JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.91, June 2018, pp.651-663

Transition in Late Quaternary Paleoclimate in Schirmacher Region, East Antarctica as Revealed from Lake Sediments

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ABSTRACT

The lacustrine sediments are one of the best sources to provide information on climate change, specially in peri-glacial climatic region. Schirmacher Oasis, located on the Princess Astrid Coast in Queen Maud Land, is one of the few areas in East Antarctica that provides valuable information on paleoclimate of the region with various depositional features formed due to deglaciation process. This Oasis is dotted with more than 100 lakes of proglacial, land-locked and epi-shelf type. The multi-proxy sedimentological data, generated from the sediment cores from land-locked lakes and grab sample from a proglacial lake, lying in the same drainage line in the central part of Schirmacher region has provided better insight into the paleoclimatic evolution of the region. The immature and chemically unaltered lake sediments have shown restricted drainage pattern. Different phases of warmer and cooler intervals are highlighted by the patterns of fluctuations in different sedimentological and statistical parameters. The dominance of glacial signatures is very clear on the lake sediments as revealed by the surface textures of quartz grains. Physical weathering has mainly controlled the overall sediments and the composition of clay fraction. The clay minerals indicate a gradual shift in the weathering regime and therewith in climate from strongly glacial to fluvioglacial specially around 42 ka. This indicates beginning of warming of the area much before the LGM. But the warm period is not strong enough to alter the overall clay chemistry. Proxy records indicate short-period climatic oscillations during late Quaternary.

INTRODUCTION

Schirmacher Oasis is one of the few regions in Antarctica that provides a valuable repository of various depositional features formed due to deglaciation process. The Schirmacher Oasis is about 17 km long with a maximum width of 3 km. This Oasis is rocky area which is elongated in west-northwest to east-southeast direction, dotted with more than 100 proglacial, land locked and epi-shelf lakes. This Oasis is located on the Princess Astrid Coast in Queen Maud Land, East Antarctica (Fig. 1) and is bound by Antarctic ice sheet on the south and epi-shelf lakes and ice shelf in the north.

This work is aimed to highlight the various climatic events with the help of multi-proxy sedimentological data generated from the sediment cores of land-locked lakes and with grab sample from proglacial lakes, lying in the same drainage line in the central part of Schirmacher region for having a better insight into the paleo-climatic evolution of the region. The grab sample will highlight the impressions of recent climatic condition. The lake sediment cores have been used to characterise the granulometry, surface morphology and clay mineral contents in addition to the OSL dating for establishing the chronology of the events to establish the palaeoclimatic evolution of this region. The pro-glacial lake 'A' is about 5 km west of Maitri station, the second Indian research base (Latitude 70.766ºS and Longitude 11.734ºE) in Antarctica, whereas the land locked lakes 'B' and 'C' (Fig. 1) are located at a distance of about 3.5 km north-west of Maitri.

METHODOLOGY

The sediment samples from pro-glacial lake and landlocked lake were collected (after removing the surface cover) from different locations in Schirmacher Oasis. These samples were properly macerated with H_2O_2 and acetic acid, before being thoroughly washed with de-mineralised water and decanted. The grain size distributions of the macerated sediment samples were obtained using a mechanical automatic sieve shaker and the standard pipetting method. The results of the sieve analysis were plotted to determine various statistical parameters (mean particle size, sorting, skewness, and kurtosis) and to facilitate graphical interpretation. The surface textures of quartz grains were studied by Scanning Electron Microscopy (SEM). 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 fine sand-sized representative quartz grains were randomly picked for detailed surface texture studies. The grains were first mounted on specially designed aluminum stubs and then coated with 150 Å gold palladium film before being studied under an SEM (EVO 40).

Proper sampling for Optically Simulated-Luminescence (OSL) dating was carried out from the study area. For OSL dating, samples were treated with 10% HCl to remove carbonates and organic matters were removed with 35% H_2O_2. The bulk sample was sieved and 75 to 250 micron size fractions were separated by dry sieving. 75 to 150 micron quartz grains were separated from these fractions using sodium poly-tungstate (sp. gr. 2.58 g/cm^3) solution. The outer 20 micron skin of quartz was etched out by treating with 35% hydrofluoric acid for 120 minutes followed by 40 minute treatment with concentrated HCL. Entire processing was done under subdued red light. Quartz grains were mounted on stainless steel discs using silicon spray. Around 50 discs were measured for each sample. The measurements were carried out on a Risoe TL/OSL DA-15 reader with attached 40 mCi ^{90}Sr beta

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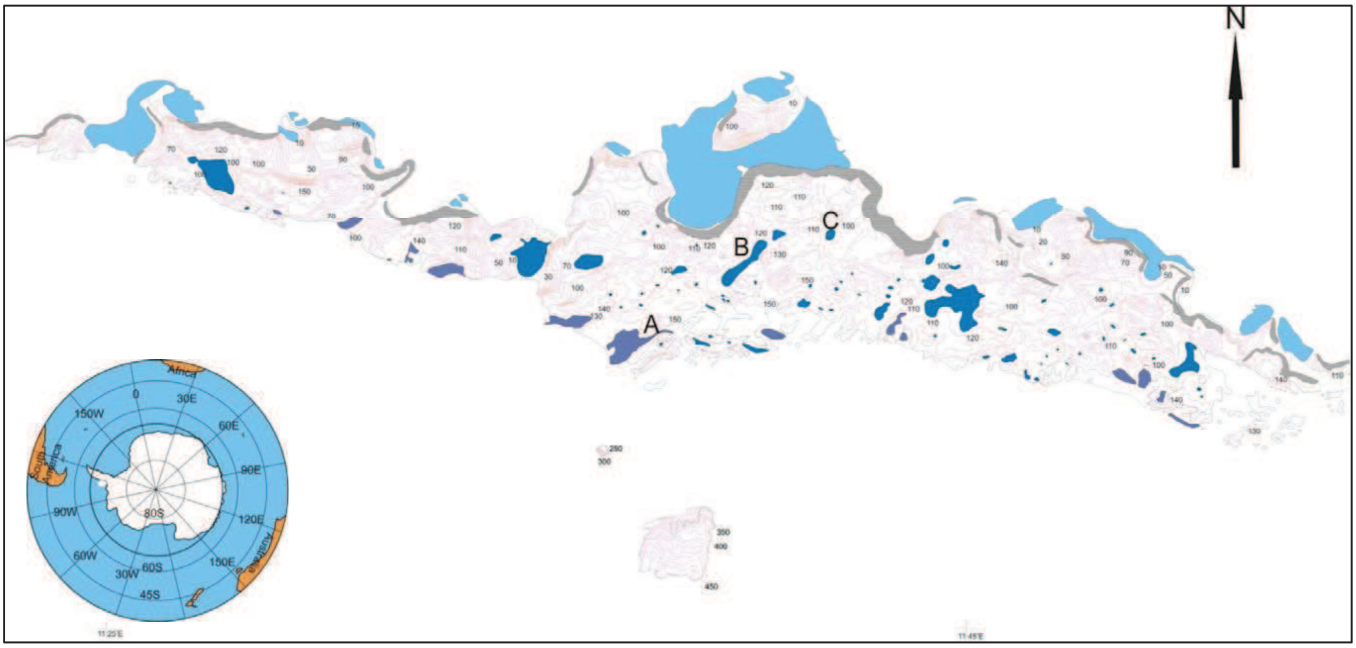

Fig.1. Location map of Schirmacher Oasis, East Antarctica and Lake 'A', 'B' and 'C'.

radiation source. Discs with recycling ratio of > 10% and recuperation of >5% were rejected.

For clay mineralogical analysis, the samples were treated with 10 ml of 30% H_2O_2 and 10% acetic acid in order to remove organic and carbonate matter, respectively. Free iron is leached out by adding 3N sodium citrate, 1N NaOH and sodium-di-thionite. From these treated samples sand fraction was removed by wet sieving and the clay fraction was separated by following the Stoke's law of settling velocity. Silt fraction was also separated by repeated pipetting. The separated clay and silt aliquot is saturated each with 1N $CaCl_2$. To prepare the slides 1 ml of clay and silt fraction was pipetted out and smeared on a glass slides. 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 at Geological Survey of India, Faridabad. To know the presence of expandable clay minerals, the Ca-saturated slide of clay & silt fraction is exposed to the vapours of ethylene glycol and then scanned again with the same setting. The clay mineral identification was done by following the standard procedures mentioned in Jacksons (1979). Crystallinity of biotite is measured as a half height width.

PREVIOUS WORK

A diverse suite of sediments covering a wide range of deposit types from Antarctic periglacial climate have been focused in several previous research studies (e.g., Margolis and Kennett, 1971; Mahaney et al., 1996; Asthana and Chaturvedi, 1998; Tulaczyk et al., 1998; Strand et al., 2003; Shrivastava et al., 2009). Asthana and Chaturvedi (1998) carried out grain-size determinations and morphoscopic studies of modern supra-glacial sediments, highlighting the polymodal distribution patterns of sediments.

The characterization of Antarctic sediments by SEM along with other properties was also carried out in several of these previous studies (Mahaney et al., 1996; Margolis and Kennett, 1971; Strand et al., 2003; Tulaczyk et al., 1998). Shrivastava et al. (2009) studied the imprint of climatic fluctuations on quartz grains from lake sediments, observing glacial, glaciofluvial, and aeolian effects. Asthana et al. (2009) and Asthana et al. (2013) characterized and highlighted surface microtextures of quartz grains originating from glaciolacustrine sediment cores. In that study, various microtextures were used to document grain damage originating from sediment transport processes, during movement of grains from inland ice and eventually into the land- locked lakes of the Schirmacher Oasis.

The sediments document an intensification of glacial action by the enhanced presence of subglacial facies (Hambrey et al., 2003) and a slight decrease in meltwater associated with sediment deposition. Based on different proxy data of lake bottom sediment core from Priyadarshini lake, adjacent to our study area, it has been inferred that the period between year 30.64 Ka and 21.68 Ka BP is cooler than period between 32.66 Ka and 30.64 Ka BP. A small period between 29.9 Ka and 28.89 Ka BP indicated by a wet period (Achyuthan et. al, 2008). Asthana et al. (2013) studied the characters of glacial sediments from two different periglacial environments of East Antarctica.

GRANULOMETRIC ANALYSIS

The granulometric analysis including size fractions, central tendency and statistical analysis show fluctuation in the weight percentages of sand, silt and clay, sorting, skewness and kurtosis in all sediment samples. Pebbles/drop stones also form an integral part of this granulometric analysis.

Sediments of pro-glacial lake 'A' consist of high percentage of pebbles and coarse sand totalling 89.9% followed by silt and clay 11.1% and 6.9% respectively. The sediments are extremely poorly sorted. Mean grain size varies between medium to coarse sand, and characterized by negatively skewed, leptokurtic distribution pattern (Table 1). Majority of polymodal (Fig. 2) grain size population represents traction and saltation as mode of transportation (Fig. 3). Sediments of lake 'B' are very poorly sorted, platy to mesokurtic, dominated by medium to coarse sand with sand percentage varying between 51.6 to 81.6%, silt percentage varying between 9.1 to 25.1% and clay percentage varying between 2.9 to 24.5% (Table 1). The dominating modes of transportation of polymodal (Fig. 4) sediments are traction and saltation as (Fig. 5). Sorting coefficient is highly variable between negative and positive values. Pebble concentration varies between 0 to 19.8% (Fig. 6). Sediments of lake 'C' show near polymodal distribution pattern (Fig. 7), having very poor sorting, platy to mesokurtic and contain dominantly fine sand to silt. Sorting coefficient is also highly variable between positive values. Traction and saltation were the main mode of transportation in these three lakes (Fig. 8). The sand, silt and clay percentages vary between 30.8 to 37.7%, 40.5 to 47.6% and 15.4 to 20.5% respectively. Pebble

Table 1. Weight percentage of pebble, sand, silt, clay and statistical parameters of sediment samples from Lake A and B, Schirmacher Oasis, East Antarctica

Sl. No.	Sample No.	Depth (cm)	Pebble (wt%)	Sand (wt%)	Silt (wt%)	Clay (wt%)	Mean (Mz)	Standard Devistion (SD)	Skewness (Sk)	Kurtosis (K)	Sorting Coefficient (So)
1	PG	2	0	81.93	11.14	6.94	0.53	2.68	-0.13	1.55	-2.4
2	33/6/1	32	2.40	69.12	16.18	12.30	3.04	2.83	0.32	0.98	4.072
3	33/6/2	30	4.08	66.67	15.95	13.29	2.88	3.21	0.22	0.90	7.12
4	33/6/3	28	0	73.96	14.87	11.17	2.77	2.85	0.31	1.11	5.780822
5	33/6/4	26	0	70.61	16.73	12.66	2.94	2.97	0.32	0.96	5.752941
6	33/6/5	24	1.83	63.65	25.15	9.37	2.92	2.68	0.22	0.97	4.449541
7	33/6/6	22	3.68	72.35	13.83	10.13	2.74	2.88	0.26	1.31	5.067568
8	33/6/7	20	0	51.65	23.85	24.50	4.30	3.02	0.19	0.71	3.716578
9	33/6/8	18	3.41	53.38	23.58	19.62	3.61	3.21	0.23	0.80	4.81203
10	33/6/9	16	3.83	72.82	16.60	6.75	2.18	2.69	0.20	1.18	7.708333
11	33/6/10	14	19.79	63.88	11.90	4.43	0.82	3.47	-0.13	1.27	-3.69333
12	33/6/11	12	3.82	81.59	10.88	3.71	1.73	2.12	0.10	1.32	5.93617
13	33/6/12	10	5.58	77.02	12.75	4.65	1.91	2.51	0.05	1.39	6.888889
14	33/6/13	8	17.81	70.10	9.12	2.98	0.72	2.94	-0.18	1.12	-2.16667
15	33/6/14	6	9.18	77.16	10.26	3.40	1.41	2.62	-0.09	1.34	-28
16	33/6/15	4	12.91	72.12	10.71	4.26	1.01	2.92	0.06	1.09	-2.69608
17	33/6/16	2	15.18	72.29	9.46	3.06	0.92	2.86	-0.15	1.14	-2.65

percentage varies between 1.8 to 8.2% (Table 2, Fig. 9). Most of the sediment samples from all the lakes show modes coarser than –1 ϕ, although some samples also showed modes finer than 2 ϕ. Interestingly, there is a prominent mode between 1 and 2 ϕ in almost all samples (Fig. 7). In the lake C, the concentration of pebbles have shown fluctuating trend which vary between 0 to 10% with higher silt+clay percentage. The concentration of finer sediments is highest in lake C as it is situated in the last of the studied drainage line.

CLAY MINERALOGY

On land, clay minerals are generally the products of weathering of rocks and soils. The type of clay minerals produced mainly reflects the climatic conditions of the catchment area, as well as the geology and topography of the region. The sharpness of peak and shape of diffractogram can be used to understand the degree up to which a mineral has undergone physical or chemical weathering. Therefore, such minerals and their pattern on diffractogram can be used as a potential tool in palaeoclimatic reconstruction (Sirocco and Lange, 1991; Dilli and Pant, 1994), and the processes which had operated on these sediments.

The XRD analysis of clay minerals from the sampled sediments showed very similar characteristics across the study site. Minerals in the clay fraction, which are present in all samples of lake sediments from Schirmacher Oasis, are quartz, plagioclase feldspars and K-

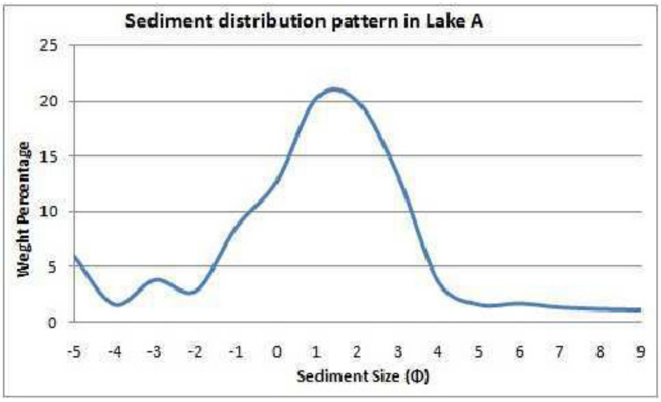

Fig.2. Sediment distribution pattern in Lake A.

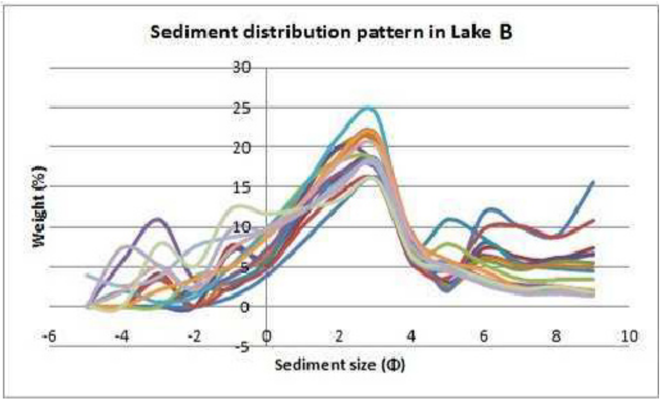

Fig.4. Sediment distribution pattern in Lake B.

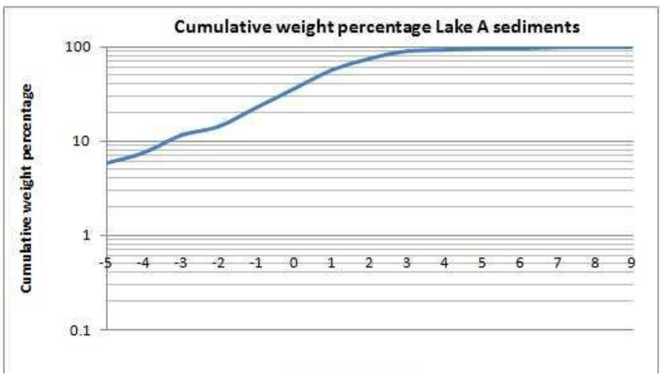

Fig.3. Cumulative weight percentage Lake A sediments.

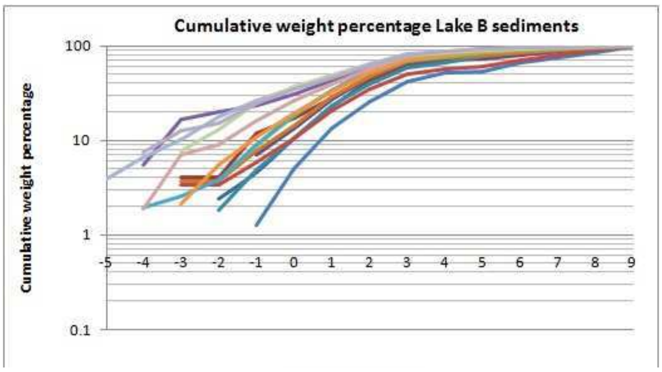

Fig.5. Cumulative weight percentage Lake B sediments.

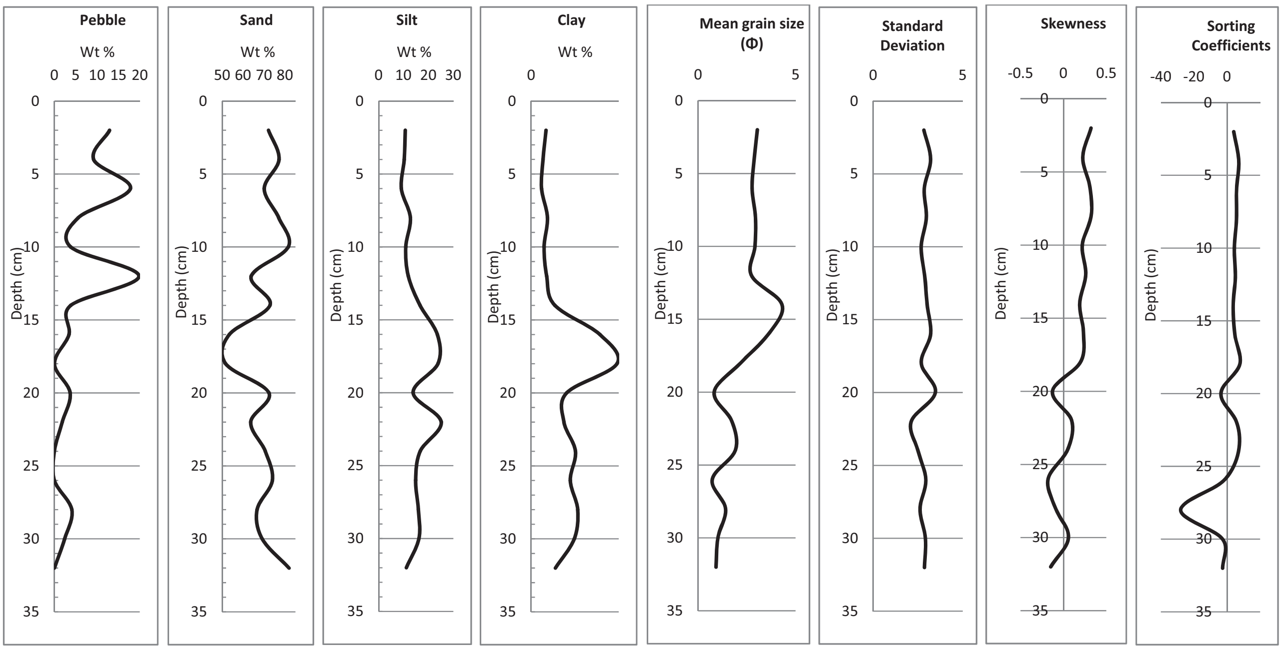

Fig.6. Weight percentage of pebble, sand, silt and clay along with statistical parameters from sediments of Lake B (Long lake), Schirmacher Oasis.

feldspar (Table 3). Biotite was the dominant mineral, and the other minerals present in subordinate amounts were chlorite, feldspar, and quartz. The sharpness and shape of the biotite peaks in the diffractograms as obtained in most of the sediment samples, indicated that this mineral had remained unaltered, and was derived from disintegration and/or mechanical processes only. Samples from lake A (pro-glacial lake) (Fig. 10) and from the upper horizons of lake B (Fig. 11) have shown effect of chemical alteration of biotite in the form of mixed layers, indicating effect of warmer temperature as compare with the deeper sediments of lake B (Fig. 12). Smectite is present in the last core (lake C) (Fig. 13), where the amount of fine sediments (clay and silt) is more than coarse fraction. Other parameters in the diffractogram remained same in lake C.

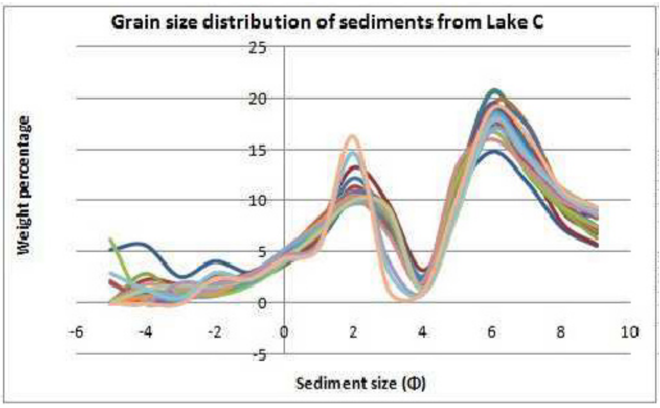

Fig.7. Grain size distribution of sediments from Lake C.

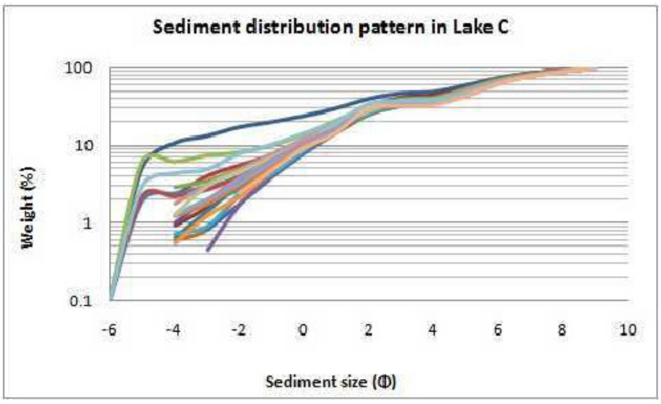

Fig.8. Sediment distribution pattern in Lake C.

SCANNING ELECTRON MICROSCOPY OF QUARTZ GRAINS

SEM studies have been carried out on glacial quartz grains to determine the diagnostic features of erosion, transportation and deposition of the glacial environment. Quartz grains in the 45–60 μm size range and of glacial origin show characteristic surface features under the electron microscope (Krinsley and Funnell, 1965). The important mechanical features include conchoidal fractures, minor striations, polished surfaces, arcuate steps, imbricate breakage blocks, and small-scale indentations. Whalley and Krinsley (1974) used the surface features of quartz grains to obtain additional information on the various glacial sub-environments. The present study identifies the differences between supraglacial and subglacial materials, and highlights the usefulness of surface precipitation features in providing information on the sequence of events. The important studies of Krinsley and Doornkamp (1973), Margolis and Kennett, (1971), Margolis and Krinsley, 1974; Whalley and Krinsley (1974), Bull (1978), Helland and Diffendal (1993) and Mahaney (1995) in this field have been used to describe the surface microtextures of quartz grains. In general the entire surface features of quartz grains are being used to determine the paleoenvironmental history.

The important morphological textures are angular and rounded outline, low relief, medium relief and high relief. The mechanical textures include large and small conchoidal fractures, arcuate and straight steps, imbricated blocks, large breakage blocks, fractured plates, subparallel linear fractures, curved grooves, straight grooves/ strations, V-shaped percussion cracks, meandering ridges, edge abrasion, surface abrasion, deep troughs and pitted surface/collision pits. Chemical textures observed are weathered surfaces, small and large precipitation features, adhering particles and new growths.

Typical morphological, mechanical, and chemical textures of quartz grains from lake A, B and C are shown in Fig. 14, 15 and 16 and frequencies of occurrence (%) of these textures are listed in Table 4.

Table 2. Weight percentage of pebble, sand, silt, clay and statistical parameters of sediment samples from Lake C, Schirmacher Oasis, East Antarctica

Sl. No.	Sample No.	Depth (cm)	Pebble (wt%)	Sand (wt%)	Silt (wt%)	Clay (wt%)	Mean (Mz)	Standard Devistion (SD)	Skewness (Sk)	Kurtosis (K)	Sorting Coefficient (So)
1	33/5/1	48	17.37	32.41	37.29	12.94	2.74	4.27	-0.40	0.93	59.30
2	33/5/2	46	3.43	41.39	41.61	13.57	4.01	2.96	-0.27	0.83	4.11
3	33/5/3	44	2.64	33.02	48.13	16.21	4.43	2.85	-0.34	0.85	3.28
4	33/5/4	42	2.90	33.60	45.52	17.98	4.44	2.96	-0.34	0.84	3.42
5	33/5/5	40	3.06	31.97	47.63	17.34	4.45	2.93	-0.35	0.86	3.33
6	33/5/6	38	2.30	32.73	45.93	19.03	4.57	2.91	-0.37	0.81	3.43
7	33/5/7	36	1.78	35.54	45.14	17.54	4.47	2.84	-0.34	0.77	3.65
8	33/5/8	34	5.50	34.15	44.37	15.98	4.26	3.15	-0.37	0.90	4.00
9	33/5/9	32	4.97	36.18	43.41	15.44	4.09	3.13	-0.30	0.88	4.13
10	33/5/10	30	2.84	35.92	44.63	16.61	4.31	2.93	-0.31	0.82	3.68
11	33/5/11	28	2.71	37.21	42.89	17.20	4.23	2.95	-0.27	0.96	2.66
12	33/5/12	26	3.05	37.74	42.49	16.71	4.17	3.03	-0.29	1.01	2.44
13	33/5/13	24	3.93	37.31	41.44	17.33	4.17	3.11	-0.30	0.75	6.04
14	33/5/14	22	3.97	35.37	43.54	17.13	4.24	3.08	-0.30	0.84	4.00
15	33/5/15	20	8.24	32.94	41.84	16.97	4.03	3.77	-0.39	1.12	4.68
16	33/5/16	18	1.78	36.90	42.63	18.69	4.45	3.02	-0.27	0.71	5.28
17	33/5/17	16	2.42	33.33	44.02	20.23	4.47	3.00	-0.33	0.79	3.67
18	33/5/18	14	2.20	36.07	42.52	19.21	4.34	3.05	-0.30	0.79	3.95
19	33/5/19	12	3.32	35.81	40.46	20.41	4.35	3.15	-0.33	0.80	4.13
20	33/5/20	10	5.03	33.37	42.82	18.78	4.20	3.25	-0.29	0.86	4.19
21	33/5/21	8	4.58	33.92	41.04	20.46	4.42	3.20	-0.35	0.84	3.91
22	33/5/22	6	3.81	33.04	43.04	20.11	4.47	3.12	-0.35	0.80	4.40
23	33/5/23	4	7.92	30.88	41.75	19.45	4.22	3.46	-0.40	0.90	4.75
24	33/5/24	2	2.47	31.06	45.97	20.51	4.74	3.11	-0.30	0.77	4.13

The quartz grains from lake A (pro-glacial lake) vary between sub-round [Fig. 11(A1)] to highly angular (Fig. 14-A2 to A8), whose shape vary between prolate [Fig. 14(A3 to A7)] to sub-spherical [Fig. 14 (A1 and A8)]. There are large and small conchoidal fractures [Fig. 14 (A2, A3, A5 and A8)] with arcuate and straight steps [Fig. 14 (A2 and A8)]. Imbricate blocks and fractured plates are less abundant [Fig. 14 (A6)]. Edge and surface abrasion varies between 5 to 80 %. These grains also show straight and curved grooves [Fig. 14 (A2 and A8)]. Weathering surface vary between 5 to 90 % with some adhering particles and new growths. Some grains also show small and large precipitates on their surface [Fig. 14 (A1 and A3)].

In lake B (land locked lake), the quartz grains are angular to sub angular [Fig. 15 (B1 to B8)] with dominant moderate and high relief features [Fig. 15 (B1 to B8)]. The shapes vary between bladed

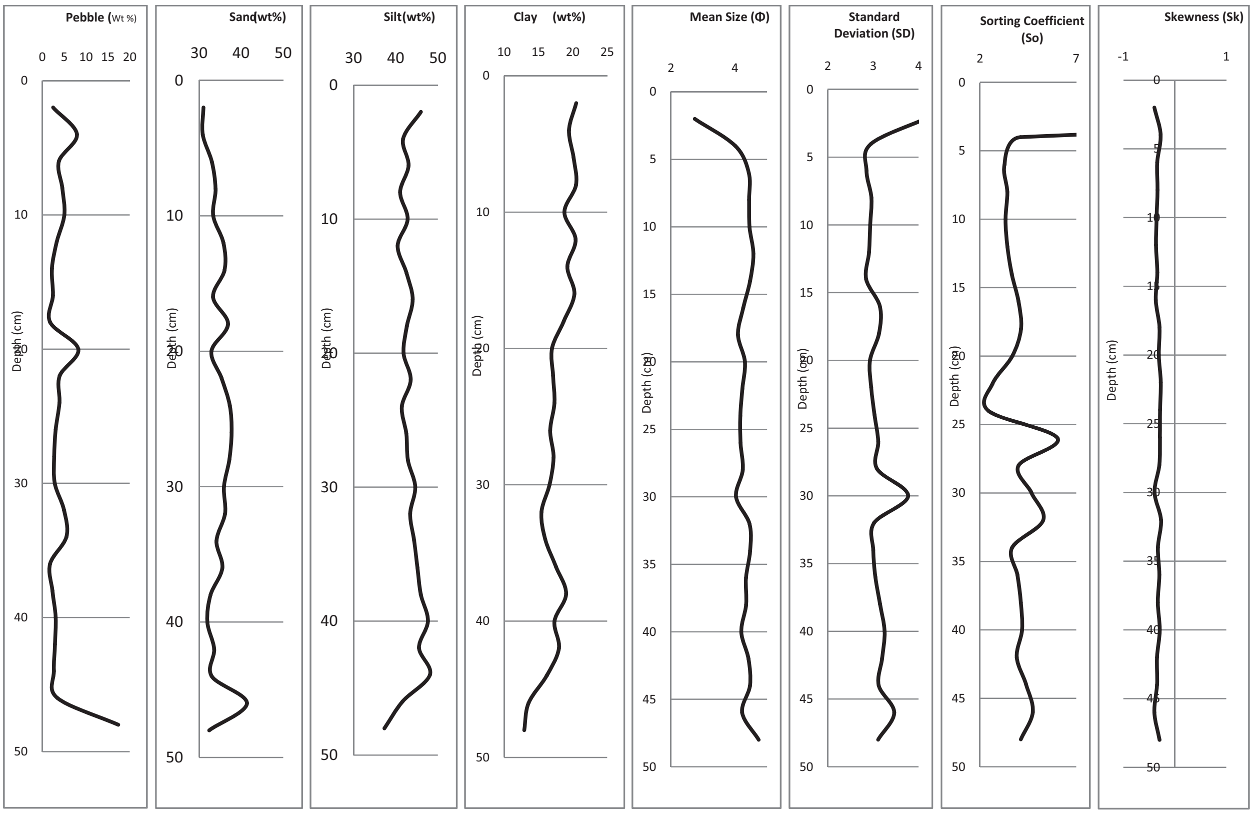

Fig.9. Weight percentage of pebble, sand, silt and clay along with statistical parameters from sediments of Lake C, Schirmacher Oasis.

Table 3. d-spacing of plagioclase feldspar, K-feldspar and Integral Breadth of biotite in clay minerals from Lake A (PG) and Lake B

Sl. No.	Sample No. (Lake B)	Depth (cm)	Pl-felds (A)	K-felds (B)	A-B	A/C	Integral Breadth (IB)
	PG (Lake A)		33.64	21.46	12.18	1.567568	0.79
1	6/33/1	32	10.6	7.3	3.3	1.452055	0.46
2	6/33/2	30	10.7	6.1	4.6	1.754098	0.5
3	6/33/3	28	7.3	4.4	2.9	1.659091	0.42
4	6/33/4	26	9	5.4	3.6	1.666667	0.44
5	6/33/5	24	7.8	6.2	1.6	1.258065	0.53
6	6/33/6	22	9.8	6.9	2.9	1.42029	0.51
7	6/33/7	20	7.5	5.1	2.4	1.470588	0.55
8	6/33/8	18	6	5.5	0.5	1.090909	0.59
9	6/33/9	16	7.6	6	1.6	1.266667	0.55
10	6/33/10	14	9.6	7	2.6	1.371429	0.64
11	6/33/11	12	12.6	6.9	5.7	1.826087	0.68
12	6/33/12	10	18.31	11.78	6.53	1.554329	0.71
13	6/33/13	8	21.16	14.04	7.12	1.507123	0.71
14	6/33/14	6	25.32	11.07	14.25	2.287263	0.86
15	6/33/15	4	15.97	9.36	6.61	1.706197	0.69
16	6/33/16	2	19.98	10.77	9.21	1.855153	0.82

Sample No. (C)	Depth (cm)	Pl-felds (A)	K-felds (B)	A-B	A/B	Integral Breadth (IB)
5/33/1	48	12.51	8.16	4.35	1.533088	0.75
5/33/2	46	21.12	11.38	9.74	1.855888	0.76
5/33/3	44	9.65	5.97	3.68	1.616415	0.67
5/33/4	42	13.39	8.54	4.85	1.567916	0.68
5/33/5	40	10.62	6.31	4.31	1.683043	0.76
5/33/6	38	15.23	8.92	6.31	1.707399	0.72
5/33/7	36	7.96	4.99	2.97	1.59519	0.78
5/33/8	34	7.83	5.7	2.13	1.373684	0.76
5/33/9	32	15.8	7.86	7.94	2.010178	0.75
5/33/10	30	8.4	3.62	4.78	2.320442	0.83
5/33/11	28	6.66	4.6	2.06	1.447826	0.8
5/33/12	26	6.89	5.73	1.16	1.202443	0.81
5/33/13	24	11.97	5.04	6.93	2.375	0.77
5/33/14	22	10.35	6.81	3.54	1.519824	0.85
5/33/15	20	9.46	6.56	2.9	1.442073	0.83
5/33/16	18	7.72	6.2	1.52	1.245161	0.84
5/33/17	16	7.54	5.55	1.99	1.358559	0.88
5/33/18	14	9.53	4.77	4.76	1.997904	0.85
5/33/19	12	5.4	3.65	1.75	1.479452	0.81
5/33/20	10	9.09	4.01	5.08	2.266833	0.83
5/33/21	8	10.26	6.46	3.8	1.588235	0.75
5/33/22	6	12.52	8.61	3.91	1.454123	0.73
5/33/23	4	6.73	5.36	1.37	1.255597	0.81
5/33/24	2	5.49	5.33	0.16	1.030019	0.84

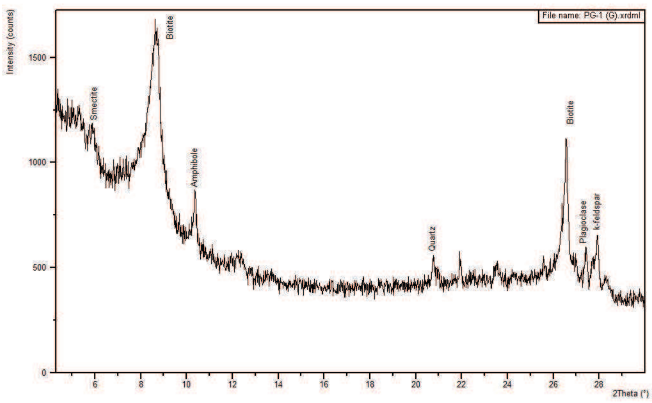

Fig.10. Diffractogram of clay minerals from the sediments of pro-glacial ('A') lake, Schirmacher Oasis, East Antarctica.

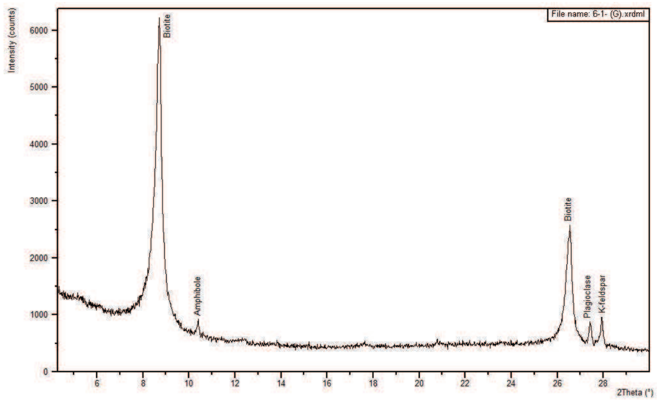

Fig.12. Diffractogram of clay minerals from the sediments of deepest level sediment of lake 'B', Schirmacher Oasis, East Antarctica.

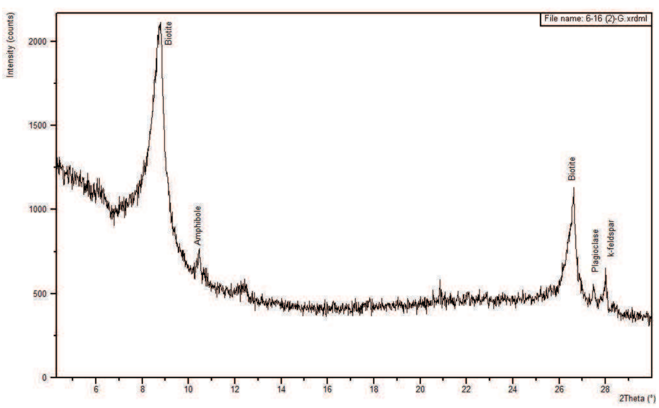

Fig.11. Diffractogram of clay minerals from the sediments of uppermost level sediment of lake 'B', Schirmacher Oasis, East Antarctica.

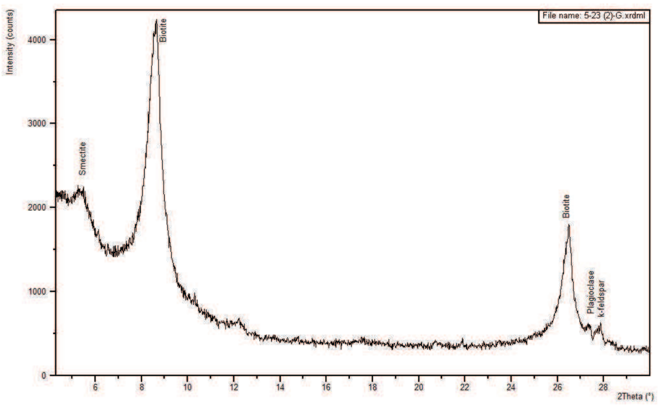

Fig.13. Diffractogram of clay minerals from the sediments of lake 'C', Schirmacher Oasis, East Antarctica.

Table 4. SEM properties of quartz grains (in %) from sediment of Lake A, Lake B and Lake C

		Sample number																							
		Lake A								Lake B								Lake C							
		A1	A2	A3	A4	A5	A6	A7	A8	B1	B2	B3	B4	B5	B6	B7	B8	C1	C2	C3	C4	C5	C6	C7	C8
Morphological Texture	Angular outline	30	95	65	30	100	60	95	100	90	100	100	100	100	95	60	100	95	65	80	100	5	100	65	100
	Rounded outline	70	5	35	70	0	40	5	0	10	0	0	0	0	5	40	0	5	35	20	0	95	0	35	0
	Low relief	10	5	35	5	5	20	2	5	10	10	5	20	5	25	20	15	25	10	20	5	5	5	0	10
	Medium relief	10	10	45	20	45	50	50	50	50	35	40	80	50	55	40	85	75	20	40	85	90	25	40	80
	High relief	80	85	20	75	50	30	48	45	40	55	55	0	45	20	40	0	0	70	40	10	5	70	60	10
	Sphericity	Sub-spherical	Sub-spherical	Prolate	Prolate	Prolate	Prolate	Prolate	Sub-spherical	Sub-spherical	Prolate	Sub-spherical	Prolate	Sub-spherical	Prolate	Sub-spherical	Bladed	Bladed	Sub-spherical	Prolate	Prolate	Sub-spherical	Sub-spherical	Equant	Prolate
Mechanical textures	Large conchoidal fractures	15	10	5	10	10			40	20	50	20		30	65	20	20		40	20	5				20
	Small conchoidal fractures	5	10	10	10	10	10		35	10	10	5	10	10		10	5	5	20		70			10	30
	Arcuate steps	3	2	5	2	5	2	10	25	2	2			10			5		5	2	15			2	15
	Straight steps	3	5		2	5	2	10	10	2		2	2	5		10	2	2	2	2	10		25	3	2
	Imbricated blocks			5	5	5	5	10	5	5	5			10	2	10	5	2		10	10		5		2
	Large breakage blocks		40	5	10		25	10	10		30	5	45	40	40	15	15	10	10	10	5	2	10	35	20
	Fractured plates			5	5	5		10	5	2	1		5	5	2	5	2	5		2		5	15	2	5
	Subparallel linear fractures	10	2	5	5	5	2	15	5	10			5	2	2	5	2	5				5	20	3	
	Curved grooves	5	2	3	1		2		2			1	2	2	2		2	1		1		2	1	2	2
	Straight grooves/strations	2	10		5		10				1	1	2	2	2		2	1	2	10	2	3	2	1	2
	V-shaped percussion cracks	3	1	1	1	1						1	1				1		1	1		1		1	1
	Meandering ridges		3	3	5	2	5		5	5	2	1	2	5	1	2	2	2	5	2	15				5
	Edge abrasion	75	15	40	80	20	80	30	5	25	10	5	30	5	5	80	2	50	10	30	20	80	15	40	10
	Surface abrasion	70	10	10	20	20	80	30	2	10	5	5	15	5	2	85	0	60	15	25	5	75	20	20	2
	Deep troughts		25	10	5	10	10	10	10	5	2		10	30	2	10	10	10	10	10	5		5	30	5
	Pitted surface/Collision pits	10	1	2	2	1		1	1	1		1	1	1	1		2	5	2	2	1	2	1	2	1
Chemical textures	Preweathered surfaces	20	90	55	80	80	10	35	95	80	90	95	80	95	95	15	98	40	80	85	90	30	90	90	95
	Weathered surfaces	80	10	45	20	20	90	65	5	20	10	5	20	5	5	85	2	60	20	15	10	70	10	10	5
	Small precipitation features	2	10	2	2	10	20	2	2		5			5	5	5	1	2	10	2	15	1	2	2	2
	Large precipitation features		45		15		60	5		5						5								2	
	Adhering particles	1	2	1		1		1	2	2		1	1	1	1	1	2	10	5	3	10		1	1	1
	New growth	1	2	1	2	1			1	2	1	5		2	3		1	20	10	2	10			1	

[Fig. 15 (B5 and B8)], prolate [Fig. 15 (B2, B4 and B6)] and sub spherical [Fig. 15 (B1 and B7)]. Large and small conchoidal fractures [Fig. 15 (B1, B2, B3 and B6)] are also present in good amount with some arcuate and straight steps. Large breakage blocks [Fig. 15 (B5 and B8)] are fairly abundant. Straight and curved grooves along with meandering ridges vary between 1 to 5 percent. Edge and surface abrasion vary between 5 to 85 percent. Weathering surface vary between 5 to 85% with some precipitates, adhered particles and new growths.

The quartz grains of lake C (land locked lake) are highly angular [Fig. 16 (C1, C3, C4, C6 to C8)], sub angular [Fig. 16 (C2)] to sub round [Fig. 16 (C5)] in outline with mostly medium relief features. The shapes vary between bladed [Fig. 16 (C1)], prolate [Fig. 16 (C3, C4 and C8)], equant [Fig. 16 (C7)] and sub spherical [Fig. 16 (C2, C5 and C6)]. Large and small conchoidal fractures [Fig. 16 (C2, C3 and C8)] are fairly present in some grains. Arcuate and straight steps [Fig. 16 (C4 and C8)], imbricate blocks [Fig. 16 (C4)], fracture plates [Fig. 16 (C6)], sub parallel linear fractures [Fig. 16 (C6)] and v-shaped percussion marks are relatively less abundant. Weather surface vary between 5 to 70 percent with few precipitated. Adhered particles and new growths [Fig. 16 (C2)] are more present in smaller quartz grains.

OPTICALLY SIMULATED LUMUNASCENCE DATING

The optically simulated luminescence (OSL) dating of systematically collected morainic samples from the study area of Schirmacher Oasis show wide variation. These ages vary in Late Quaternary period indicating different stages of glaciation and de-glaciation during late Quaternary. Two samples from moraine gave 145±12 Ka and 79±7 Ka of age indicating deglaciation ages. One sample from lake sediment samples from a depth of 18-20 cm gave 42±3 Ka age. The details of different parameters are given in Table 5 and 6. The age from both the moraine samples (145±12 Ka and 79±7 Ka) represents major episodes of deglaciations in Schirmacher region whereas the age from lake sediments (42±3 Ka) marks the beginning of warming phase in Schirmacher Oasis.

Table 5. OSL dating of quartz grains from lake sediments and moraines of Schirmacher Oasis, East Antarctica.

Sl. No.	Sample	U (ppm)	Th (ppm)	K (%)	Average equivalent dose (De) in gray scale	Dose rate (Gray/Ka)	Age (Ka)
1	OSL-5	1.29	11.97	2.3	431±16	2.97±0.2	145±12
2	OSL-8	0.9	10.79	2.15	214±10	2.73±0.2	79±7
3	10B-Top	1.32	10.72	2.35	114±3	2.4±0.2	42±3

Table 6. Measurements made on Risoe-TL/OSL Reader (DA-15C/D, DA-20C/D)

Dating Protocol	Single Aliquot Regeneration Protocol (SAR) with IR	Pre heat temperature	260°C
Mineral used	Quartz (90-150 micron)	TL/cut heat temperature	260°C
Mineral etching	HF (35%)	Recycling ratio	<10%
Felspar check	IRSL	Recuperation	<5%
Stimulation source	Blue light from LED's (470nm)		
Detection	Approx. 380 nm (HoyaUV-340)		
Wavelength irradiation source	Sr-90		
Age software	Grun Age, 2003		
Dose rate evaluation	U & Th by ICPMS K by Flame photometer		

DISCUSSION

The studies based on organic geochemistry, environmental magnetism and radiocarbon dates have shown that the Schirmacher region has experienced different stages of glacial and interglacial phases (Mahesh et al., 2015, Warrier et al., 2014, Achuthan et al., 2008) in Late Quaternary time. The work of Srivastava et al. (2012) has highlighted the hydrodynamic condition of Schirmacher sediments. The paleoclimatic condition of Holocene time has been explained by Phartiyal et al. (2011). The granulometric analysis of the present work has indicated the fluctuations in the sedimentological parameters and in related paleoclimate. The type of polymodal distribution with one or more modes coarser or finer than 2 ϕ, is interpreted to represent sediment transport in the basal zone of the glacier by traction (Boulton et al., 1974; Boulton, 1978). The majority of sediments sampled from these locations fall in the medium to very coarse sand fractions. Sand and clay+silt percentages are inversely related in the sediment cores and higher sand percentage along with lower silt+clay percentage indicates higher discharge of melt water and vice-versa. This can be correlated with the prevailing climatic conditions. Based on increase and decrease in sand-silt-clay weight percentage, lake 'B' indicates six brief alternating relatively warm and cold periods respectively. Likewise, sediments of lake 'C' also indicate relatively six brief warmer and cooler phases. Lake 'C' shows a prominent cold phase in the middle horizon represented by very low sand percentage and very high clay+silt percentage. The weight percentage of pebbles or drop stone, deposited by melting of ice cover, has shown fluctuating trend but in general it has increased in the upper horizon in sediment core of Lake B, specially in 0 to 20 cm depth. In general there is a shift in the trends of all the granulometric parameters above 20 cm depth. Hence the depth of 20 cm suggest shift in climatic condition corresponding to high energy environment.

Poor crystallinity is often associated with chemical weathering and intense degradation processes, whereas physical weathering under a glacial climate tends to produce better crystallinities (Petschick et al., 1996). Another cause for the poor crystallinities could be grain size. Generally, larger smectites have a better crystallinity than smaller smectites. With intense glacial scour on the Antarctic continent resulting in diamicts with abundant silt and clay, poorer crystalline and finer smectites is expected (Ehrmann et al., 2005). The crystallinity of biotite from the study area is not due to re-deposition of glacial sediments and it does not reflect the proximity of the ice. The warm period is not strong enough to alter the overall clay chemistry. Clay size fractions of the sediments are largely composed of quartz, biotite, feldspar, amphibole and little smectite. This shows that the sediments are immature, chemically unaltered nature and have restricted drainage pattern. The glacial signal is very clear in this region, and physical weathering has exclusively controlled the composition of clay fraction. Biotite in clay fraction is detrital clay mineral, which produce from physical weathering and glacial scour, and are typical of the recent high latitudes. It is derived particularly from crystalline rocks, (Biscaye, 1965; Windon, 1976). The crystallinity of biotite is classified as very well crystalline (<0.4), well crystalline (0.4-0.6), moderately crystalline (0.6-0.8) and poorly crystalline (>0.8) (Diekmann et al., 1996). The crystallinity and chemical composition of biotite in clay fraction seems to indicate gradual sediment facies changes and changes the boundary of good crystallinity with the moderate crystallinity at 20 cm depth. In particular, there are no major or systematic differences in the overall clay mineral assemblages of proximal and distal lacustrine sediments, nor between coarse-grained and fine-grained sediments, suggesting

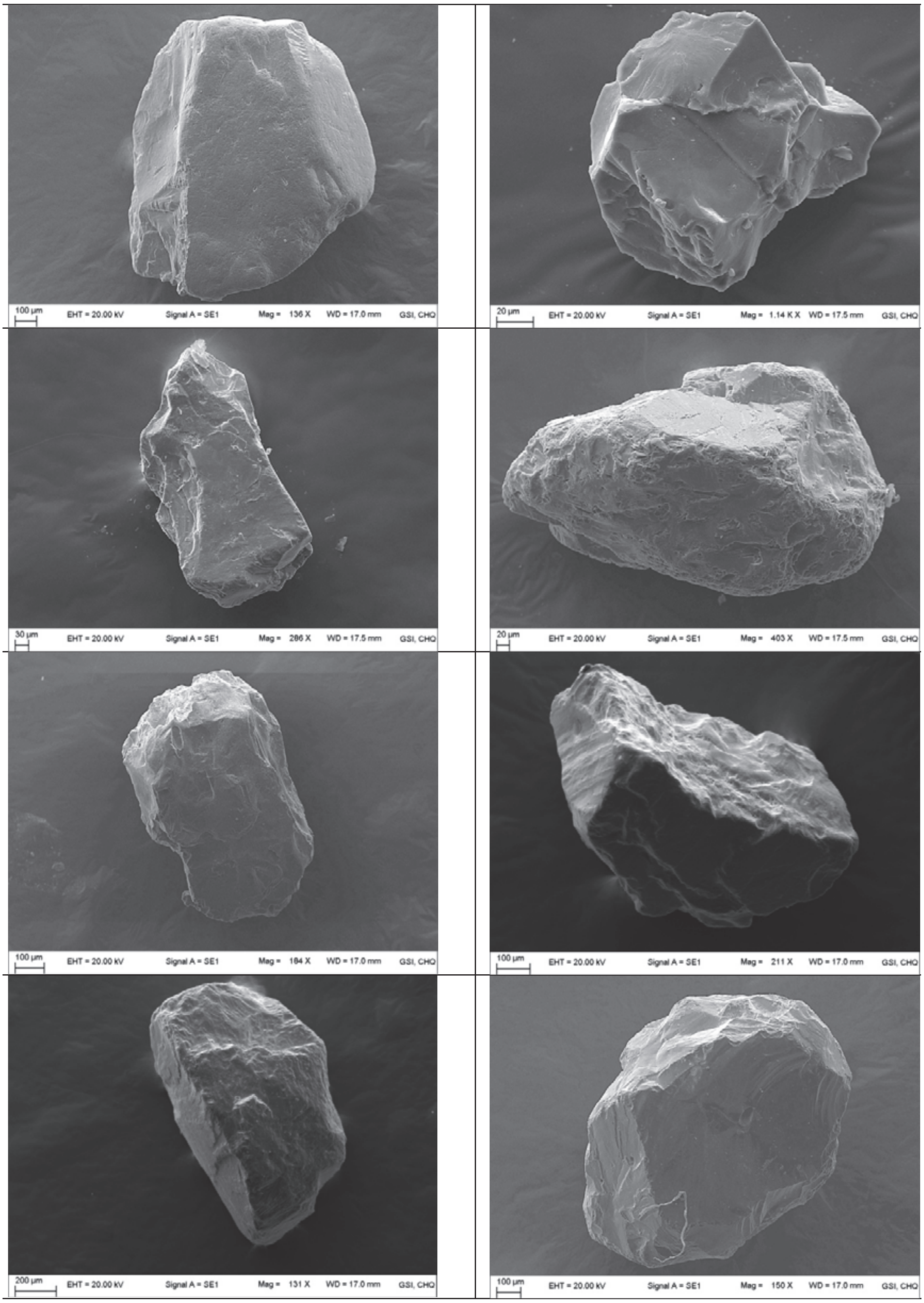

Fig.14. Scanning electron microscopy of quartz grain from sediments of Lake A. **A1:** Sub-round, sub-spherical grain with polished surface and grooves. **A2:** Highly angular with large conchoidal fractures. **A3:** Prolate, highly angular, fractured plate. **A4:** Prolate, sub-round, precipitation feature. **A5:** Prolate, angular, large and small conchoidal fractures. **A6:** Imbricate blocks and fractured plates. **A7:** Angular, fractured plate. **A8:** Highly angular, large and small conchoidal fractures.

that the clay mineral assemblages are not influenced by transportation, sedimentation or reworking processes. This also implies that the clay minerals are probably not the result of diagenetic alteration of appropriate detrital minerals. The main controls on the composition of the clay fraction, therefore, have to be climate and source area. Thus, the clay minerals indicate a gradual shift in the weathering regime and therewith in climate from strongly glacial to fluvioglacial. The clay mineral composition is controlled by the interplay between different source rocks and the main sedimentary processes taking place in the streams sediment deposition, like the size-sorting processes and bed load structures.

Glacial action produces a number of typical features which are marked on the surface of quartz grain as revealed by SEM studies. In this process, the degree of etching, formed due to dissolution on quartz

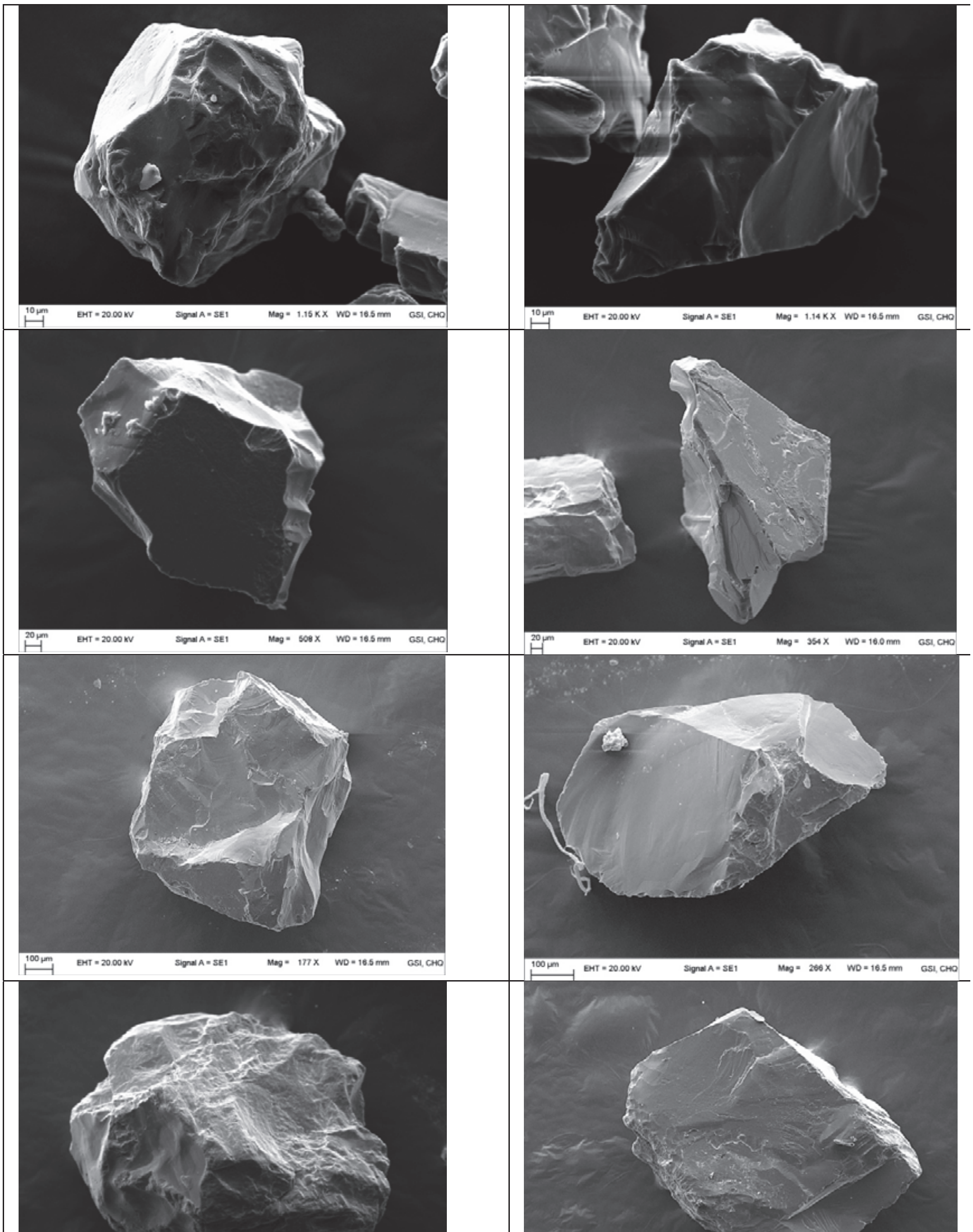

Fig.15. Scanning electron microscopy of quartz grain from sediments of Lake B. **B1:** Sub-spherical, angular, high relief. **B2:** Prolate, angular, large conchoidal fractures. **B3:** Sub-spherical, angular, adhered particle. **B4:** Prolate, sub-angular, fractured plate. **B5:** High angular, breakage block. **B6:** Large conchoidal fractures, angular, adhered particle. **B7:** Sub-spherical, angular, fractured plates. B**8:** Bladed angular, fractured plate, breakage block.

grain in glacial diamicts is often indicative of pre-weathering condition of grain prior to its transportation. More angular and devoid of overgrowths are characteristic features of quartz grains derived from glacial grinding or crushing of granites/gneisses. High cryostatic pressure is responsible for the formation of mechanically-upturned plates (<10% and generally <5%) (Mahaney, 1990). Likewise, arc shaped steps, deep troughs and grooves are considered to have formed due to thick ice (Mahaney, 1990). Small adhering particles on the surface resulted due to glacial grinding (Smalley, 1966). Surface and edge abrasion are very common on many quartz grains, particularly if they have a source area under the inland ice sheet. It develops firstly on pre-weathered surface and later modified during glacial transport. Fracture faces or cleavage faces and/or cleavage planes, which have been tentatively linked to mechanical weathering, are also known form during release from the source rock (Krinsley and Doornkamp, 1973; Mahaney et al., 1996). They may survive transport following mechanical weathering without being crushed, or they result from glacial comminution. Lattice shattering, which under low magnification looks like dissolution etching (Mahaney and Kalm, 1995), appears with greater frequency than mechanically-upturned plates, may also

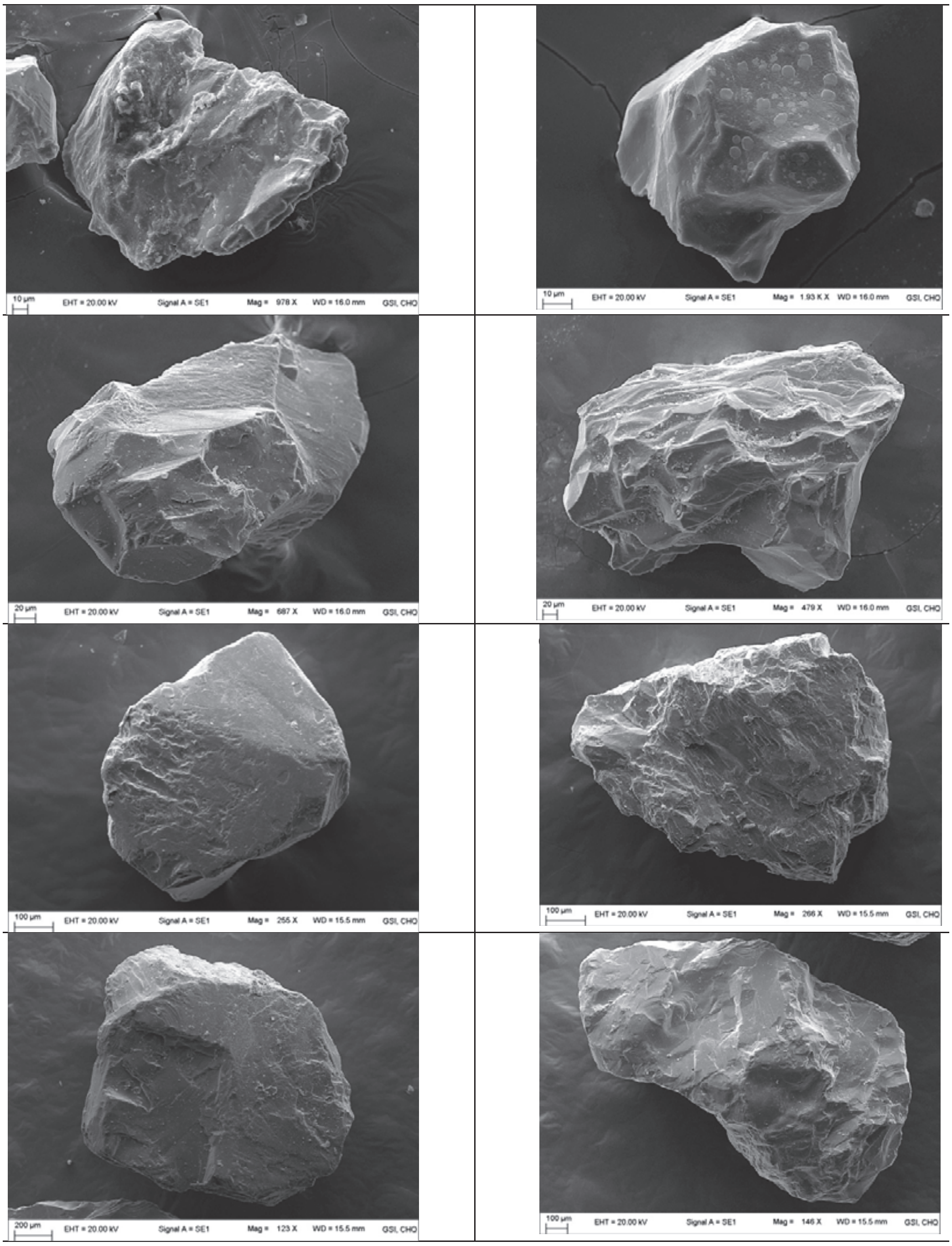

Fig.16. Scanning electron microscopy of quartz grain from sediments of Lake C. **C1:** Angular, bladed, adhered particles. **C2:** Sub-angular, sub-spherical, new growths. **C3:** Angular, prolate, large and small conchoidal fractures. **C4:** Angular, arcuate and straight steps. **C5:** Sub-round, polished surface and grooves. **C6:** Angular, sub-spherical, fractured plates. **C7:** Equant, moderate relief, breakage block. C**8:** Angular, prolate, arcuate and straight steps.

signify high cryostatic pressure. A reasonably high degree of weathering and/or diagenesis, which is due to glaciofluvial action and must predate glacial transport or after deposition results in dissolution, etching, precipitation and occasional new growth. The v-shaped percussion cracks on the surface of quartz grain indicate glaciofluvial transportation of grains. Some other glacial surface textures such as crescentic gouges, arcuate steps, conchoidal fractures, subparallel linear fractures, angularity and high relief are also diagnostic features of crushing and abrasion (Margolis and Kennett, 1971; Williams and Morgan, 1993; Mahaney and Kalm, 1995; Mahaney et al., 1996; Helland and Holmes, 1997).

Grain to grain collisions in subaqueous environments also produces irregular impact pits, large breakages, as well as a variety of chemical textures, such as solution pits and channels, etch patterns and crystalline overgrowths (Manker and Ponder, 1978; Georgiev and Stoffers, 1980; Linde and Mycielska-Dowgallo, 1980; Manickam and Barbaroux, 1987; Williams and Thomas, 1989; Passchier et al., 1997).

In supraglacial sediments, most of the quartz grains are of high angularity and low sphericity. A wide range of surface textures was observed in the supraglacial quartz grains. The basic form is of angular grains with the fracture planes, arcuate step, sub-parallel and arc-stepped grooves. Englacial sediments shows a medium amount of precipitation on some areas with upturned plates, certain facets are still apparently devoid of precipitated silica. Once in the glacier, surface texture undergoes relatively little modification. There is, therefore, little distinguishable difference between quartz grain textures in an englacial position and those which are found supraglacially. In subglacial sediments, grains formed by crushing of the samples sample. Grains from the lake show some modification to the facet edges and some precipitation.

Glacial grains are characterised by angular outlines, a wide variety of conchoidal fractures, deep entrenched grooves and striations. Crystalline overgrowths are typical indicators of burial diagenesis. Some micro textures may be overprinted by other micro textures. This is certainly the case for multi-cycle sediments, for which it is important to find the cross-cutting relationships between over printings. The overall features of surface micro-textures of quartz grains can be summarised as follows,

Lake A: The finer quartz grains are angular in outline with low sphericity and having medium to low relief. Edge abrasion varies from very low to moderate degree. Grains are with large conchoidal fractures, curved and straight steps and groves, large breakage blocks, pitted surface, meandering ridges and v-shaped pits. Chemical activities in the form of silica precipitation and new growths are low as compared to the grains of earlier lakes. Overall the microfeatures indicate variety of environment ranging from supraglacial to subglacial sediments with some glaciofluvial action.

Lake B: The finer quartz grains from the upper horizon vary between highly angular to sub-angular with low to medium relief. The grains show large conchoidal fracture, straight steps, polished surface and edge abrasion. Most of the grains have suffered from chemical activities and precipitation of silica took place. The finer grains show a mix population of supra glacial and englacial environment. The coarse grains show large breakage blocks, arcuate and straight steps polished surface, fractured planes, pitted surface and adhered particles. These coarse grains represent mix population of subglacial and supraglacial environment. There are effects of glaciofluvial action over these quartz grains. The grains from deeper level show straight and curved grooves along with other mechanical textures, indicating effect of dominant glacial action.

Lake C: Apart from different surface textures, the quartz grains show highest amount of chemical (solution) activities in the form of precipitation. There is precipitation of silica on the edges, surfaces and on straight / curved steps. Adhered particles are also common on the quartz grains. Some grains also show straight grooves. These features indicate that the glacial quartz grains have experienced considerable fluvial action just before their settlement in the lake.

CONCLUSIONS

The multi-proxy sedimentological data, generated from the sediment cores of land locked lakes and a grab sample from pro-glacial lake, lying in the same drainage line in the central part of Schirmacher Oasis has provided better insight into the paleoclimatic evolution of the region. The glacial signal is very clear and dominating in this region. The lake sediments are immature, chemically unaltered in nature, have restricted drainage pattern and derived from medium to high grade metamorphic terrain. The patterns of fluctuations in different sedimentological parameters, such as weight percentages of sand, silt, and clay and statistical parameters including mean grain size, sorting, sorting coefficient, skewness, kurtosis show alternate warmer and cooler phases at different intervals. The surface textures of quartz grains show dominant glacial and glaciofluvial actions. The finer quartz grains have shown maximum new growths and silica precipitation, while the coarse grains are mostly fresh, representing sub-glacial to supraglacial environment of transportation.

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 warm period is not strong enough to alter the overall clay chemistry. The effect of warming is visible on the sediments of upper horizon and in pro-glacial sediments in the form of mixed layers in clay minerals. The crystallinity of biotite has changed gradually from good crystalline to moderate crystalline towards upper horizon in the sediment core. Exclusively physical weathering has controlled the overall sediments and composition of clay fraction.

The evidence of gradual warming in Schirmacher region started much before 42 ka, at the end stage of Late Quaternary in phases. The area was covered by ice during the early phase of late Quaternary which gradually thinned and became ice-free in the late Holocene.

Acknowledgements: Authors are thankful to Director General, ADG-NMH, Dy. DG and Head, NR, and Dy. Director General, Mission IV-C, Geological Survey of India for providing opportunity to work in Schirmacher Oasis of East Antarctica. Authors are also thankful to National Centre for Antarctic and Ocean Research, Goa for providing logistic support during 33rd Indian Antarctic Expedition. Thanks are also due to the director and officers of XRD Laboratory, Petrology Laboratory, TL-OSL Laboratry, Chemical Division, GSI Faridabad respectively for providing valuable support and facility to work. We offer our gratitude to director and officers of Paleontology Division – I, GSI Kolkata for their excellent job on quartz grain morphology. Last but not the least, we are thankful to the expedition members for their constant help during the expedition, and all the officers of Polar Studies Division, for their overall support. HBS is thankful to the Head Department of Geology, Banaras Hindu University for providing the necessary facilities.

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(Received: 6 May 2017; Revised form accepted: 27 December 2017)