A Review of the paleoclimatic Studies from Lake Sediments of Schirmacher Oasis, East Antarctica

Pawan Govil and Abhijit Mazumder

Abstract Paleoclimate of Antarctica has remained a prime subject of study throughout the past half of the last century to understand the global perspective of temperature variability during the late Quaternary. Of the few restricted rocky regions within the Antarctica ice sheet, Schirmarcher Oasis attracts scientific workers for its immense potential for paleoclimatic studies because of several lakes within this area and the different meltwater sources feeding these lakes. Major paleoclimatic/paleoenvironmental studies from this region reveal several episodes of alternating warm-cold events during Holocene and even beyond, based on a large number of various proxies, mainly biological, geochemical and sedimentological parameters. The morphological evolution of the lakes and paleoclimatic reconstruction of the Schirmacher Oasis has been deciphered based on these data. These works collectively offer enormous scope to explore further the high resolution paleoclimatic/paleoenvironmental work of Schirmacher Oasis.

Keywords Schirmacher oasis · East Antarctica · Dronning maud land · Paleoclimate

1 Introduction

Antarctica and its surrounding Ocean are crucial in regulating the earths' climate system. The climate system of the earth is a complex system in view of the exchange of heat between the atmosphere and Ocean in effect of the oceanic current systems and trade winds (Massom et al. 2010). The oceanic currents, trade winds, snow cover, vegetation etc. affect the climate system and vice versa. Antarctica contributes around 90% of the world's freshwater due to its ice-sheets. It also plays a crucial role in the high southern latitudes' radiative forcing and is one of the major driving components for the circulation systems (Turner et al. 2009).

P. Govil (✉) · A. Mazumder
Birbal Sahni Institute of Palaeosciences, Lucknow, UP 226007, India

The climate system of Antarctica as well as surrounding Southern Ocean waters form due to the interaction of the ice sheets, oceanic circulation, sea ice extent, and atmospheric circulation, which altogether respond in the past and present climate forcing (Mayewski et al. 2009). Antarctic region acts as the Southern Hemisphere atmospheric heat sink, which is critical for both the air and sea-surface temperatures. The floating ice, which calves from ice shelves near the Antarctic coastal regions and also sea-ice are the main contributor to climate change. Taken together, both the oceanic and atmospheric mechanisms are connected for the climate system (Bargagli 2005).

The anthropogenic activities in the Antarctic region are least thereby Antarctic pristine is the best for deciphering the natural (un-biased) climatic changes in the past. Such changes are helpful for understanding how biotic components were affected by climate and how the permanent glaciers retreated or advanced in Antarctica along with how it affects the climate change of the earth. The past climatic changes of Antarctica are reconstructed using long ice-cores to better understand the air temperature changes in the polar region (Jouzel et al. 1989, 2007). Although ice-core records presented long-term glacial-interglacial climatic variability, ice core studies' within the Holocene from East Antarctica's coastal areas has not delivers much promising results. Also, the minor variations in isotopic results suggest less climatic variations and therefore needs to be resolved. The inland records from Antarctic regions were collected mostly from the inshore sites (Bromwich et al. 1998; Verleyen et al. 2011), and a also from the high central plateau (Masson et al. 2000). The ice cores from the coastal areas of Antarctica helped reconstructing the dynamic nature of the ice sheet at a higher resolution (Hodgson et al. 2005). It transforms lake and coastal marine sediment into valuable archives for the paleoclimatic study. Therefore, lake sediments are best suite of collections for targeting the Holocene climatic variability by using different proxies. Moreover, the Pleistocene-Holocene boundary in East Antarctic sediments recorded the data to exhibit the deglaciation initiation after the Last Glacial Maximum (LGM) in the coastline areas (CLIMAP 1981; Huybrechts 1990; Hughes 1998), making lakes present in those regions favourable sites for paleoclimatic studies.

The present chapter reviews all the literature that addresses paleoclimatic studies over the Pleistocene and Holocene in the Schirmacher Oasis region. However, paleoclimatic interpretations, specifically in Antarctica, are greatly influenced by the location, geology, geomorphology, and glaciology of the sampling location. Thus, a brief on these have also been included in the chapter.

2   The Geographical Extent of Schirmacher Oasis

The Schirmacher Oasis (SO) (70°44′21″–70°46′04″ S to 11°26′03″–11°49′54″ E) is an ice-free vast plateau along the Princess Astrid Coast in Dronning Maud Land, East Antarctica (Fig. 1), which has around 118 freshwater lakes. These lakes are characterized as epishelf, land-locked, and pro-glacial types. The oasis is mainly

situated between the Antarctic Ice Sheet and the NovolazarevskayaNivl Ice Shelf. As SO is a part of Central Dronning Maud Land in eastern Antarctica, it is a rocky terrain of about 17 km long and around 0.7–3.3 km wide. The vertical elevation of the area varies between 0 and 228 m above the mean sea level. Topographically, SO comprises four distinct units, namely, the southern continental ice sheet, rocky hill slopes, a vast central pro-glacial lake, and northern undulatory shelf ice.

3 Geology

The Schirmacher Oasis, Queen Maud Land, a part of the east Antarctic Precambrian shield, is composed of Precambrian polymetamorphic gneisses. The main rock types of this area are charnockites, underbites, garnet-sillimanite gneisses, garnet-biotite gneisses, quartzofeldspathicaugen gneisses including some foliated lamprophyres, amphibolites, dolerite, metagabbro, and metabasalt. The gneisses show mylonitization, polyphase deformation and have undergone upper amphibolite to granulite facies metamorphism (Sengupta 1988). The ages of these gneisses range from 460 to 845 Ma (Grew and Manton 1983; Ravich and Krylov 1964; Kampf and Stackebrandt 1985). The gneissic basement is intruded by pegmatites basic sills, lamprophyres, gabbro, dolerite and basaltic dykes (Sheraton and England 1980; Shiraishi et al. 1988). Lamprophyres dykes in Schirmacher Oasis are 1 km in length and 10–15 m in width, trending NW-SE. These are coarse-grained, having a panidiomorphic texture with phlogopite and pyroxene phenocrysts in a groundmass of K-feldspar, diopside, amphibole, quartz, plagioclase, appetite, and calcite. Based on the mineralogy, lamprophyres are classified as Minette. Lamprophyres dykes intrude on the late Proterozoic metamorphic terrain of Schirmacher Oasis. The study also reveals that the main fault is situated in the north-east corner, intersecting the geomorphological units, namely, shelf ice, rocks, and continental ice sheet. Several lamprophyre dykes of calc-alkaline (shoshonitic) nature are reported from Schirmacher Oasis, Queen Maud Land, in Eastern Antarctica. These dykes are characterized by high K_2O/Na_2O (avg. 5.81) ratios, high Rb, Sr, Zr, and Th abundances. REE distribution patterns show significant enrichment of LREE against HREE (avg. $La_n/Yb_n =$ 27.51) without any Eu anomaly. It appears that these ultrapotassic dykes have been derived from partial melting of a thickened lithosphere (Jafri 1997). The studies from Sangewar (1987) recorded the surface features and temporal changes in different Antarctic ice types and carried out glacial-geomorphological studies in Schirmacher Oasis. Geological studies were also carried out, which revealed the existence of olivine basalt, hornfels, pyroxenite, and skarn rocks in the Skaly IGA nunatak area.

The rock units predominantly represent Grenvillean (1000 Ma), and Pan-African (550 Ma) events. Rb-Sr whole-rock/mineral isochrone ages of two lamprophyres dykes are 450 ± 12 Ma ($Sr_i = 0.70886 \pm 5$) and 458 ± 6 Ma ($Sr_i = 0.71388 \pm 98$). This Lamprophyres dyke's Schirmacher Oasis activity may be interpreted as an appearance of post-orogenic alkaline magmatism related to the Ross orogeny

of the Trans-Antarctic Mountains (Dayal and Hussain 1997). The whole-rock Rb-Sr isochron age of 514 ± 59 Ma has been obtained for granites from the Nordevestoya area, Humboldt Mountains (Ravindra and Pandit 2000). The minettes were found to be abundant with the compatible elements as well as high mg values (58–75), which indicates that these rocks' petrogenesis is mainly derived from mantle (Hoch and Tobschall 1998). The higher values of incompatible elements, especially LREE, and Ba, Rb, K, Sr were also found. The Chondrite-normalized REEs' distribution patterns exhibit differentiated enrichments and high concentration in the LREE (240–530 × chondrite) in comparison to low and nearly stable enrichments of the La/Yb-ratios from 28 to 52 and HREE (11–15 × chondrite). The samples also show higher 87 Sr/86 Sr (0.70775–0.71337) and low 143 Nd/144 Nd (0.51229–0.51135) with εNd = -6.5 to −21.5. It shows 207 Pb/204 Pb ranging between 15.46–15.57 together with high 208 Pb/204 Pb (38.06–39.79) and unradiogenic 206 Pb/204 Pb (16.77–18.08). Rb/Sr-dating yields two different age groups of the time (430 and 703 Ma) of intrusion of the lamprophyre dikes.

Joshi (1997) delineated tectonic features of Schirmacher Oasis using total field geomagnetic suggests that the exposed rocks have little magnetic contrast. The exposed rock has undergone multiple episodes of metamorphism, migmatization, and deformation. However, nine profiles were obtained crossing different geological units, which was subjected to identify the faults and shear zones by Bormann et al. (1986) from the photogeological map. It is observed that the rock type gradation varies from east to west. The same banded and leucocratic rocks show different magnetic characteristics in Central Schirmacher Oasis for that in the eastern region. The absence of foliation in the banded gneiss in Central Schirmacher Oasis has been observed.

Scheinert (2001) investigated geodynamic phenomena in Schirmacher Oasis using a variety of geodetic observation techniques. Satellite-based techniques (Interferometric SAR) were combined with terrestrial methods (for instance, surveying, static, and kinematic GPS) for inferring the ice dynamics, especially the horizontal velocity field of the inland ice and the dynamics of the shelf ice. GPS epoch observations were used to describe the ocean, ice, and solid earth dynamics and interactions. New gravity field data of the planet, and investigation of ice sheet will be provided by future satellite missions (e.g. CHAMP, GRACE, GOCE, ICESat/GLAS, CRYOSAT, and ENVISAT). Using satellite data and airborne data, namely, gravimetry, laser altimetry, and radio-echo sounding helped to explore geodetic, geodynamic, and glaciological features for extended regions in Antarctica.

The data (during January–March 2005) of eight MT stations studied by Murthy et al. (2012) showed high resistive upper crust followed by a comparatively conductive lower crust comparable to the southern Granulite Terrain with a lateral heterogeneity in the crust's electrical conductivity across the Schirmacher Oasis.

Siddiqui et al. (1988) carried out the study of seismic reflection, higher energy sparker source (405 line km), bathymetric (458 line km), and magnetic (452 line km) studies of the Astrid ridge, a comprehensive bathymetric feature was recorded in the water depths of about 1520–2900 m towards the continental margin, Dronning Maud Land.

4 Glaciology

The Schirmacher Oasis observation and data suggests the southern part of the ice sheet (blue ice) is uncovered. The contour line starting from 180 to 10 m shapes at the snout of glacier, which is intersected by NE-SW to NNE-SSW trending several fractures. Two transient supraglacial streamlets derive towards an NNE direction. Overall meteorological data shows that the area falls under a dry polar climate. Snowfall is very common throughout the winter periods. However, one way snow deposition is regular over the leeward hillock's side and the other way strong winds clean the rock surfaces.

According to observations made in to the glaciology between 1983 and 1996, surveys from two fixed points using electronic distance measurement (EDM) or theodolite, the glacier is continuously retreating annually with an average retreat at the rate of 70 cm/annum. The moderate annual recession during 1997–2002 was in the range of (~48.7–74.9 cm), with an average of 65.3 per/annum during 1997–2002, and it is in agreement with the interpretation for the preceding years from1983 to 1996 with a decline rate of 7 m/decade (Chaturvedi et al. 2004).

The study of the snow accumulation/ablation over the ice shelf near the first Indian station Dakshin Gangotri (70°05′37″ S Lat.; 12°00′00″ E long.) was launch by fixing a 100 m by 100 m network of wooden stakes in 1982–1983. Consequently, much-reduced accumulation has been noticed during austral summer (November-January) in the last twenty years compared to the rest of the year. The polar winter shows the maximum snow accumulation. Vaikmäe (1991) reported that the isotopic composition of ice, fire, and snow data decipher, recent structures and Holocene evolution of this marginal area of East Antarctica from northern Queen Maud Land near 12° E. Isotopic analysis from the ice cover samples situated south of the Schirmacher Oasis suggests that under the Holocene ice, the thick relics of the Pleistocene ice cover with $\delta^{18}0$ values of -38 to $-48‰$.

Analysis of thermal structure and estimation of heat budget for lake Priyadarshini, during December'96–March'97, reveal that weak thermal stratification prevailed in the lake for the significant part of the period of observation during mid-summer. However, the lake becomes unstratified as the winter approaches. The heating cycle of the lake is a function of the climate and morphometry of the lake itself. The National Geophysical Research Institute (NGRI), India in 1997, initiated the studies on seismotectonic and geodynamical processes by using the seismology and GPS-Geodesy. The scientific proposals to study the crustal deformation and geodynamical processes between Antarctica and India were continued up to 2005 and achieved the prime objectives. NGRI launched several programes to improve the outcomes on the interplate and intraplate strain accumulation and the seismicity within the Antarctica by setting up the seismic stations and using densifying GPS near Maitri and third station (named Bharati) at Larsemann Hills. The critical evaluation of the deformation processes examined by the IGS GPS stations, Casey and Davis which are far away from Maitri. To understand the Antarctica and the Southern Indian Peninsula's geodynamical system, Antarctica's internal deformation processes has

been estimated very precisely using the planned array of 5 GPS stations Near to Maitri. Similarly, a Seismic array with 5 Broadband seismometers has been installed around Maitri. To achieve the long-term objectives of the program, this Seismic array helped to identify the major and minor magnitudes of the earthquakes occurred in and around Antarctica and to assess, the velocity and crustal structure below Maitri and the nearby region.

Detailed analysis of the measurement of the ozone hole depth, during the 16th and consecutive three (21st, 22nd, and 23rd) Indian Antarctic Scientific Expedition was done from a high latitude isolated area near Indian Station Maitri, Schirmacher Oasis of East Antarctica. The lowest ozone value recorded over Maitri was 135 ($\pm$9.3) DU in 1997, 185 ($\pm$12) DU in 2002, 126 ($\pm$9.7) DU in 2003 and 159.8 ($\pm$8.8) DU in 2004 spring. During Antarctic spring (day 225–365), concentration of Ozone below 220 DU shows 45.1%, 20.7%, 62.7% and 60% in 1997, 2002, 2003 and 2004, respectively. The Ozone loss (below 220 DU ozone values) during days from 225 to 365 in 2003 was observed to be increased by a factor of 0.4 compared to 1997 and 2 compared to 2002. The data collected from Maitri also exhibited the significant event of stratospheric warming during 2002. In 2002, the ozone hole was not severe and improved early, in contrast to 1997, 2003 and 2004. Experimental columnar ozone values has been used to decipher the increase in UV irradiance theoretically during the deep Ozone Hole period (30-09-2004 to 10-10-2004). During the intense ozone hole period, the maximum increase in UV irradiance theoretically was estimated to be an average loss of 44% total ozone with 403% at 305 nm, 84% at 312 nm, and 24% at 320 nm. To understand and calculate the variation in direct UV irradiance per DU change (range 320–100 DU) in columnar ozone at different solar zenith angle, the TUV model investigated the relationship between the columnar ozone and direct UV irradiances.

Survey of India (SOI) has been participating in the Indian Scientific Expedition to Antarctica since 10th Expedition (1991–92). The SOI set the objective to carry out the survey and respective mapping of the area and finally to provide technical assistance to the different participating organisations. Originally, conventional triangulation and Global Positioning System (GPS) techniques were employed to deliver major outcome. Later, with contour interval 1 m, the mapping on scale 1:1000 and with contour interval 5 m, the mapping on scale 1:5000 has been commenced. The SOI has already established Geodetic and Geophysical Control in and around Schirmacher Oasis for better scientific investigations in the field of glaciology and climatology. In this process, Control points was provided for India's Geological Survey, the Indian Meteorological Department and assistance was given to the survey work to the National Environmental Engineering Research Institute and National Physical Laboratory, Defense Electronics Application Laboratory. From 2003–2004, neotectonic and glacier movement assessments has been completed with the aim of undertaking the varied geodetic works, such as establishment of 40 nos. of GPS control points (with permanent documentation). Later on, these data connect High Precision Leveling, and provide precise gravity values, repetition of levelling, gravity, and GPS observations for at least three epochs. As much as 28 stations have been established for this studies along with seven days GPS observation at Maitri station
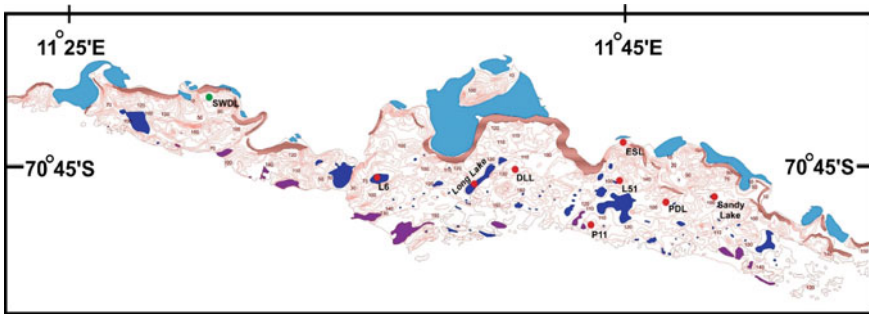
Fig. 1 Sediment core locations in Schirmacher Oasis, East Antarctica (after Govil et al. 2018)

from 23rd Expedition till date. In and around Schirmacher Oasis, a area of 5.7 sq km of the has been surveyed. This Survey has published in form of large scale maps (both in analogue and digital format) covering most of the area of interest.

5 A Review of the Paleoclimatic Reconstructions at Schirmacher Oasis

5.1 Pleistocene Paleoclimatic Record

An early attempt to study freshwater lakes in East Antarctica was made in 1984–85 to describe the freshwater microfaunal components in Schirmacher Oasis (Ingole and Parulekar 1993). This study was followed by very few investigations on lake sediments from this region (Sharma et al. 2000; Sinha et al. 2000a; Sinha and Chatterjee 2000; Sharma et al. 2007a) to reconstruct the palaoclimate, transportation of palynodebris and pollen (Sharma et al. 2002; Bera 2004) and report of the presence of freshwater protozoans—Arcellaceans (Mathur et al. 2006). Hydrogen and oxygen isotopic studies has been carried out from water samples of different lakes in Schirmacher Oasis (Sinha et al. 2000b); and preliminary study of quartz grains morphology and microtextures from surface sediments from lakes in Schirmacher Oasis was done to recognize their provenance and depositional environments (Asthana and Chaturvedi 1998). Furthermore, Schirmacher Oasis, being one of the larger coastal oases in eastern Antarctica, remains a significant region for paleoenvironmental and paleoclimatic studies., Lacustrine sediments should be addressed to understand the paleoclimatic variations as they preserve the sediments reflecting long term and abrupt changes through the geological period. However, Schirmacher Oasis has remained a less worked region in Antarctica regarding paleoclimatic studies of lake sediments (Bera 2004; Sharma et al. 2007b; Phartiyal et al. 2011; Phartiyal 2014; Warrier et al. 2014, 2015; Mahesh et al. 2015; Govil et al. 2016; Govil et al. 2018).

Nevertheless, the rapid climatic changes affirm the internal climate changes involving the interaction between the atmosphere and the ocean during a stable climatic condition and possible internal and external forcing of earth, such as solar or volcanic effects (Stuiver et al. 1995). Climate variability information can be obtained from these forcings and transformed into the paleoclimatic data based on spectral analysis (Ghil et al. 2002). Sediment core samples from pro-glacial lake P-11 have been analyzed for the quartz grains. Quartz grains has been used over any other available minerals present in the lakes due to its higher preservation potential and their resistance to weathering (Krinsley and Doornkamp 1973; Mahaney 1995; Mahaney 2002). The Quartz grains have the record of different provenances, which were derived mechanically or chemically along with through wind-driven aeolian activities (Stanley and DeDeckker 2002). Quartz grain microtextures and morphology, such as shape of grain, different patterns, such as step patterns, fracture patterns etc., principally depend on the transportational conditions and depositional environment and hence provide data of the paleoenvironmental as well as paleoclimatic conditions (Whalley and Krinsley 1974; Mahaney et al. 1996; Helland and Holmes 1997; Hart 2006; Mathur et al. 2009).

To decipher the provenance of clay minerals in the sediments and reconstruct Schirmacher Oasis's paleoclimate, a detailed clay mineralogical study has been carried out from glacial deposits found near the lakes (Srivastava et al. 2011). This study exhibits prominent peaks of five clay minerals: kaolinite, illite, chlorite, smectite, and vermiculite. These clay minerals were formed under cold climatic settings from the weathered and altered rocks, such as igneous or metamorphic rocks. Further study has been carried out on the sediment samples collected from surface of two epi-shelf lakes in Schirmacher Oasis to investigate the sedimentological and mineralogical properties of surficial sediments (Shrivastava et al. 2012). The study based on the quartz grains concluded that the grains were deposited in these epi-shelf lakes by different physical weathering and chemical precipitation processes. Chemical analysis revealed that the sediments were gneissic in composition, and saltation and suspension were two main modes of transportation of the poorly sorted glaciofluvial sediments. Sediment samples from different regions in the Schirmacher Oasis, such as ice-free lakes, polar ice, and the coastal shelf area, reveal that the Schirmacher Oasis was formed predominantly by glacial processes, with some glaciofluvial and aeolian influences (Srivastava et al. 2012). Glacial sediments from different Schirmacher Oasis locations were investigated to assess the palaeodepositional environment (Srivastava et al. 2013). Mineralogically, the rare earth and trace elemental data indicates that heavy minerals enriched in the coarse fraction over finer one. The transportation of sediments happened mostly by fluvial as well as aeolian agents, including the minor influence of gravity and glacier actions. The overall conclusion was that almost all the deposits collected show similar geochemical and mineralogical characteristics.

5.2 Holocene Paleoclimatic Evidence

The evolutional history of Schirmacher Oasis (SO) from 13 kyr BP to Recent was reconstructed based on the data of loss-on-ignition (LOI) and magnetic susceptibility (MS) from seven sediment profiles of five palaeo-lake deposits (Phartiyal et al. 2011). It has been deciphered that glaciers dominated the entire SO from 13 to 12.5 kyr BP and the today's land-locked lakes were designated as the glacial lakes. In the beginning of Holocene warming (11.5 kyr BP), five large pro-glacial lakes situated the low-lying valleys of SO were formed due to the recession of glaciers. On the other hand, the landlocked lakes got dried up due to the absence of water influx during summer months because of the retreat of glaciers, diminished meltwater inflows, lesser snow accumulation, stronger winds, and sublimation of the lake due to ice-cover for longer period. However, both the pro-glacial and the epishelf lakes were fed by the continuous melt-water flux from the ice shelf and continental ice sheet. An analysis of remnant magnetism in the lake sediments of SO reconstructed the paleoclimatic condition of this area (Phartiyal 2014). In this study, a total of six phases of climatic variation were recorded from 13 to 3 kyr BP, and Phase 1 is a short one of climatic event occurred at ca. 12.9 kyr BP, which was followed by Phase 2 at 12.5 kyr BP. Both phases correspond to comparatively warmer climatic condition. At ca. 11.8–11 kyr BP, Phase 3 records similar climatic conditions to those of Phase 1. After that, a better and longer Phase 4 was recorded from 11 to ca. 8.7 kyr BP, which can corresponds to worldwide Holocene Optimum event, and a significant period of shelf areas deglaciated in the Antarctic in this period. Lastly, Phase 5 shows an arid and cold climatic condition with the period of 8.7 to 4.4 kyr BP. Two shorter and comparatively warmer climatic periods during 7.9–7.1 and 6.4–5.6 kyr BP were sandwiched within Phase 5. From 5.3 kyr BP onwards, the climatic condition became increasingly warmer recorded in most Antarctica areas till 3 kyr BP, which is comparable to mid-Holocene Hypsithermal (Bentley et al. 2005). In SO, the time period of 4.6–4.4 kyr BP was reported as a time of intermediate climatic conditions. The period of the mid-Holocene Hypsithermal shows a considerable variation in different regions of Antarctica as compared to ca. 4.4–3 kyr BP in SO; such as 4–2.7 kyr BP (Bentley et al. 2005, 2009) to 4.5–2.8 kyr BP on the Antarctic Peninsula, and 3.8–1.7 kyr BP in maritime Antarctica (Hodgson and Convey 2005; Jones and Bowser 1978).

Sedimentological parameters along with quartz grain morphology and microtextures of surface sediments from Schirmacher Oasis have been analysed to comprehend the transportation and depositional processes in this region (Asthana et al. 2013). It has been concluded that fluvioglacial activity with some variations of energy conditions played a vital role in this area. It has also been surmised that the deposition of sediments in periglacial lakes of SO is dominated by sedimentary and glacial processes.

Paleoclimatic reconstruction for the past 42.5 kyr BP has been performed using the environmental magnetic properties of sediments deposited in Sandy Lake, SO

(Warrier et al. 2014). Coldest periods of the surrounding region were recorded consecutively during 40.7, 36.0, 34.5, 29.0 and, 28.0–21.4 kyr BP. Intermittent relatively warm periods were intercalated during 38.4–39.2 kyr BP, 33.7–29.8 kyr BP and 28.5 kyr BP. The LGM in the SO has described as a widespread glacial condition. The following Holocene period was also intersected by changing phases of relatively warmer (12.5–9.8 kyr BP and 4.2–~2 kyr BP) to colder (9.2–4.2 kyr BP and from ~2 kyr BP onwards) periods.

Most of these alternative warm and cold periods can be easily correlated with the climatic events recorded from other lake sediments and ice-core records from the SO as well as other East Antarctic areas. Overall, it has been surmised that the SO was not affected by complete glaciation during the past 40 kyr BP. Study of sedimentological parameters along with quartz grains morphology and microtextures from the sediments of Sandy Lake were examined to infer the provenance of the sediment and the transport mechanism during the past 42.5 kyr BP (Warrier et al. 2016). It was concluded that the sediments were mainly transported by glaciers and meltwater inflows. During the period of last glaciation, the climate was colder with the prominent aeolian transportation activity. On the other hand, post-LGM enhanced the energy for the transportion, hence meltwater stream played an active role under glaciogenic conditions. The study also surmised that the various kinds of physical and chemical weathering, mostly of glacial conditions during the transportation affected Quartz grains A study of organic geochemistry and sedimentology from sediments from Long Lake, SO, depicted a history of the paleoclimatic condition during the last 48 kyr BP (Mahesh et al. 2015a). The extended ice-cover period for a freezing environment lowered the productivity of the last glacial period as well as a significant part of Holocene. The Holocene warm period around the lake would have resulted a extended ice-free environment starting around 6 kyr BP. Collectively, the productivity and sedimentation of the Long Lake related to the response of the glaciated conditions controlled by Antarctic climate.

The presence of *Pohlianutans* moss species was the first ever record of this sub-fossil from the central Dronning Maud Land region dated 10.6 kyr BP in a sediment core from Lake L6 in SO (Singh et al. 2012). This is one of the common species found even in the other part of Antarctica (Singh et al. 2012). The moss population data can assess the variation of its distribution and diversity in the SO region and decipher the paleoclimatic and palaeoenvironmental conditions. Another study from Lake L-6 within the SO was carried out extensively with a multiproxy approach to reconstruct the paleoproductivity and paleoclimatic changes during Holocene (Govil et al. 2016). This study exhibits a warm period during the Pleistocene-Holocene boundary (~11.6 to ~10 cal kyr BP) with the record of elevated paleoproductivity and reducing environment as organic matter decayed in the bottom water of the lake. Later, a rapid shift happened from deglaciation to glaciation during the commencement of the Holocene (~10 kyr BP). A relatively colder phase has been recorded from the entire stretch of Early to Late Holocene (~10 to ~3.1 kyr BP) due to the extension of continental ice sheet from the southward to the northward in this area. This phase was characterized by lowering of paleoproductivity within the lake and lessening of the rate of sedimentation (~2.9 cm/kyr). The Late Holocene period (~3.1 kyr BP to Recent)

experienced a stepwise warming that corresponds to the winter and summer solar insolation. This stepwise warming event in East Antarctica has ultimately affected the paleoproductivity in the lake. During this period, lakes had received an adequate amount of meltwater from the continental ice sheet and snow around the lake that increased the lake water level. Another study reveals the paleoclimatic shift from the last glacial period to the Holocene (Govil et al. 2018), which was substantially juxtaposed with the changes that occurred during Holocene (Johnsen et al. 1992a).

Paleoenvironmental studies from a pro-glacial lake in SO were performed based on quartz grain morphology and microtextures (Mazumder et al. 2017). This study exhibits the predominantly colder climatic condition at the advent of the Holocene. During the beginning of the Holocene, melting of the glaciers started in this region. Middle Holocene is characterized by relatively warmer conditions, while in Late Holocene the reappearance of a somewhat colder climatic condition occurred in this region. Thus, this study suggest an interchanging glacial-interglacial environmental phase during Holocene.

Sediment cores from few landlocked lakes and a grab sample from the pro-glacial lake in the central part of SO have been analysed using multi-proxy sedimentological approach to reconstruct the paleoclimatic history of the region (Srivastava et al. 2018). The lake sediments exhibit a glacial signature derived from medium to high-grade metamorphic terrain under restricted drainage pattern. The different sedimentological parameters show alternate warmer and colder phases at different time intervals. This study concluded that the gradual warming in SO began much before 42 kyr BP. During the early stage of the Late Quaternary, this area was covered by ice, which gradually waned to expose an ice-free area in the Late Holocene. The dominance of sand from sediment cores of Antarctic lakes GL-1, V-1, and L-6 deciphered the high degree of mechanical weathering, which weathered coarse-grained particles from the provenance to the depositional area transported by the fluvioglacial process (Choudhary et al. 2018). The grain size variation of lake system was controlled by many factors, such as amount and energy of meltwater, aeolian action, the surface area of the lake, geology of the catchment area, and local hydrodynamic settings.

5.3   A Case Study from Schirmacher Oasis (SO)

The recent study from the L-51 landlocked lake focused on two observations. The first observation to distinguish the effect of the reservoir age in the lake sediment from entire Schirmacher Oasis (SO). The second observationis based on one of the well-documented events of Antarctic Cold Reversal (ACR) (Jouzel et al. 1989; Blunier et al. 1997; Pedro et al. 2011). The 2.2 kyr age was subjected to subtract from all radiocarbon ages individually and the corrected reservoir ages for the core L-51 was obtained in SO. The considered corrected reservoir age was finalized after calculating the mean of all ages obtained from four lake sediment top samples within SO. The core tops from the lake L-6, lake P-11, epishelf lake (ESL) and sandy lake, situated within 3 km of present southern boundary glacier in the SO, interpret the

ages of 640 years (Govil et al. 2016), 3320 years (Mazumder et al. 2017), 3685 years (unpublished data) and 1245 years (Warrior et al. 2014), respectively. Earlier, the reservoir age correction of 640 years has been standerdizedfrom the lake L-6 (Govil et al. 2016) because of the depositionof the old carbon to the core site through the glacial meltwater. If the glacial meltwater inflows with depleted ^{14}C move lesser distance in the catchment area of the lake and suggests the equilibrium condition within the atmospheric gas exchanges (Doran et al. 1999; Wagner et al. 2004). The reservoir age effect can be neglected if temporary ice covers the lake, but it will gradually enhance during the colder periods with the enhancement of meltwater influx from surrounding glaciers (Wagner et al. 2004). However, measurement of this transported carbon, both incoming and outgoing, along with the mobility and the meltwater flux is difficult to obtain accurately. Hence, to attain the corrected reservoir ages, 2.2 kyr was subtracted from all radiocarbon ages individually.

Moreover, detailed work from SO samples obtained from trenches and dry lakes also confirms comparatively older ages at the top 0–10 cm as the raw radiocarbon dates show a rangebetween 3.11 and 11.1kyr BP (Phartiyal et al. 2011). But these radiocarbon dates have not been used in calculating the average value in reservoir age due to the collection of these samples and some sediment core samples collected from pits, channels and dry lakes. However, the upper part of sediment collected from the entire SO contains older carbon in it (Phartiyal et al. 2011). The large and small lakes situated in SO receive sedimentation through the meltwater flux of glaciers from the surrounding regions during SO warm summer period. The top sediments from lakes ESL and P-11 represent the old raw radiocarbon ages in the present scenario. However, L-51 sediment core should precisely be assessed by the incurred chronology before insuring further inferences. Hence, the reservoir age and its corrections should be established to apprehendpaleoclimatic and palaeoenvironmental settings accurately from the SO lake sediment cores.

A multiproxy study from the different sediment proxies (percentage of sand-silt-clay, mean diameter of the sediment and roundness), percentage of biogenic silica (BSI %) as well as spectral examination of the available data to determine the significant periodicities (at >95% significance) deciphers the presence of Antarctic Cold Reversal (ACR) around 14–11.8 kyr BP, which was characterized by the increase of freshwater runoff in the lake followed by early-Holocene climate optimum and Holocene climate optimum around 11.8–7.2 kyr BP (Govil et al. 2018). However, the Antarctic ice sheet mass loss, Melt-water Pulse 1A (WMP1A), and enhanced iceberg flux during the Antarctic cold reversal (ACR) in the Southern Ocean were documented (Weber et al. 2014; Fogwill et al. 2017), though the effect of ice of Antarctica on the MWP1A during the ACR is questionable (Liu et al. 2016). The ACR timing was reported to be during 14.7–13 kyr BP, which corresponds with the major warming event, namely Bølling–Allerødevent from the north Atlantic region (Pedro et al. 2016). A detailed comparative study between Antarctica and Greenland ice core record depicts an unsynchronized relationship between the two poles, designated as 'bipolar seesaw' (Blunier et al. 2007). Hence, there is ambiguity regarding the meltwater flux during ACR that questions the intensity of the ACR signals in the SO in East Antarctica. Furthermore, in present study the sedimentological proxies

has been used on the sediments from the L-51 lake of SO. The analysis of grain size infers that during the 18.5–14.4 kyr BP, the clay variesfrom 3.6 to 2.5% (Fig. 2c), silt ranges between 52.9 and 40.0% (Fig. 2b), and sand ahows a range of 57.4–43.6% (Fig. 2a) along with the mean diameter changes from 143.65 to 102.61 μm (Fig. 2d) and sorting varies from 28.0 to 25.7% (Fig. 2e). However, the BSI percentage ranges from 1.2 to 0.5% from 18.5 to 14.4 kyr BP (Fig. 2f). Within the 14.4–12.6 kyr BP period, the clay varies from 2.9 to 1.0% (Fig. 2c), silt ranges between 42.6 and 25.3% (Fig. 2b), and sand varies between 73.5 and 54.3% (Fig. 2a) along withthe mean diameter varies from 256.8 to 136.3 μm (Fig. 2d) and the values of sorting range from 36.9 to 26.9% (Fig. 2e). On the other hand, the BSI percentage shows a range from 1.8 to 0.6% within 14.4–12.6 kyr BP (Fig. 2f). During Holocene (~11.7 kyr BP to Recent), the data from the analysis of grain size shows that the clay varies between 5.3 and 1.4% (Fig. 2c), silt ranges from 76.5 to 35.2% (Fig. 2b), sand shows a range between 61.2 and 20.5% (Fig. 2a) as well asthe values of mean diameter range between 228.5 and 44.5 μm (Fig. 2d) and sorting shows a variation between 38.3 and 24.2 (Fig. 2e). During the Holocene the BSI percentage varies from 3.6 to 0.4% (Fig. 2f). The paleoclimatic data obtained from the ice cores from Antarctic decipher that the Antarctic cold reversal (ACR) interrupted significantly post-LGM warming in the Southern Hemisphere around 14.5 to 13 kyr BP (Blunier et al. 1997; Pedro et al. 2011, 2016; Jouzel et al. 1989). In the present study, the increased sand percentage by ∼20%, mean diameter by ∼164 μm, sorting by ∼10% and BSI percentage by ∼0.9% along with the decrease in clay percentage ∼2% and silt percentage by ∼17% have been noticed during a short time span after 14.7–12.2 kyr BP (Fig. 2). Simultaneously, increase in sand percentage, mean diameter and sorting indicates that coarser grain was transported through enhanced meltwater flux in the result of the retreat of ice cover and hence deposited at the centre of the lake (Fogwill et al. 2017). This hypothesis also supported the reason of the possible initiation of the ACR signal (14.6–12.7 ka BP) due to sufficient meltwater flux into the Southern Ocean. During MWP1A a significant quantity of meltwater has been released into the Ocean that contributed to maintain the stratification in ocean and hence enhance the ice cover retreat. Moreover, the probable methods of the retreat of grounded ice may be attributed to the subsurface ocean warming (Golledge et al. 2014) and substantially reduction of Antarctic bottom water (AABW) formation in the Southern Ocean resulting to the enhancement of the cooling in atmosphere over Antarctica during this period (Parrenin et al. 2007). Thereafter it reduced the sea surface temperature of the Southern Ocean (Siani et al. 2013; Nielsen 2004) and finally happened to increase the sea ice extension. Furthermore, the sea ice extension affected on the reduction in the ventilation from surface water to deeper water and enhanced subsurface temperature in the ocean as well as the Antarctic coast (Menviel et al. 2010). The grounded ice melting resulted due to this warming lowered the ice sheet surface that enhanced the horizontal release (Fogwill et al. 2017). Finally, the feedback mechanism over the climate system of Antarctica seems to be a conflict between the differences of ocean and atmospheric heat fluxes, which trigger the regional climate change of the SO.
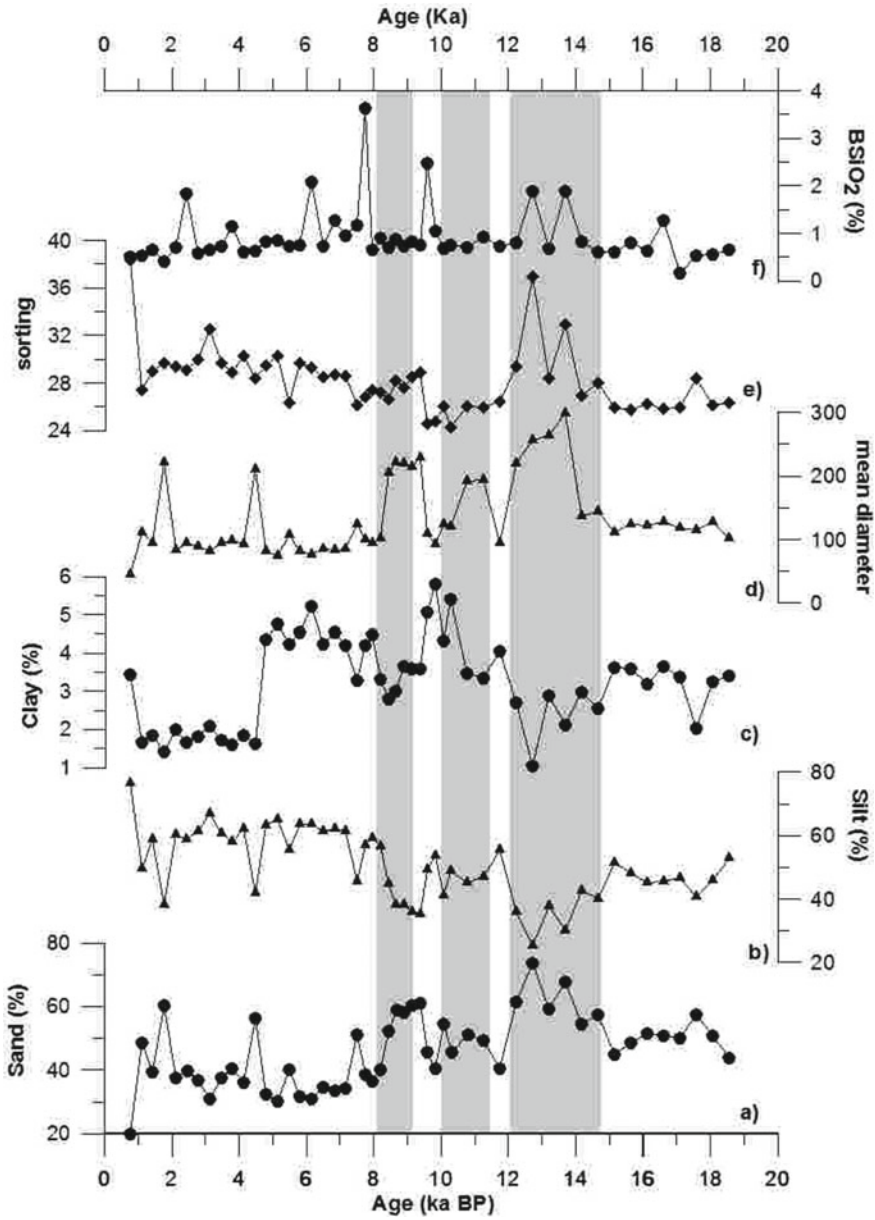
Fig. 2 Grain size distribution, Biogenic silica and sorting variation with the chronological sequence of lake L-51 **a** Sand (%). **b** Silt (%). **c** Clay (%). **d** Mean diameter (µm). **e** Sorting (%). **f** Biogenic Silica (BSI %). Three dark band shows the meltwater flux episodes in SO (also refer Govil et al. 2018)

Although limitations arise in the present study due to the radiocarbon dating uncertainties, it was obvious that increase of meltwater flux correlated with the event of ACR. However, the data of grain size distribution along with biogenic silica demarcate three prominent episodes of meltwater flux (Fig. 2). They may trigger to the recession of the southern glacier boundary towards more south in SO. During pre-Holocene deglaciation period, the episodes of glacier meltwater flux corresponds to the event of ACR. This time, the lake L-51 have received maximum meltwater derived from ice cover and hence increased the deposition of coarse sediments. The Holocene climate optimum (11.2–8.4 kyr) exhibits a mixed signals of aeolian deposition and surroundings snow meltwater flux as well as ice sheet meltwater flux. Later, from 7.2 kyr BP to Recent core site received the majority of the sediments mainly because of surrounding snow meltwater flux along with aeolian deposition rather than ice sheet meltwater flux.

6 Conclusions and Recommendations

This chapter deals with review work by many Institute/Universities research workers in the Schirmacher Oasis over the period or the initiation of the Indian Expedition to East Antarctica (Schirmacher Oasis). The geographical location, the geology of the area, and paleoclimatic work show the research work's progression in the Schirmacher Oasis. The main emphasis is on the high-resolution paleoclimate reconstruction based on the lake sediments and the multiproxy dataset. But, the work on biological proxies such as Diatom or any other biota is less explored. The relation between the biological component with geochemistry requires more attention in the SO.

Furthermore, the radiocarbon dating in the lake sediment core is required more attention as the reservoir ages have to be calculated based on other dating techniques. One of the case studies shows 640–2200 years; radiocarbon ages may be used as a reservoir age correction within the present lakes system and used to interpret the paleoclimatic/paleoenvironmental conditions.

References

Asthana R, Beg MJ, Swain AK, Dharwadkar A, Roy SK, Srivastava HB (2013) Sedimentary processes in two different polar periglacial environments: examples from Schirmacher Oasis and Larsemann Hills. East Antarct Geol Soc Lond Spec Publ 381:411–427

Asthana R, Chaturvedi A (1998) The grain-size behaviour and morphoscopy of supraglacial sediments, south of Schirmacher Oasis, East Antarct J Geol Soc India 52(5):557–568

Bargagli R (2005) Antarctic ecosystems. Ecological studies series 175, pp 1–395. Springer, Berlin

Bentley MJ, Hodgson DA, Smith JA, Cofaigh CO, Domack EW, Larter RD, Roberts SJ, Brachfeld S, Leventer A, Hjort C, Hillenbrand CD (2009) Mechanisms of Holocene palaeoenvironmental change in the Antarctic Peninsula region. The Holocene 19(1):51–69

Bentley MJ, Hodgson DA, Sugden DE. Roberts SJ, Smith JA, Leng MJ, Bryant C (2005) Early Holocene retreat of the George VI ice shelf, Antarctic Peninsula. Geology 33:173e176

Bera SK (2004) Late Holocene Palaeo winds and climatic changes in Eastern Antarctica as indicated by long-distance transported pollen spores and local microbiota in polar lake core sediments. CurrSci 86:1485–1488

Blunier T, Schwander J, Stauffer B, Stocker T, Dällenbach A, Indermühle A, Tschumi J, Chappellaz J, Raynaud D, Barnola JM (1997) Timing of the Antarctic cold reversal and the atmospheric CO2 increase with respect to the younger Dryas event. Geophys Res Lett 24(21):2683–2686

Blunier T, Spahni R, Barnola JM, Chappellaz J, Loulergue L, Schwander J (2007) Synchronization of ice core records via atmospheric gases. Clim past 3:325–330

Bormann P et al (1986) Structure and development of the passive continental margin across the Princess Astrid Coast, East Antarctica. J Geodyn 6(1–4):347–373

Bromwich D, Zhong L, Rogers AN (1998) Winter atmospheric forcing of the Ross Sea polynya. In: Jacobs SS, Weiss RF (eds) Ocean, ice and atmosphere, interactions at the Antarctic continental margin, vol 75, pp 101–133. American Geophysical Union, Antarctic Research Series

Chaturvedi A, Beg MJ, Keshavprasad AV (2004) Monthly patterns of advance and retreat of Dakshin Gangotri glacier snout in Schirmacher range. In: Nineteenth Indian expedition to Antarctica, Scientific report, DOD, Tech Publ No 17, pp 21–31

Choudhary S, Tiwari AK, Nayak GN, Bejugam P (2018) Sedimentological and geochemical investigations to understand source of sediments and processes of recent past in Schirmacher Oasis, East Antarctica. Polar Sci 15:87–98

CLIMAP Project Members (1981) Seasonal reconstructions of the Earth's surface at the last glacial maximum. Geol Soc Am Chart Ser MC-36

Dayal AM, Hussain SM (1997) Rb-Sr ages of lamprophyre dykes from Schirmacher Oasis, Queen Maud Land, East Antarctica. J Geol Soc India 50(4):457–460

Doran PT, Berger GW, Lyons WB, Wharton RA, Davisson ML, Southon J, Dibb JE (1999) Dating quaternary lacustrine sediments in the McMurdo dry valleys Antarctica. Palaeogeogr Palaeoclimatol Palaeoecol 147(3):223–239

Fogwill CJ, Turney CSM, Golledge NR, Etheridge DM, Rubino M, Thornton DP, Baker A, Woodward J, Winter K, Van Ommen TD, Moy AD (2017) Antarctic ice sheet discharge driven by atmosphere-ocean feedbacks at the Last Glacial Termination. Sci Rep 7:39979

Ghil M, Allen MR, Dettinger MD, Ide K, Kondrashov D, Mann ME, Robertson AW, Saunders A, Tian Y, Varadi F, Yiou P (2002) Advanced spectral methods for climatic time series. Rev Geophys 40(1)

Golledge NR, Menviel L, Carter L, Fogwill CJ, England MH, Cortese G, Levy RH (2014) Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning. Nat Commun 5:5107

Govil P, Mazumder A, Asthana R, Tiwari A, Mishra R (2016) Holocene climate variability from the lake sediment core in Schirmacher Oasis region, East Antarctica: multiproxy approach. Quat Int 425:453–463

Govil P, Mazumder A, Ram R, Singh DS, Azharuddin S (2018) Meltwater flux and climate change record of last 18.5 ka from Schirmacher Oasis East Antarctica. Polar Sci 18:135–141

Grew ES, Manton WI (1983) Geochronologic studies in East Antarctica: reconnaissance uranium/thorium/lead data from rocks in the Schirmacher Hills and Mount Stinear. Geology 77:1405–1418

Hart JK (2006) An investigation of subglacial processes at the microscale from Briksdalsbreen Norway. Sedimentology 53(1):125–146

Helland PE, Holmes MA (1997) Surface textural analysis of quartz sand grains from ODP Site 918 off the southeast coast of Greenland suggests glaciation of southern Greenland at 11 Ma. Palaeogeogr Palaeoclimatol Palaeoecol 135:1–4; 109–121

Hoch M, Tobschall HJ (1998) Minettes from the Schirmacher Oasis, East Antarctica—indicators of an enriched mantle source. Antarct Sci 10:476–486

Hodgson DA, Convey P (2005) A 7000-year record of oribatid mite communities on a maritime-Antarctic island: responses to climate change. Arct Antarct Alp Res 37(2):239–245

Hughes TJ (1998) Ice sheets: New York, Oxford University Press, 343 p

Huybrechts P (1990) The Antarctic ice sheet during the last glacial-interglacial cycle: a three-dimensional experiment. Ann Glaciol 14:115–119

Ingole BS, Parulekar AH (1993) Limnology of freshwater lakes of Schirmacher Oasis, East Antarctica

Jafri S (1997) Calc-alkaline Lamprophyres from Schirmacher Oasis, Queen Maud Land, East Antarctica. In: Thirteenth Indian Expedition to Antarctica, Scientific report, Department of Ocean Development, Technical Publication No 11, pp 227–236

Johnsen SJ, Clausen HB, Dansgaard W, Fuhrer K, Gundestrup N, Hammer CU, Iversen P, Jouzel J, Stauffer B (1992) Irregular glacial interstadials recorded in a new Greenland ice core. Nature 359(6393):311–313

Johnsen SJ, Clausen HB, Dansgaard W, Fuhrer K, Gundestrup N, Hammer CU, Iversen P, Jouzel J, Stauffer B, Steffensen J-P (1992) Irregular glacial interstadials recorded in a new Greenland ice core. Nature 359:311–313

Jones BF, Bowser CJ (1978) The mineralogy and related chemistry of lake sediments. In: Lakes, pp 179–235.Springer, New York, NY

Joshi MS (1997) Delineation of tectonic features of Schumacher Oasis, East Antarctica using total field geomagnetic profiling. In: Thirteenth Indian Expedition to Antarctica, Scientific eeport, Department of Ocean Development, Technical Publication Scientific Report 11, pp 237–244

Jouzel J, Raisbeck G, Benoist JP, Yiou F, Lorius C, Raynaud D, Petit JR, Barkov NI, Korotkevitch YS, Kotlyakov VM (1989) A comparison of deep Antarctic ice cores and their implications for climate between 65,000 and 15,000 years ago. Quatern Res 31(2):135–150

Jouzel J, Masson-Delmotte V, Cattani O, Dreyfus G, Falourd S, Hoffmann G, Minster B, Nouet J, Barnola JM, Chappellaz J, Fischer H (2007) Orbital and millennial Antarctic climate variability over the past 800,000 years. Science 317(5839):793–796

Kampf H, Stackebrandt W (1985) Crustal evolution of the Eastern Antarctic Craton (Schirmacher Oasis, Dronning-Maud Land). GerlandsBeitragezurGeophysik 94(4–6):251–258

Krinsley DH, Doornkamp JC (1973) Atlas of Quartz Sand Surface Textures. Cambridge University Press, 91 pp

Liu J, Milne GA, Kopp RE, Clark PU, Shennan I (2016) Sea-level constraints on the amplitude and source distribution of Meltwater Pulse 1A. Nat Geosci 9(2):130

Mahaney WC, Kalm V (1995) Scanning electron microscopy of Pleistocene tills in Estonia. Boreas 24:13–29

Mahaney WC et al (1996) Geochemistry and clay mineralogy of termite mound soil and the role of geophagy in chimpanzees of the Mahale Mountains, Tanzania. Primates 37(2):121–134

Mahaney WC (2002) Atlas of Sand Grain Surface Textures and Applications. Oxford University Press, 237 pp

Mahesh BS, Warrier AK, Mohan R, Tiwari M, Babu A, Chandran A, Asthana R, Ravindra R (2015) Long Lake sediments to Antarctic climate: a perspective gained from sedimentary organic geochemistry and particle size analysis. Polar Sci 9(4):359–367

Mahesh BS, Warrier AK, Rahul M, Tiwari M, Babu A, Chandran A, Asthana R, Ravindra R (2015) Response of Long Lake sediments to Antarctic climate: a perspective gained from sedimentary organic geochemistry and particle size analysis. Polar Sci 9:359–367

Massom RA, Stammerjohn SE (2010) Antarctic sea ice change and variability–physical and ecological implications. Polar Sci 4(2):149–186

Masson V, Vimeux F, Jouzel J, Morgan V, Delmotte M, Ciais P, Hammer C, Johnsen S, Lipenkov VY, Mosley-Thompson E, Petit JR (2000) Holocene climate variability in Antarctica based on 11 ice-core isotopic records. Quatern Res 54(3):348–358

Mathur AK, Asthana R, Ravindra R (2006) Arcellaceans (thecamoebians) from core sediments of Priyadarshini Lake, Schirmacher Oasis. East Antarct Curr Sci 90:1603–1605

Mathur AK, Mishra VP, Singh J (2009) Study of quartz grain surface texture by electron microscopy–a tool in evaluating palaeoglacial sediments in Uttarakhand. Curr Sci 1377–1382

Mayewski PA et al (2009) State of the Antarctic and Southern Ocean climate system. Rev Geophys 47:1

Mazumder A, Govil P, Kar R, Gayathri NM (2017) Paleoenvironments of a proglacial lake in Schirmacher Oasis, East Antarctica: Insights from quartz grain microtextures. Polish Polar Res 38(1)

Menviel L, Timmermann A, Timm OE, Mouchet A (2010) Climate and biogeochemical response to rapid melting of the West Antarctic Ice Sheet during interglacials and implications for future climate. Paleoceanography 25(4)

Murthy DN, Veeraswamy K, Harinarayana T, Singh UK (2012) Electrical structure beneath the Schirmacher Oasis, East Antarctica, from Magnetotelluric measurements. In: Asthana R (ed) Twenty fourth Indian expedition to Antarctica. Technical Publication No 22, pp 207–226. National Institute of Science Communication and Information Resources, Council of Scientific and Industrial Research, New Delhi

Nielsen S (2004) Deglacial and Holocene Southern Ocean climate variability from diatom stratigraphy and paleoecology. PhD thesis, University of Tromsø

Parrenin F, Barnola JM, Beer J, Blunier T, Castellano E, Chappellaz J, Dreyfus G, Fischer H, Fujita S, Jouzel J, Kawamura K (2007) The EDC3 chronology for the EPICA Dome C ice core. Clim past 3:485–497

Pedro JB, Bostock HC, Bitz CM, He F, Vandergoes MJ, Steig EJ, Chase BM, Krause CE, Rasmussen SO, Markle BR, Cortese G (2016) The spatial extent and dynamics of the Antarctic Cold Reversal. Nat Geosci 9(1):51–55

Pedro JB, Rasmussen SO, van Ommen TD, Morgan VI, Chappellaz J, Moy AD, Masson-Delmotte V, Delmotte M (2011) The last deglaciation: timing the bipolar seesaw. Clim Past 7

Phartiyal B (2014) Holocene paleoclimatic variation in the Schirmacher Oasis, East Antarctica: a mineral magnetic approach. Polar Sci 8:357–369

Phartiyal B, Sharma A, Bera SK (2011) Glacial lakes and geomorphological evolution of Schirmacher Oasis, East Antarctica, during late quaternary. Quatern Int 235(1–2):128–136

Ravich MG, Krylov AJ (1964) Absolute ages of rocks from East Antarctica. Antarct Geol 579–590

Ravindra R, Pandit MK (2000) Geochemistry and geochronology of A-type granite from northern Humboldt Mountain, East Antarctica: a vestige of Pan-African event. J Geol Soc India 56(3):253–262

Sangewar CV (1987) Some geological and glaciological observations during reconnaissance of the terrain South of Dakshin Gangotri Station, Antarctica. In: Fourth Indian Expedition to Antarctica, Department of Ocean Development, Technical Publication 4, pp 99–104

Scheinert M (2001) Geodynamic Investigations in Dronning Maud Land/Antarctica. JoumeesLuxembourgeoises De Geodynamique 89:12–14

Sengupta S (1988) Precambrian rocks of the Schirmacher range, east Antarctica. ZietschriftfürGeologieWissenschaften 16:647e660

Sharma C, Bera SK, Upreti DK (2002) Modern pollen-spore rain in Schirmacher Oasis. East Antarct CurrSci 82:88–91

Sharma C, Chauhan MS, Sinha R (2007) Studies on Holocene climatic changes from Priyadarshini Lake sediments East Antarctica: the Palynological Evidence. J Geol Soc India 69:92–96

Sharma C, Chauhan MS, Sinha R (2007) Studies on Holocene climatic changes from Priyadarshini Lake sediments, East Antarctica: the palynological evidence . J Geol Soc India 69:92–96

Sharma C, Chauhan MS, Bera SK, Sinha R, Upreti DK (2000) Early Holocene sedimentological and palynological studies from Lake Priyadarshini, Eastern Antarctica. In: Volume of Abstract, 10th International Palynological Congress, Nanjing, China, pp 151–152

Sheraton JW, England RN (1980) Highly potassic mafic dykes from Antarctica. J Geol Soc Aust 27(1–2):129–135

Shiraishi K, Kanisawa S, Ishikawa K (1988) Geochemistry of post-orogenic mafic dike rocks from the eastern Queen Maud Land, East Antarctica

Shrivastava PK, Asthana R, Roy SK, Swain AK, Dharwadkar A (2012) Provenance and depositional environment of epishelf lake sediment from Schirmacher Oasis, East Antarctica, vis-a-vis scanning electron microscopy of quartz grain, size distribution and chemical parameters. Polar Sci 6:165–182

Siani G, Michel E, De Pol-Holz R, DeVries T, Lamy F, Carel M, Isguder G, Dewilde F, Lourantou A (2013) Carbon isotope records reveal precise timing of enhanced Southern Ocean upwelling during the last deglaciation. Nat Commun 4(1):1–9

Siddiquie HN, GopalaRao D, Ramana MV, (, (1988) Geology and structure of the Astrid Ridge, Dronning Maud Land Antarctica. Paleoceanography 3(5):583–599

Singh SM, Ochyra R, Pednekar SM, Asthana R, Ravindra R (2012) A Holocene moss species preserved in lake sediment core and the present moss diversity at Schirmacher Oasis Antarctica. Antarct Sci Inst Subscr 24(4):353

Sinha R, Chatterjee A (2000) Lacustrine sedimentology in the Schirmacher Range Area, East Antarctica . J Geol Soc India 56:39–45

Sinha R, Sharma C, Chauhan MS (2000a) Sedimentological and pollen studies of Lake Priyadarshini. East Antarct Palaeobot 49:1–8

Sinha R, Navada SV, Chatterjee A, Kumar S, Mitra A, Nair AR (2000b). Hydrogen and oxygen isotopic analysis of Antarctic lake waters. Curr Sci 992–995

Srivastava AK, Randive KR, Khare N (2013) Mineralogical and geochemical studies of glacial sediments from Schirmacher Oasis, East Antarctica. Quatern Int 292:205–216

Srivastava AK, Ingle PS, Khare N (2018) Controlling factor for nature, pattern and accumulation of the glacial sediments of Schirmacher Oasis, East Antarctica: comments on paleoclimatic condition. Polar Sci 18:113–122

Srivastava AK, Khare N, Ingle PS (2011) Characterization of clay minerals in Schirmacher Oasis's sediments, East Antarctica: their origin and climatological implications. Curr Sci 363–372

Stanley S, Dedeckker P (2002) A Holocene record of allochthonous, aeolian mineral grains in an Australian alpine lake; implications for the history of climate change in southeastern Australia. J Paleolimnol 27:207–219

Stuiver M, Grootes PM, Braziunas TF (1995) The GISP2 $\delta18O$ climate record of the past 16,500 years and the sun, ocean, and volcanoes' role. Quat Res 44(3):341–354

Turner J (2009) Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophys Res Lett 36(8)

Vaikmae R, Hermichen W, Kowski P, Strauch G, Savatyugin L (1991) Glaam-Ocean-Aoncaphmbumctions. In: Proceedings of the International Symposium held at St Petersburg, September 1990. IAHS Publ no 208, 1991. Deciphering recent structures and Holocene evolution of the marginal East Antarctic ice cover in Queen Maud Land. In Glaciers--ocean-atmosphere interactions: proceedings of the International Symposium held at St Petersburg, 24–29 September 1990 (No. 208, p. 3). IAHS Press, Institute of Hydrology

Verleyen E, Hodgson DA, Sabbe K, Cremer H, Emslie SD, Gibson J, Hall B, Imura S, Kudoh S, Marshall GJ, McMinn A (2011) Post-glacial regional climate variability along the East Antarctic coastal margin—evidence from shallow marine and coastal terrestrial records. Earth Sci Rev 104(4):199–212

Wagner B, Cremer H, Hultzsch N, Gore DB, Melles M (2004) Late Pleistocene and Holocene history of lake terrasovoje, Amery Oasis, East Antarctica, and its climatic and environmental implications. J Paleolimnol 32(4):321–339

Warrier AK, Mahesh BS, Mohan R, Shankar R, Asthana R, Ravindra R (2014) Glacial-interglacial climatic variations at the Schirmacher Oasis, East Antarctica: the first report from environmental magnetism. Palaeogeogr Palaeoclimatol Palaeoecol 412:249–260

Warrier AK, Pednekar H, Mahesh BS, Mohan R, Gazi S (2015) Sediment grain size and surface textural observations of quartz grains in late quaternary lacustrine sediments from Schirmacher Oasis, East Antarctica: paleoenvironmental significance. Polar Sci 10:89–100

Warrier AK, Pednekar H, Mahesh BS, Rahul M, Gazi S (2016) Sediment grain size and surface textural observations of quartz grains in late quaternary lacustrine sediments from Schirmacher Oasis, East Antarctica: paleoenvironmental significance. Polar Sci 10:89–100

Weber ME, Clark PU, Kuhn G, Timmermann A, Sprenk D, Gladstone R, Zhang X, Lohmann G, Menviel L, Chikamoto MO, Friedrich T (2014) Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation. Nature 510(7503):134

Whalley WB, Krinsley DH (1974) A scanning electron microscope study of surface textures of quartz grains from glacial environments. Sedimentology 21(1):87–105