting an admixture of aquatic macrophytes and terrestrial bryophytes. The input of terrestrial organic matter would be possible when the lakes are ice-free. The information on terrestrial organic matter from the catchment area is aided by fluvial input from the snow and ice-sheet melt-water. Higher C/N ratios throughout the Holocene suggests steady warmer conditions in the Schirmacher Oasis. The provenance of the organic matter can be further understood by studying the bi-plots of C/N rates vs $\delta^{13}C$ values (Mahesh et al. 2015, 2017, 2019). The bi-plots from these three records distinctly indicates that the organic matter is sourced from both aquatic macrophytes (bacteria and freshwater algae: autochthonous) and terrestrial bryophytes (lichens and moss: allochthonous).

The down-core $\delta^{13}C$ values in these lakes vary between −10 and −24‰ (Fig. 2). The glacial stage records depleted values (~−16 ± 4‰). This is most likely due to the utilization of CO_2 by aquatic organisms resulting in a deposition of ^{13}C-poor organic matter in the sediments (Meyers and Terranes 2001). The terrestrial input matter can also result in depleted values, but this is very unlikely as the $\delta^{15}N$ values have recorded enriched values indicating the predominance of aquatic organisms during the same period. Low productivity under consistently ice-covered lake surface during the cold glacial period is documented in these lakes. Enriched values during the Holocene indicates a shift in the balance of supply/demand on DIC with possible enhanced contribution from the terrestrial OM and hence suggest a dominance of in-situ productivity.

The $\delta^{15}N$ values are enriched during the glacial stage for the lakes in Schirmacher Oasis. Prolonged enrichment of $\delta^{15}N$ values during the glacial phase suggest that the lake was ice-covered, limiting lake-to-atmosphere exchange of gases leading to low productivity. Such common productivity conditions have been recorded in sub-glacial lakes (Smith et al. 2006; Hodgson et al. 2009). Sustained enrichment of $\delta^{15}N$ values generally reflects ammonification and denitrification/nitrification, which occurs under ice-cover and mineralization of organic matter by sedimentary and suspended bacteria (Talbot 2001; Meyers and Teranes 2001). The $\delta^{15}N$ values exhibit depleted values during the Holocene. This shift in $\delta^{15}N$ values from enriched (glacial stage) to exhausted (Holocene) values in the sedimentary record suggest a change of lake environment from an oxygen-depleted (ice-cover) to an oxygen-rich (ice-free) condition. In summary, the sedimentary organic proxies (C_{org}%, N%, $\delta^{13}C$, $\delta^{15}N$ and C/N ratios) have been well utilized to understand the climate trends by reconstructing the productivity trends provenance in the lake ecosystem.

3 Grain Size Variation and Climate Change

The input of terrestrial derived erosional products to the lake system helps understand the transferring agent's energy, which depends on the climatic conditions that prevail in Antarctica. The input of erosional products is predominant in the austral summer (Simmons et al. 1986), indicating the significant role of melt-water in transporting to the lake (Mora et al. 1994; Retelle and Child 1996; Spaulding et al. 1997). Westerlies-borne aeolian dust from mid-latitude deserts also contributes to erosional products to the lakes (Sugden et al. 2009; Petit et al. 1990) along with dust deposited by the wind from the surrounding area. The glacier action also contributes to the lake sedimentary deposits (Squyres et al. 1991; Hendy et al. 2000).

The sand-clay-silt content measured for the three lakes provides an overview of the depositional pattern of terrigenous sediments in Schirmacher Oasis over the glacial-interglacial stage. The down-core variations for the three lakes show sand dominance (Fig. 3), followed by silt and clay. The content of sand is lower during the glacial stage, while silt content is higher. The increased contribution of mud to the lake during the glacial phase suggest enhanced wind delivered detritus to the lake. During the warm Holocene period, more increased sedimentation is primarily due to enhanced sediment load delivery to the lake through increased frozen/snow melt-water to an open lake. Warmer summer resulting in higher melt-water (high energy) would bring in coarser sediments into the lake. In comparison, a milder summer would lead to low melt-water (low power) with deposition of clayey particles.

Even though the sediment records' resolution is low (200–600 years), major climatic events such as Antarctic Cold Reversal, Antarctic Warming Event and Antarctic Isotope Maxima were recorded in the down-core variations of the proxy records. This suggests that the climate in Schirmacher Oasis responded well to the

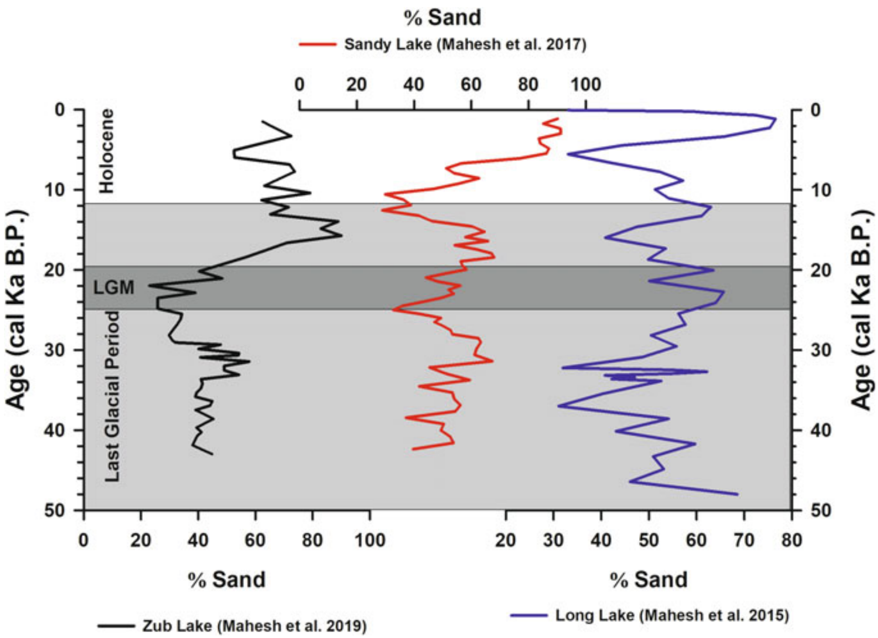

Fig. 3 Down-core variations of sand content in the sediment cores of Zub (L-49) Lake, Sandy Lake and Long Lake, Schirmacher Oasis

general Antarctic climate. The beginning of deglaciation and attainment of Holocene optimum is inconsistent between the lake records suggesting that regional factors such as the geomorphology plays an essential role in influencing the lake ecosystem.

4 Magnetic Mineral Records of Glacial-Interglacial Climatic Changes

Iron oxide minerals are omnipresent and can be effectively used to reconstruct past variations in the environment (Evans and Heller 2003). The environmental magnetic method deals with the systematic study of concentration, grain size and mineralogy of magnetic minerals present in soils and sediments (Walden et al. 1999; Thompson and Oldfield 1986). These minerals, which may be formed, carried away and deposited in different deposition basins, can be accurately studied using environmental magnetism. These iron oxides exhibit specific properties under a particular climatic phase, such as abundance, grain size, and mineralogy. However, as the climate changes, these properties also vary. Sediments deposited in the lakes and oceans record this signal through temporal variations in the concentration, grain size, and iron oxide carriers' mineralogy. Due to its several advantages (like rapid measurements, sensitive, inexpensive, non-destructive), an environmental magnetic technique has found applications in different facets of earth sciences like paleoclimate/paleoceanography (Sandeep et al. 2015), archaeology (Warrier et al. 2011), environmental pollution (Warrier et al. 2014a), soil genesis and erosion (Sandeep et al. 2012).

A couple of models can be used to explore the potential of using environmental magnetic parameters as a proxy to reconstruct the paleoenvironmental conditions. The first model is applied chiefly to the tropical regions' sediments and is explained by Warrier et al. (2014b). In the second model, high (low) values of magnetic susceptibility (X_{lf}) generally represent colder (relatively warmer) climatic conditions. The more callous climatic regime is also supported by coarse (somewhat more nuanced) magnetic grains, which indicates colder (relatively warmer) climatic conditions. The crude lithogenic magnetic minerals are mainly derived due to the mechanical weathering of the rocks present in the lake catchment (Reynolds and King 1995). They could be easily transported from the catchment into the lake basin by the movement of glaciers or by melt-water streams and winds (Li et al. 2006). The cracks that develop on the lake-ice are suitable hosts for wind-transported sediments that fall on to the lake ice's surface. When the ice melts, these wind-transported materials fall through the lake waters and get mixed with the lake sediments (Spaulding et al. 1997). A few studies have been made on the lake sediments of Schirmacher Oasis by using environmental magnetic techniques.

Warrier et al. (2014b) reconstructed the paleoenvironmental conditions in the Schirmacher Oasis on glacial-interglacial timescales (past 43,000 cal years BP) They studied the abundance, grain size, and mineral assemblage of the iron oxide minerals present in Sandy Lake's sediments and reconstructed periods of relatively warm and icy climatic conditions. During the glacial period, frost weathering gave rise to catchment-derived, primary, coarse grains of ferrimagnetic minerals later deposited within the lake sediments. These coarse-grained ferrimagnets' presence was evident by the increased values of X_{lf} (Fig. 4) and reduced X_{ARM}/X_{lf}. During the interglacial period, a relatively warm and wet climate accelerated the catchment rocks' chemical weathering, leading to enhanced soil formation. The environmental magnetic parameters showed an opposite trend when compared to the glacial period. From 42.5 to 11.86 cal ka BP., the glacial period was recorded within the Schirmacher Oasis, which alternated between exceedingly colder (40.78, 36.08, 34.51, 29.03, 28.02–21.45 cal ka BP) and relatively warmer climates (38.44–39.22, 33.73–29.81 and 28.52 cal ka BP; Fig. 4). Deglaciation commenced at about 20 cal Ka BP followed by the early Holocene optimum at around 12.55 cal Ka BP. In the Holocene, alternating warm (12.55–9.88, 4.21–2 cal ka BP) and cold events (9.21–4.21 cal ka BP and from 2 cal ka BP onwards) were also observed. Most of these out and warm phases showed a broad correlation with significant climatic events seen in lake-sediment records and ice-core records from different East Antarctica regions (Fig. 4). However, circumstances such as the Medieval Warm Period and the Little Ice Age were absent due to the core-top loss during coring operation. Phartiyal et al. (2011) reconstructed the climate history for the past ~13 ka of the Schirmacher Oasis based on the analysis of magnetic concentration, mineralogy and grain-size dependent parameters. The

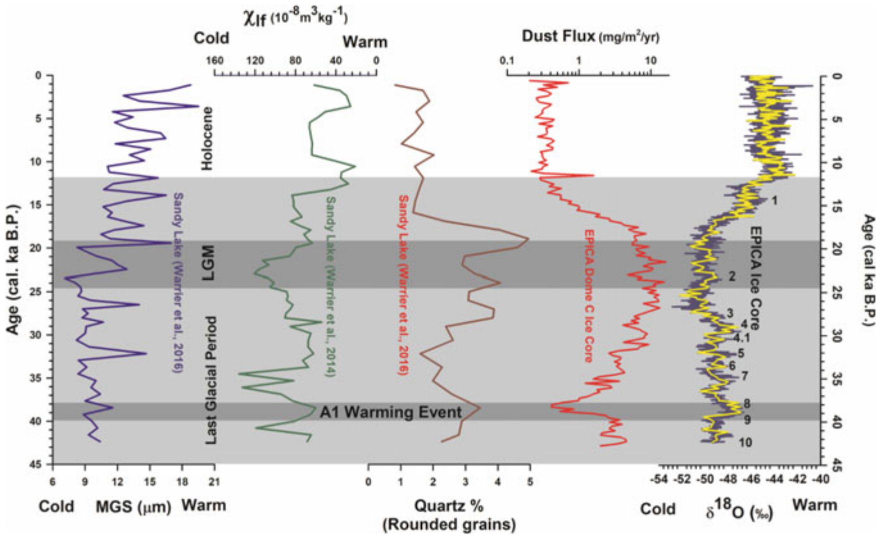

Fig. 4 A comparison of multi-proxy data like mean grain size, magnetic susceptibility, rounder quartz grains (%) of Sandy Lake with dust (Lambert et al.2012) and oxygen isotopic data (EPICA Community Members 2006) of EPICA ice core. The A1 event is one of the seven warming events during the past 90 cal ka BP documented from Antarctica (Blunier and Brook 2001)

study reported that colder periods recorded higher magnetic concentration-dependent values and relatively warmer periods show reduced values. Based on multivariate cluster analysis, the paleoclimate record (13–3 ka BP) of the Schirmacher Oasis was divided into six phases. The periods 12.5 ka BP (late Pleistocene), 11–8.7 ka BP (Holocene Optimum) and 4.4–3 ka BP (Mid-Holocene Hypsithermal) represented phases of warmer climatic conditions. Higher values of magnetic mineral concentrations (X_{lf}, SIRM) were observed for colder glacial periods and lower values for warmer interglacial periods (Phartiyal 2014). The studies show that environmental magnetic techniques can be successfully used to reconstruct the past variations in the climate and the associated changes in the lake catchment that bring about a difference in the magnetic concentration, grain size and mineralogy.

5 Petrographic Studies

Detrital minerals such as quartz, feldspar, mica, garnet have been successfully used to reconstruct the past climate in the polar regions as they are mainly derived from physical weathering (Pistolato et al. 2006; Chamley 1989). According to Bowen's reaction series, quartz (SiO_2) is the last mineral to crystallize at lower temperatures. Due to this, it is very stable and found in greater abundance in all the rock types. Due to its hardness (7 according to Moh's scale), it is a mechanically and chemically resistant mineral. Therefore, it has higher chances of getting preserved in the sediments (Krinsley and Doornkamp 1973; Mahaney 1995, 2002). Surface texture observations can also be made on the quartz grains that will reveal the type of transportation and deposition environment the mineral was subjected to in the previous sediment cycle. Surface microtextures, degree of angularity, chemical features, and grain-size analysis of quartz grains collectively reveal the sedimentary and physicochemical processes that acted on the grains during different geological phases.

The quartz grains present in the sediments may be transported by melt-water streams from the snow's melting in the catchment or may also be picked up by strong winds and transported to different regions. Besides, biogenic silica may also form a part of the sediments due to silica microfossils' burial like diatoms (Stanley and DeDeckker 2002). Several works have been published in recent decades, highlighting the significance of scanning electron microscopic (SEM) observations of quartz grains. These studies have established that quartz grains affected by different geological processes exhibit distinct grain surface features and micro-textural characteristics (Helland and Holmes 1997; Mahaney 1995; Strand et al. 2003). Although several studies have been made on quartz grains in Schirmacher Oasis, they are primarily on surface sediments and soils. Only a couple of studies have been reported from Schirmacher Oasis wherein the quartz grains deposited in the lake sediment cores have been used to perceive the modes of transportation, weathering processes, sediment maturity and its relation to regional climate (Warrier et al. 2016). Statistical parameters of particle size data indicated a fluvioglacial deposition of sediments.

Despite the coarse resolution of rounded quartz data, a significant correlation between the round quartz data and the high-resolution dust-flux data of EPICA ice-core suggested a peak in aeolian transport sediments during the Last Glacial Period (LGP) (Fig. 4). The low value of mean grain size of deposits from the LGP (colder climate) showed an increasing trend after the LGM corresponding to increased energy of transporting agent (melt-water streams) and temperature. The mean grain size of sediments showed peaks at 38 and 32 cal ka BP when warmer climatic conditions prevailed, which might have corresponded to the Antarctic Warming Event A1 (Fig. 4). The Holocene epoch was characterized by alternating periods of more or less warm and cold climate as evidenced by a cyclic variability of mean grain size of sediments. Mazumder et al. (2017) studied the quartz petrography and sedimentological analysis on a sediment core from a proglacial lake (P 11) in Schirmacher Oasis. The microtextural and morphological observations of quartz grains revealed a combination of the glacial, aeolian and fluvioglacial mode of transport in the study area. Three prominent climatic zones were identified from the study in the period spanning from 13.9 to 3.3 ka BP alternating between relatively warmer and colder phases.

6 Scope for Future Work

Several studies have been made on lake sediments from the Schirmacher Oasis to reconstruct the paleoclimate and the paleoenvironmental changes recorded in the region. However, only a few of them report the environmental variations on glacial-interglacial timescales. Many of these studies are based on a coarse temporal resolution and, as a result, do no record the finer scale climatic variations. Events like the Mid Holocene Hypsithermal and neoglacial cooling are poorly represented in the current studies. Future coring operations should be carried out to obtain the longest possible sediment cores to get a detailed paleoclimate record of the SO. Higher resolution studies will allow us to better constrain the small scale climatic fluctuations and correlate with other archives such as ice-core records that produce high-resolution climate data.

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