Late Quaternary Climate Change in Schirmacher Region, East Antarctica: As Revealed from Terrestrial Diamicts and Lacustrine Sediments

Prakash Kumar Shrivastava, Rajesh Asthana, and Sandip Roy

Abstract The multi-proxy data, generated from the moraines and sediment cores of variety of lakes from Schirmacher region, cDML, East Antarctica has provided better insight into the Late Pleistocene to Holocene paleoclimatic evolution of the region during Late Quaternary. This chapter highlights the glacial signatures which are very well preserved in all kinds of sediments of this region. The clay minerals indicate a gradual shift in the weathering regime and therewith in climate from strongly glacial to fluvio-glacial during Late Quaternary. The results of surface textures of quartz grains have been discussed depth wise and in the same samples. In general it shows dominant glacial and glaciofluvial actions. The OSL chronology on moraines has provided information on different events of deglaciation in Schirmacher region, East Antarctica. The retreat of EAIS initiated much earlier than it was thought (sometime prior to 171 ka). There is no evidence of morainic deposits belonging to the Last Glacial Maximum. Formation of lake sediments started before 42 ka marks the beginning of climate change from glacial to glaciofluvial.

Keywords Surface textures · Lake sediments · Late Quaternary · Clay minerals · Climate change

1 Introduction

Climate change is a very complex phenomenon and involves terrestrial as well as extra-terrestrial variables. Earth was subjected to drastic climate changes since its birth, which has been well recorded in geological formations. The time between Proterozoic to Recent has marked by different phases of evolution and extinction. Many of these phases are directly related to climate changes. The latest among them, the Late Quaternary time, has witnessed culmination in all modern-day species. Although many places worldwide have preserved paleoclimatic records in their

P. Kumar Shrivastava · R. Asthana (✉) · S. Roy
Geological Survey of India, Kolkata, India

N. Khare (ed.), *Assessing the Antarctic Environment from a Climate Change Perspective*, Earth and Environmental Sciences Library,
https://doi.org/10.1007/978-3-030-87078-2_6

natural formations, the higher latitudes areas serve best proxies to study paleoclimatic changes due to their undisturbed nature.

Antarctica is an island continent with about 13.66 million sq. km., almost entirely covered by ice. It’s total area changes on an annual basis and also known as the ’pulsating continent’. The freezing of the surrounding ocean adds up another 18.8 million sq. km. The ice sheet over the continent is average ~3500 m thick, with the maximum thickness being 4776 m at Terra Adelie in East Antarctica. This enormous ice cap locks up about 90% of ice of the earth, which is equivalent to ~70% of the freshwater of our planet. Exposed rocks in Antarctica are less than 2% of the area, confined chiefly to its peripheral outcrops, Dronning Maud Land and the Trans-antarctic mountain range.

It is the continent of extremes, being coldest, windiest, driest, highest and virtually uninhabited. The coldest temperature ever recorded on earth was in Antarctica −94.7 °C (−135.8°F), which happened in August 2010. The old record had been −89.2 °C (−128.6°F) in Vostok (Russian Station) in July 1983. The temperature on the polar plateau ranges from −5 °C to −80 °C, while in the coastal areas, the climate remains in between 0 °C and −35 °C. Such an extreme cold freezes most of the moisture in the atmosphere, which gets precipitated as snow, having annual precipitation as low as less than 5 cm in the interior areas making Antarctica a ’cold desert’, and coupled with the polar day and night cycles, giant low-pressure systems moving around the continent from west to east cause extreme weather conditions giving rise to unique set-up on the earth carving unique geomorphological milieu. Its unique geographical position with all its extremities has made it very special for scientists and researchers worldwide and provides valuable information on various aspects of the scientific knowledge base. Far away from the significant pollution sources, these regions also act as natural laboratories, rendering sharper easier to interpret scientific observations.

Antarctica has seen glaciations and deglaciations throughout geological time on a different scale (Pollard and DeConto 2009). The most continuous data has been retrieved from the Vostok ice core, indicating fluctuating climate during the past 800 ka with eight glacial and interglacial cycles (Lambert et al. 2008; Cortese et al. 2007; Petit et al. 1999). Such periodic changes in Antarctica’s climatic condition determined the evolution of different geomorphic landforms and the overall landscape.

Cosmogenic isotope-based evidence of minor changes in the ice thickness over the past 100 ka has been reported from different central Dronning Maud Land (cDML), including the Gruber, Petermann Humboldt mountains (Altmaier et al. 2010) areas. Optically stimulated luminescence dating of glacio-fluvial and glacial lake shoreline sediments indicates that in the Bunger Hills and cDML regions, the most recent large-scale retreat of EAIS began around 40 ka (Gore et al. 2001). Post 40 ka till the present (including the period of last glacial maximum), these areas were never covered with ice sheet (Hodgson et al. 2001; Gore et al. 2001).

The grounding line zone of EAIS in the north of the cDML area has been nearly stationary over the past 30 ka (Anderson et al. 2002; Livingstone et al. 2012; Mackintosh et al. 2011, 2014). Mackintosh et al. (2011; 2014) suggested that in this interval, the ice sheet was restricted to 800 m in Lambert/Amery Glacier system, and Larsemann Hills and Bunger Hills did not carry signatures glaciations. The presence of nunataks and striations in the cDML region suggested thinning the ice sheet by ~100 m. This estimate arrived based on the nature of indentation on the bedrock. A consensus also exists that the retreat of EAIS at the Lambert/Amery Glacier system began at around 18 ka, at ~14 ka in Mac Robertson Island and during ~12 ka to 6 ka at other places (Mackintosh et al. 2014).

Schirmacher Oasis (70°44′30° S-70°46′30"S & 11°22′04” E-11°22′04"E) is a ~17 km long and ~3 km wide semi-linear exhumed Neo-Proterozoic terrain (Fig. 1) and is amongst few regions in Antarctica that have preserved sedimentary records of different stages of deglaciation. Baalsrudfjellet is located in the South-East direction of Schirmacher Oasis. The sediment cover in this oasis and the adjoining areas are thin because of low debris volume and weak fluvial activities (Fitzsimons 1996). Schirmacher Oasis was exposed and evolved through the continental ice sheet retreat, leading to different glacial and glaciofluvial geomorphic features.

In coastal Antarctica, few landmasses are exposed to freshwater lakes. These landmasses are known as Oases. With the climatic fluctuations in the past, other than glaciological agents, the oases have experienced other active geomorphic agents, viz. fluvial and aeolian processes, in reshaping the existing landforms factors to the geomorphic evolution of the area. The Schirmacher Oasis is an exhumed terrain among few Antarctica regions that have preserved sedimentary records of different deglaciation stages. Schirmacher Range is Antarctica’s few areas that provide distinct geomorphic features (Fig. 2) formed due to the deglaciation process. This oasis in the rocky area elongated in the west-northwest to east-southeast direction, dotted with more than 100 pro-glacial, landlocked and epi-shelf lakes (Ravindra et al. 2002; Verlecar et al. 1996). This oasis is located on the Princess Astrid Coast in Queen Maud Land, East Antarctica (Fig. 1) and is bound by the Antarctic ice sheet on the south and epi-shelf lakes and ice shelf in the north.

Fig. 1 Location map of Schirmacher Oasis, East Antarctica

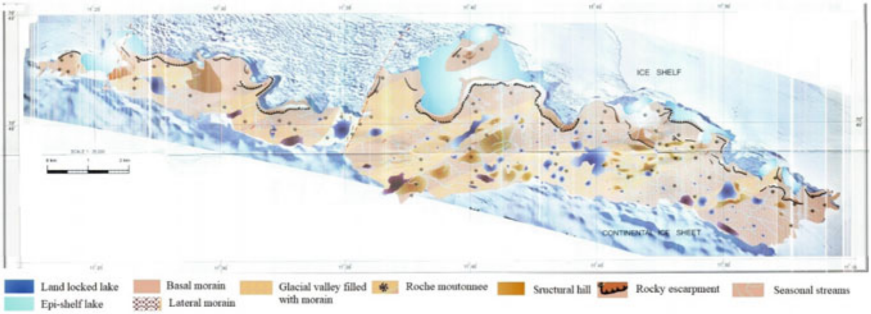

Fig. 2 Geomorphological map of Schirmacher Oasis (*modified after GSI map 2006*)

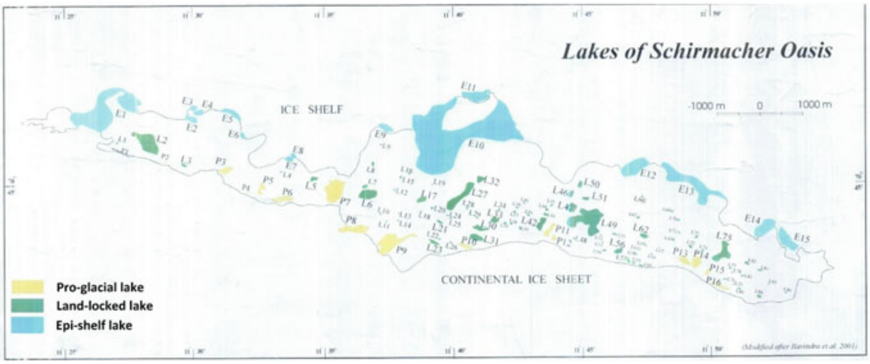

Fig. 3 Epi-shelf, Land-locked and Pro-glacial Lakes of Schirmacher Oasis, East Antarctica

The Schirmacher region in East Antarctica is characterized by a very distinct periglacial environment having typical geomorphological units. The oasis is dotted with more than 100 lakes of Pro-glacial, Land-locked and Epi-shelf nature (Fig. 3). The landscape, including erosional and depositional features (Fig. 2), offers a scope to study paleoclimatic changes significantly during the Late Quaternary time. The recent works of Warrier et al. (2014), Mahesh et al. (2015) and (2017) have explained the climate change phenomena in this area. The lake sediments offer an opportunity to study residues' hydrodynamics, resulting in a change in environmental parameters. The immature and unsorted sediments in this periglacial environment are transported and deposited by meltwater (Srivastava et al. 2018). The visible layers in lake sediments are not present in the entire Schirmacher region. But the indirect approach led to the identification of different layers, and these sedimentary layers contain chronologically ordered information on the paleoclimatic evolution of the region. The ice sheet recession deposited various moraines, helping in understanding climate change in a better way. Understanding the geomorphology and paleoclimatic evolution of

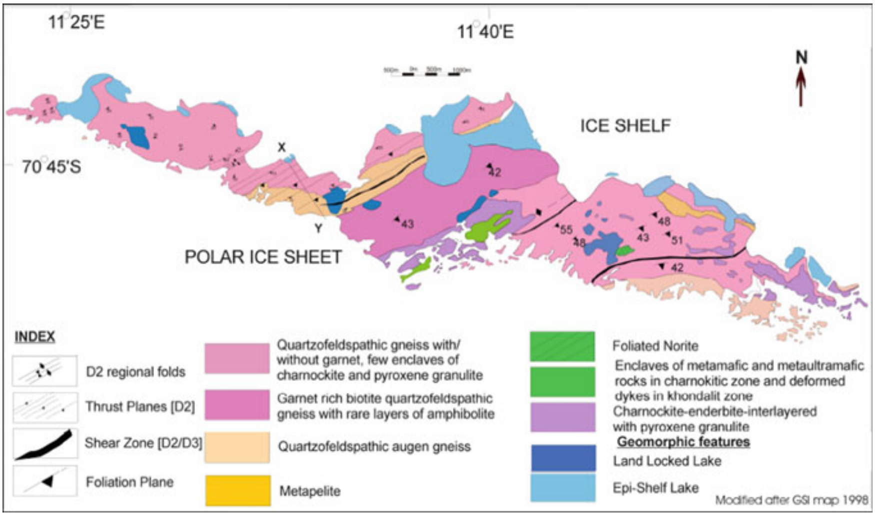

Fig.4 Geological map of the Schirmacher Oasis (modified after GSI map, 1998)

the Schirmacher region will contribute significantly to the present knowledge of palaeoclimatic information and sedimentation characteristics.

2 General Geology of Schirmacher Oasis

The Schirmacher Oasis has undergone complex tectono-metamorphic evolution and emplacement of various intrusives. The rocks of the Schirmacher Oasis were subjected to multiple events of metamorphism and deformation. Several earlier workers (Sengupta 1986, 1988; Peach and Stackebrandt 1995; Ravikant et al. 2004; Bose and Sengupta 2003) studied the detailed geological history of the area. The modified geological map of GSI (1998), Fig 4, shows NE-SW trending litho-units represented mainly by orthogneiss, paragneiss, mafic granulite, ultramafic enclaves and lamprophyre dykes. These rocks later underwent a subsequent amphibolite facies equilibration along a retrogressive P-T path resulting in symplectitic textures in various litho-units (Ravikant and Kundu 1998; Bose and Sengupta 2003).

3 Methodology

The Late Quaternary paleoclimatic history of the Schirrmacher region has been explained with the multi-proxi approach's help. This includes sedimentological studies, sediment geochemistry, OSL geochronology etc. A brief description of these methods are as follows;

(i) Granulometric analysis: The granulometric study is an excellent method to understand the hydrodynamic condition of sediment transport and deposition. The sediment core from the lacustrine environment provides regular data on this aspect. The sediment samples from the lacustrine environment were macerated adequately by following the methods given by Jacksons (1979). The pattern of grain size distributions of the macerated sediment samples has been obtained using a mechanical automatic sieve shaker and the standard pipetting method. The sieve analysis results are plotted to determine various statistical parameters (mean particle size, sorting, skewness, and kurtosis) and facilitate graphical interpretation.

(ii) Clay mineralogy: For clay mineralogical analysis, oriented slides for clay minerals have been prepared after following the methods given by Jackson 1979. These slides were then allowed to dry in air and subsequently scanned from 3 to 30° 2θ on a PANalytical X-ray diffractometer (X'Pert PRO) using Ni-filtered Cu Kα radiation. To know the presence of expandable clay minerals, the Ca-saturated slide of clay & silt fraction is exposed to ethylene glycol vapours and then scanned again with the same setting. The crystallinity of biotite is measured as a half-height width.

(iii) Scanning Electron Microscopy (SEM): SEM can obtain the quartz grain's high-resolution surface texture. For this, about 10 g of each sample was collected after coning and quartering and treated with dilute HCL and $SnCl_2$ (5M). From these chemically cleaned sediment samples, medium to refined sand-sized representative quartz grains was randomly picked for detailed surface texture studies. The grains were first mounted on specially designed aluminium stubs and then coated with 150 Å gold-palladium film before being studied under an SEM (EVO 40). The surface textures of quartz grains were classified in mechanical and chemical features to describe the processes which had acted on them. The work of Krinsley and Doornkam (1973), Krinsley and Funnell (1965), Krinsley and Margolis (1969), Krinsley and Smith (1981), Mahaney (1990), Mahaney and Kalm (1995) and Mahaney et al. (1996) have been used in explaining the surface texture of quartz grains.

(iv) Optically Simulated Luminescence (OSL) dating: OSL dating of glacial sediments from this type of Antarctic environment proved somewhat tricky as the luminescence sensitivity of the samples was low and many samples contained feldspars (possibly as inclusions) that could not be removed entirely even after repeated quartz-feldspar separation and treatment with mild HF. Therefore, an infrared stimulation step was introduced in the SAR protocol to optically remove the feldspar signal (Jain and Singhvi 2001). The samples were processed with 10% HCl and 30% H_2O_2 to remove carbonates, and organic matter under subdued red LED light (~650nm). These were then dried and sieved to obtain a 90–210 μm grain size fraction. Quartz and feldspar mineral fractions were isolated using sodium-polytungstate heavy liquid ($\rho =$

2.58 g/cm^3). Magnetic grains were separated using Franz magnetic separator. Quartz grains were etched using 40% HF for 80 minutes with continuous magnetic stirring (followed by a treatment of 12N HCl for 30 minutes, to remove insoluble fluorides. The resultant fraction was dried and checked for purity using IRSL stimulation. Samples with finite IRSL signal were re-etched for 10 min with HF followed by 12N HCl, re-sieved and retested with IRSL.

The annual radiation dose rate was determined by measuring the radioactivity concentration (Singhvi et al. 2001; Murray and Olley 2002). Dose-rate estimates were based on either or a combination of thick source ZnS (Ag) alpha counting for Uranium and Thorium's elemental concentrations using the Daybreak-582 alpha counters and K using gamma-ray spectrometry.

(v) Total Organic Carbon (TOC): Sub-samples from the untreated bulk sediment samples were analyzed for TOC by heat treatment.

4 Results

The multi-proxy data generated from the moraines and sediment cores of various lakes from the Schirmacher region, cDML, East Antarctica has provided better insight into the Late Pleistocene Holocene paleoclimatic evolution of the area during the Late Quaternary.

The glacial signatures are very well preserved in all kinds of sediments of this region. The sediments from the lacustrine environment are immature, chemically unaltered, have microscopic drainage pattern (Srivastava et al. 2018). The provenance of these sediments is from medium to high-grade metamorphic terrain. The patterns of fluctuations in different granulometric and statistical parameters (Fig. 5) show

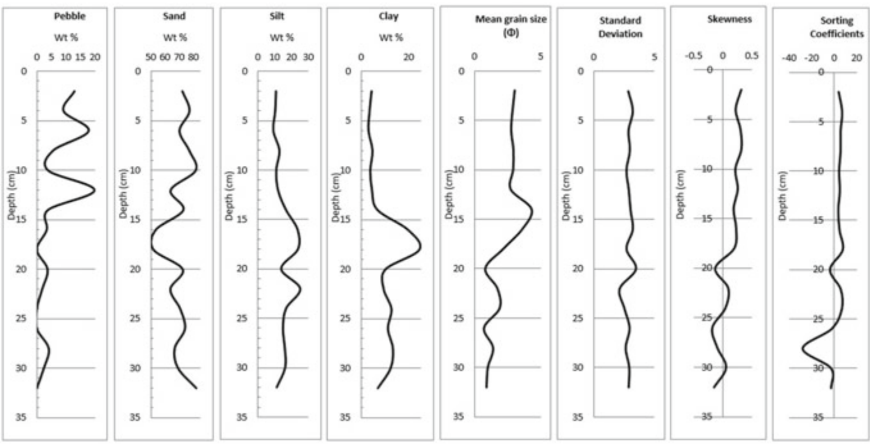

Fig. 5 Granulometric variation in lake sediments from Schirmacher Oasis, East Antarctica

alternate warmer and cooler phases at different intervals. At 15–20 cm depth, a noticeable change in the pattern (a dominant warming phase) has been observed.

The clay minerals indicate a gradual shift in the weathering regime and that in climate from strongly glacial to fluvioglacial during Late Quaternary. But the warm period has not altered the overall clay chemistry. The effect of warming is visible on the sediments of the upper horizon and in pro-glacial sediments. Exclusively physical weathering has controlled the widespread sediments and composition of the clay fraction. The mixed layers of biotite have evidenced the evidence of gradual warming.

The results of surface textures of quartz grains have been discussed depth-wise and in the same samples. In general, it shows dominant glacial and glaciofluvial actions. The more refined quartz grains have shown maximum new growths and silica precipitation, while the coarse grains are primarily fresh, representing sub-glacial to supraglacial transportation. The quartz grains show wide variations in their surface textures when compared with depth and size. New growths, straight grooves and arcuate steps show a positive correlation with depth in refined quartz grains (63 μm) and are dominant in older glacial sediments. A similar result has also been demonstrated by medium quartz grains (250 μm). The role of glacial crushing and grinding is more pronounced on the coarser quartz grains (250–500 μm). The fluvioglacial system's effect is evident with a mix population of these surface textures, especially in the middle horizon lake sediments. This effect becomes more pronounced with an increase in size. The younger quartz grains show a dominance of fluvial impact and lacustrine environment, especially in the coarser grains. Edge abrasion and surface abrasion are high in older sediments as well as in coarser grains. The coarser quartz grains have preserved glacial action better than, the more refined grains (Srivastava et al. 2018).

The OSL chronology on moraines has provided information on different events of deglaciation in the Schirmacher region, East Antarctica. The retreat of EAIS initiated much earlier than it was thought (sometime before 171 ka). Since then, it has receded in different phases. In the first phase of retreat, the exposure of some of the highest points (>200 m msl) of Schirmacher Oasis took place. The ice sheet behaves partially as a valley glacier by moving along the pre-existing structural and topographical valleys. This happened in the second phase of retreat (~95 ka to 65 ka). Deglaciation of the area was almost complete by the end of this phase. Few localized remnants of ice sheet remained in the exposed valleys' lower reaches, which vanished around 22 ka. There is no evidence of morainic deposits belonging to the Last Glacial Maximum. Formation of lake sediments started before 42 ka marks the beginning of climate change from glacial to glaciofluvial.

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