Polar Science 10 (2016) 89–100

Contents lists available at ScienceDirect

Polar Science

journal homepage: http://ees.elsevier.com/polar/

Sediment grain size and surface textural observations of quartz grains in late quaternary lacustrine sediments from Schirmacher Oasis, East Antarctica: Paleoenvironmental significance

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ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form
1 December 2015
Accepted 25 December 2015
Available online 30 December 2015

Keywords:
Quartz
Surface texture
Aeolian
Weathering
Climate
Schirmacher oasis
East Antarctica

ABSTRACT

In this study we report the sediment grain size parameters and surface textural observations (using scanning electron microscopy (SEM)) of quartz grains from sediments of Sandy Lake, Schirmacher Oasis, East Antarctica. The sediment core spans the last 43 cal ka B.P. The statistical parameters of grain size data (sorting, skewness, kurtosis, mean grain size, D_{10}, D_{50}, D_{90} and SPAN index) indicate that the sediments are primarily transported by melt-water streams and glaciers. However, during the last glacial period, sediments seem to be transported due to wind activity as evident by the good correlation between rounded quartz data and dust flux data from EPICA ice-core data. The mean grain size values are low during the last glacial period indicating colder climatic conditions and the values increase after the last glacial maximum suggesting an increase in the energy of the transporting medium, i.e., melt-water streams. The sediments are poorly sorted and finely skewed and show different modes of grain size distribution throughout the last 43 cal ka B.P. SEM studies of selected quartz grains and analyses of various surface textures indicate that glacigenic conditions must have prevailed at the time of their transport. Semi-quantitative analyses of mineral (quartz, feldspar, mica, garnet and rock fragments & other minerals) counts suggest a mixed population of minerals with quartz being the dominant mineral. Higher concentration of quartz grains over other minerals indicates that the sediments are compositionally mature. The study reveals the different types of physical weathering, erosive signatures, and chemical precipitation most of them characteristic of glacial environment which affected these quartz grains before final deposition as lake sediments. The palaeoclimatic signals obtained from this study show similarities with ice-core and lake sediment records from Schirmacher Oasis and other ice-free regions in East Antarctica.

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1. Introduction

Sediments deposited in the lakes and oceans surrounding Antarctica offer tremendous potential to understand the different sedimentary processes under harsh climatic conditions (Damiani et al., 2006; Mahesh et al., 2015). These sediments are made up of organic and inorganic materials which can be classified as *allogenic*, *endogenic* and *authigenic*. This classification is made purely on their mode of genesis (Engstrom and Wright, 1984). *Allogenic* (also known as detrital) minerals are brought into the lake basin with the help of surface streams, shoreline erosion, mass movement, wind activity, sheet flood etc. Minerals that originate within the lake water column due to inorganic or biological processes are termed as *endogenic* and those formed due to diagenetic alteration are known as *authigenic*. Detrital mineral grains give a true reflection of the interaction between different geological processes such as tectonic framework of the depositional basin, provenance of sediments, type and intensity of weathering processes in the catchment, and/or transportation processes responsible for the delivery of sediments into the lake (Last, 2001). These detrital grains can therefore be used to infer past changes in drainage basin size and morphology (Henderson and Last, 1998; Olsen, 1990) and fluctuations in the climatic regime within the catchment (Schütt,

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http://dx.doi.org/10.1016/j.polar.2015.12.005
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1998; Dean, 1997; Menking, 1997). In the Polar Regions, quartz, feldspars, mica, garnet etc. are few important examples of detrital minerals that have been widely used for paleoclimate reconstruction, as they are products of physical weathering processes (Pistolato et al., 2006; Chamley, 1989). According to the Bowen's reaction series, the mineral quartz (SiO_2) crystallizes at the end at lower temperature and is the most stable and commonly found rock mineral on the earth's surface. It has a lower tendency to weather compared to other minerals and therefore has high preservation potential in lake/marine sediments (Krinsley and Doornkamp, 1973; Mahaney, 1995b, 2002). It provides an ideal substrate for micro-textural study because of its durability, hardness and lack of cleavage. Surface micro features, angularity, chemical features, and grain-size analysis of quartz grains, collectively reveal the sedimentary and physicochemical processes that acted on the grains during different stages of their geological history. Quartz grains in lake sediments can have different sources i.e., locally derived quartz grains due to mechanical and chemical weathering of catchment rocks, aeolian quartz, that has been transported by wind and dropped within the lake catchment or onto the lake, and biogenic silica which comprises the remains of siliceous organisms such as diatoms (Stanley and DeDeckker, 2002). Several studies have underlined the importance of scanning electron microscopic (SEM) observations of sand-sized quartz grains. The results from these studies have established that sediments affected by different geological processes, transport and deposition display distinct grain surface features and micro textural characteristics (Helland and Holmes, 1997; Mahaney, 1995a, b; Strand et al., 2003).

In this study, we present the results of a preliminary investigation of sedimentary grain size studies and morphological features of quartz grains and semi-quantitative analysis of minerals deposited in the sediments of Sandy Lake, Schirmacher Oasis (SO), East Antarctica, with an aim to evaluate the modes of transport, weathering characteristics, maturity of sediments and effect of regional climate on these sediments.

2. Study area

Schirmacher Oasis (SO) is a 35 km^2 ice-free area and is located in the Queen Maud Land, East Antarctica (Fig. 1a). It lies between the margins of the ice-shelf and the continental ice sheet (Fig. 1a). It is made up of several hills of low elevation (~200 m; Srivastava and Khare, 2009). There are about 120 lakes and depending on their geomorphic evolution are classified as epishelf, proglacial and landlocked (Ravindra, 2001). Sandy Lake ($70^0 45' 45.9''$S; $11^0 47' 34.7''$E) is one of the small, land-locked lake (Fig. 1a) situated ~2.5 km in the east-north-east direction from the Indian Research Station – *Maitri*. Rocks in the Schirmacher Oasis are predominantly gneissic with the felsic variety making up > 85% of the exposed bed rocks (Rao, 2000). Pyroxene granulites, enderbites, calc-granulites and khondalites are the other rock types found in SO (Bose and Sengupta, 2003).

The weather conditions in SO are harsh with a dry climate and extremely low temperatures and strong winds. The summer season lasts from November to February. During this period, the maximum and minimum temperature varies from 0.4 to −2.6 °C and from −2.7 to −8.8 °C, respectively. During winter (March to October), the maximum temperature dips between −4.5 and −12.9 °C and the minimum temperature varies from −10.4 to −20.9 °C (Lal, 2006). The annual average wind speed is 17.5 knots and they blow mainly from the southeast direction (Lal, 2006). Precipitation is scanty and is frequently received between April and September in the form of snowfall.

3. Materials and methodology

3.1. Sampling

A 68-cm long sediment core was raised during the 28th Indian Scientific Expedition to Antarctica. The core was retrieved by manually hammering an acrylic pipe into the lake bed from its periphery when it was ice-free. The sediment core was neatly labelled, packed and stored in a deep-freeze at −18 °C. The core was transported to the laboratory and sub-sampled at 1 cm interval to obtain high resolution paleoenvironmental data. The sub-samples were packed in labelled polythene covers, stored in a deep-freeze and used for laboratory studies.

3.2. Geochronology

The chronology of the Sandy Lake sediments was established using accelerated mass spectrometry (AMS) ^{14}C dates obtained on the bulk organic matter in the sediments. The dates were calibrated using CALIB 6.0 (Stuiver and Reimer, 1993) software. The age-depth model obtained suggests a mean sedimentation rate of 0.015 mm/year with a low of 0.013 mm/year during marine isotopic stage (MIS) 3 and a high of 0.019 mm/year during MIS 2. The youngest age of the sediment core is 1116 cal. years B.P. (0–2 cm depth) and the oldest age is 42,357 cal. years B.P. Further details of AMS ^{14}C dating, calibration and age-depth model are given by Warrier et al. (2014).

3.3. Petrographic studies

Thirty five samples from the sediment core were selected for this study. Approximately 2 g of the sediment samples were oven-dried at 50 °C and treated with 10 ml of 30% H_2O_2 to eliminate the organic matter. The samples were thoroughly rinsed with deionised water and were oven-dried. Ten ml of sodium hexametaphosphate (calgon) solution was added to every sample to separate the clay coatings and fine-grained particles adhered to quartz grains (Lewis and Armstrong, 1994; Helland and Holmes, 1997). The samples solutions were then wet-sieved using 125 μ sieve. The >125 μ fraction was transferred to a pre-weighed beaker and oven-dried. Representative samples were prepared by sub-sampling the >125 μ fractions with the help of a Rifle sample divider (McManus, 1988). Each sample was split five times into representative portions until a sample of desired quantity was obtained. The individual grains from these split samples were observed and counted under a stereo zoom magnifying microscope (Nikon SMZ-1500). Detrital minerals like quartz, feldspar, micas, garnet, rock fragments (RF) and other minerals were observed and counted.

3.4. Sediment grain size analysis

Sediment samples were pre-treated with hydrogen peroxide and glacial acetic acid to eliminate organic matter and carbonate, respectively (Schumacher, 2002). The biogenic silica content in the sediments was quite negligible and hence no pre-treatment was carried out to eliminate the effect of the same. Ten ml of calgon (sodium hexametaphosphate) solution was added to the sample. The sand fraction was separated using a 63 μ sieve. The >63 μ fraction was transferred to a pre-weighed beaker and oven-dried. The silt + clay fractions were later analysed with a Beckman-Coulter LS-13320 (0.04–2000 mm). The data output was processed using the Gradistat software for sediment parameters (Blott and Pye, 2001). Apart from the basic statistical parameters (Folk and Ward, 1957) such as mean grain size, sorting, skewness and kurtosis, the 10th (D_{10}), 50th (D_{50}) and 90th (D_{90}) percentile particle size data was also extracted. The parameter SPAN (a

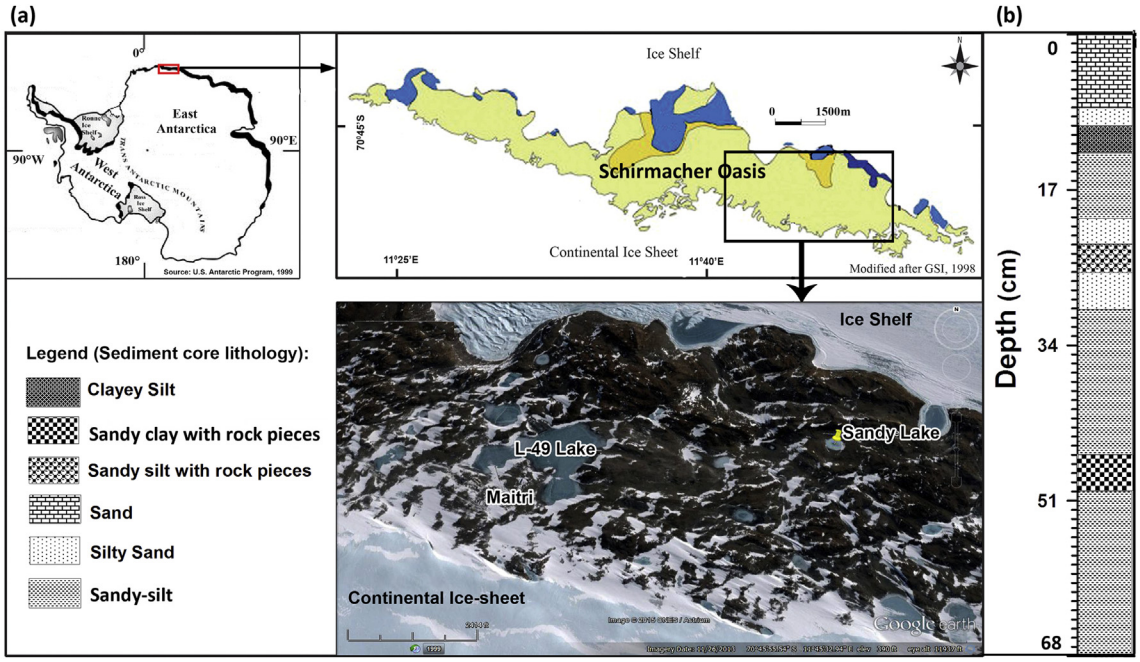

Fig. 1. (a) General map of Antarctica showing the location of Schirmacher Oasis. Map of Schirmacher Oasis (modified after Geological Survey of India (1998)) showing the location of Sandy Lake and satellite image of the area around Sandy Lake (obtained from Google Earth); (b) litholog of the Sandy Lake sediment core (Warrier et al., 2014).

dimensionless sorting index; Foster et al., 2008) was obtained by the following formula $[(D_{90}-D_{10})/D_{50}]$

3.5. Scanning electron microscopic observations of quartz grains

Quartz grains from 12 sediment samples at different depths in the core were hand-picked under the stereo zoom microscope and were prepared for SEM observations according to Trewin (1988). The grains were sputter-coated with platinum (~2 nm thickness) and examined at 150× using a JEOL-JSM-6360 LV SEM operated at 5–15 keV. Elemental analysis of the quartz extract was performed using an OXFORD INCA 200 Energy Dispersive Spectrometer (EDS). We have followed the studies of Vos et al. (2014), Helland and Holmes (1997), Mahaney (1995b) and Strand et al. (2003) to study the quartz grain surface micro texture classification.

4. Results and discussion

4.1. Grain size data and semi-quantitative analysis of mineral fraction

The grain size distribution patterns suggest that the sediments of Sandy Lake have different modes (bimodal, unimodal, trimodal and polymodal) of distribution and are not uniform (Fig. 2a). The ternary diagram (Fig. 2b) representing the sand, silt and clay fractions suggest that the sediments are silty in texture with a few samples plotting in the sandy silt section. This was also confirmed by the lithology for the sediment core (Fig. 1b; Warrier et al., 2014). Down core variations in particle size parameters is shown in Fig. 3 and the summary statistics are provided in Table 1. The mean grain size (MGS) values ranges between 7.15 and 19.53 μm with an average value of 11.53 μm (Table 1). The MGS values show a decreasing trend from 43 cal ka B.P. to 24 cal ka B.P. after which it increases towards the core-top. Sorting indicates the range of forces which determine the sediment size distribution (Briggs, 1977; Dyer, 1986; Folk, 1974). Lower sorting values correspond to better sorting processes of sediment samples. The sorting index indicates that the Sandy Lake sediments are very poorly sorted from 43 cal ka B.P. to 24 cal ka B.P. after which the sediment texture is poorly sorted (Fig. 3). This is because the sediments deposited during the last glacial period have a mixed population of sediments that have been transported by both wind and glacio-fluvial activities. According to Friedman (1961), the statistical parameter, skewness measures the asymmetry of frequency distribution with respect to the median value of sediment grain size. The sediments of Sandy Lake are symmetrical (43–24 cal ka B.P.) to finely skewed (24 cal ka B.P. to the Present; Fig. 3). The sediments are platykurtic (43–24 cal ka B.P.) and become mesokurtic after this period. It can be seen that during MIS 3, the diameters of the 10th (D_{10}), 50th (D_{50}) and 90th (D_{90}) percentile particle sizes were low (Fig. 3). The D_{90} values do not show much variation when compared with the D_{10} and D_{50} values. However, after around 24 cal ka B.P. there is a steady increase in these three parameters suggesting an increase in sediment grain size and hence indicating a change in the energy conditions of the transporting medium. The sorting index (SPAN) is high from 43 cal ka B.P. to 24 cal ka B.P. and tends to decrease towards the core-top, suggesting that the sediments are poorly sorted (Fig. 3). The sorting *vs.* skewness biplot (modified after Guyard et al., 2007) indicates two different grain size distribution patterns (Fig. 4). A large portion of the last glacial samples are finely skewed and are very poorly sorted, whereas the Holocene samples are poorly sorted and finely skewed. It is interesting to note that one sample from the Holocene period (8.54 cal ka B.P.) is close to a few samples from the last glacial period. During this time period, extremely cold conditions prevailed in the Schirmacher Oasis (Warrier et al., 2014; Phartiyal et al., 2011), due to which the sediments from this time-period are finely skewed and very poorly sorted.

All the different population of sediments (unimodal, bimodal, trimodal, polymodal) are deposited in Sandy Lake (Fig. 2a), suggesting multiple modes of sediment transport to the different parts of the lake (Last, 2001). These might be due to combination of a variety of sedimentary processes (Shrivastava et al., 2012). Sedimentation in Antarctic lakes are primarily due to movements of

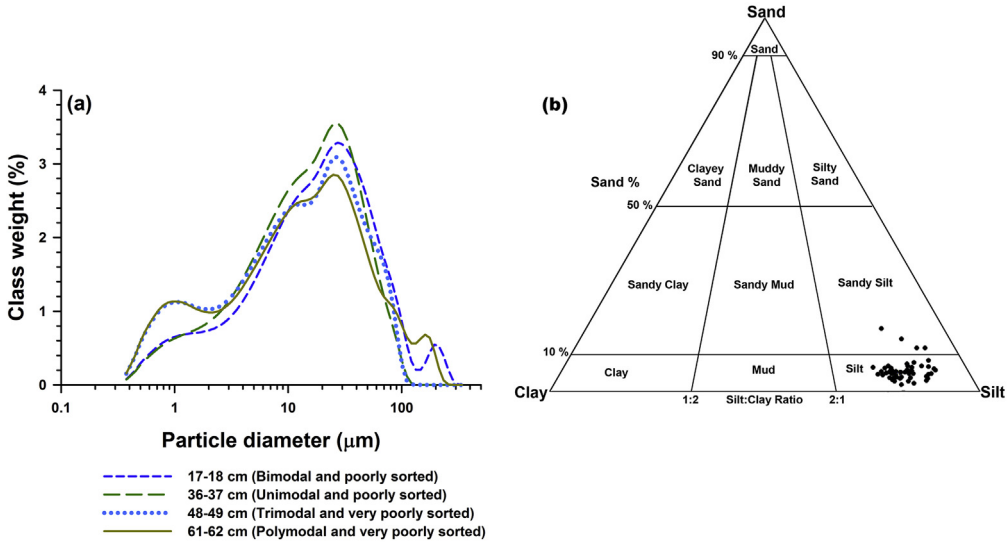

Fig. 2. (a) Plot of grain-size data for representative samples from the Sandy Lake sediment core. Note: The sediments show different modes of distribution (unimodal, bimodal, trimodal and polymodal) and (b) Ternary plot showing the distribution of sand-, silt- and clay sized sediments. *Note*: The texture of Sandy Lake sediments is predominantly silty.

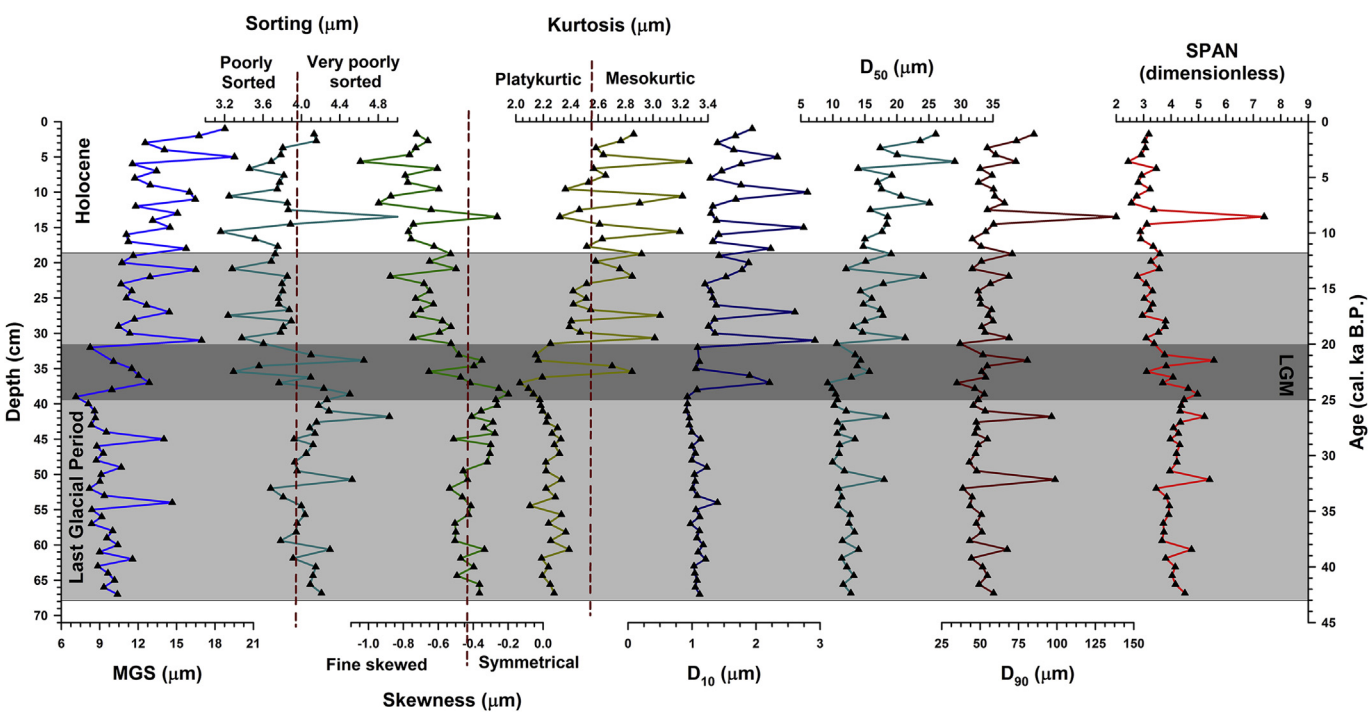

Fig. 3. Down-core variations in the mean grain size, sorting, skewness, kurtosis, D_{10}, D_{50}, D_{90} and SPAN index parameters for the Sandy Lake sediments during the past 43 cal ka B.P.

glaciers, meltwater streams (during austral summer) and eolian transport. The statistical parameters of the sedimentary grain size data indicate that the sediments in Sandy Lake could have been transported either by glaciers, melt-water streams and also wind. The lakes of Schirmacher Oasis are mainly drained by glaciers and meltwater streams. These agents carry the different population of

Table 1
Statistical summary of grain-size parameters (geometric mean (μm); Folk and Ward, 1957) for Sandy Lake sediments (n = 66). The parameters were calculated using Gradistat software (Blott and Pye, 2001).

	Mean (x)	Sorting (σ)	Skewness (Sk)	Kurtosis (K)	D10	D50	D90	SPAN
Average	11.53	3.92	−0.54	2.46	1.40	15.01	56.23	3.75
Maximum	19.53	5.01	−0.20	3.26	2.92	29.04	138.51	7.39
Minimum	7.15	3.16	−1.05	2.03	0.91	9.19	34.92	2.44
Standard Deviation	2.61	0.36	0.19	0.30	0.49	4.31	15.94	0.82

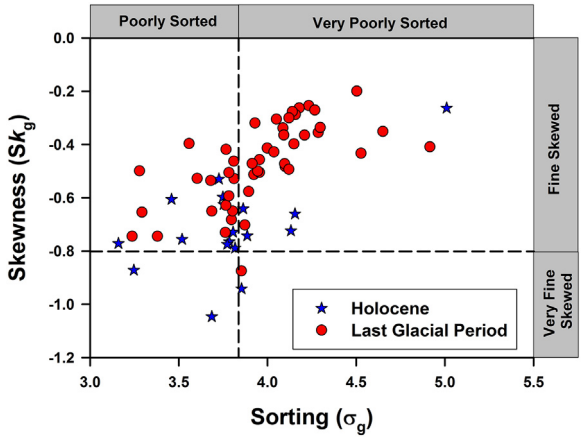

Fig. 4. Biplot of skewness *vs.* sorting (modified after Guyard et al., 2007) for Sandy Lake sediments.

sediments and deposit them in these lakes. Apart from the glaciers and the meltwater streams, sediments are also transported by wind (Li et al., 2006). Strong winds pick up and carry sediment particles and deposit them on the lake-ice when wind energy reduces. The sediment gets trapped in cracks present in the lake-ice. According to Spaulding et al. (1997), during glacial summer, melting or fracturing of ice sheets would allow these sediments to penetrate through vertical conduits and reach the lake floor and mix with the different population of grains which were derived due to meltwater streams or glacier transport (Shrivastava et al., 2012).

Semi-quantitative analysis of sediments with respect to their mineralogical composition and particle shape/morphology of quartz grains provide valuable information on compositional and textural maturity of sediments, respectively. Fig. 5 represents the down core variations in the relative percentages of mineral components (quartz, feldspar, mica, garnet and RF and other minerals). It can be seen that quartz is the most dominant mineral present in the Sandy Lake sediments followed by feldspar, mica, garnet and rock fragments & other minerals. According to Tucker (1981), the composition of clastic sediments is mainly governed by catchment rocks and the type of weathering processes involved, and climate. Maturity of sediments refers to the cumulative changes that sedimentary particles undergo during erosion, weathering, transport till its final state of deposition as sediments. Sediments having high compositional maturity will have a high percentage of quartz and feldspar compared to other minerals present. Generally, more the sediments have been reworked more the percentage of quartz and feldspar, whereas sediments having high textural maturity will be well sorted and most of the grains will be rounded in nature whereas poorly sorted grains exhibit low textural maturity.

4.2. Scanning electron microscopic (SEM) observations of quartz surface textures

Application of SEM techniques to study the surface textures of quartz grains is a potential tool in palaeoclimatic studies. This is due to the fact that surface textures are easier to modify and they preserve an imprint of the last depositional environment. The energy conditions within each environment will tend to produce surface textural features that reflect that particular environment and these features will differ for different environmental processes. Owing to its superior hardness and chemical stability, quartz is commonly considered to be the most appropriate material to record the surface textural features produced in each environment. The surface textures present on quartz grains are dependent on the physical and chemical processes that has been subjected on these grains (Krinsley and Doornkamp, 1973), hence, making them a useful tool in reconstructing the past climate/environment (Hodel et al., 1988; Mahaney, 1995b). Surface texture observations of quartz grains have been previously made on sediments from polar lakes to characterize glacial sediments (Narayana et al., 2010; Mazzullo and Anderson, 1987) and to reconstruct the transport and weathering mechanisms (Mahaney et al., 1996; Helland and Holmes, 1997). A range of different types of mechanical microtextures (including angular to rounded outline/shape, surface relief, conchoidal fracture, straight & arcuate steps, edge and surface abrasion features (descriptive terms derived from the work of Mahaney et al., 1996; Vos et al., 2014), as well as chemical features, were used in this study to characterize the quartz grains deposited in the Sandy Lake sediments.

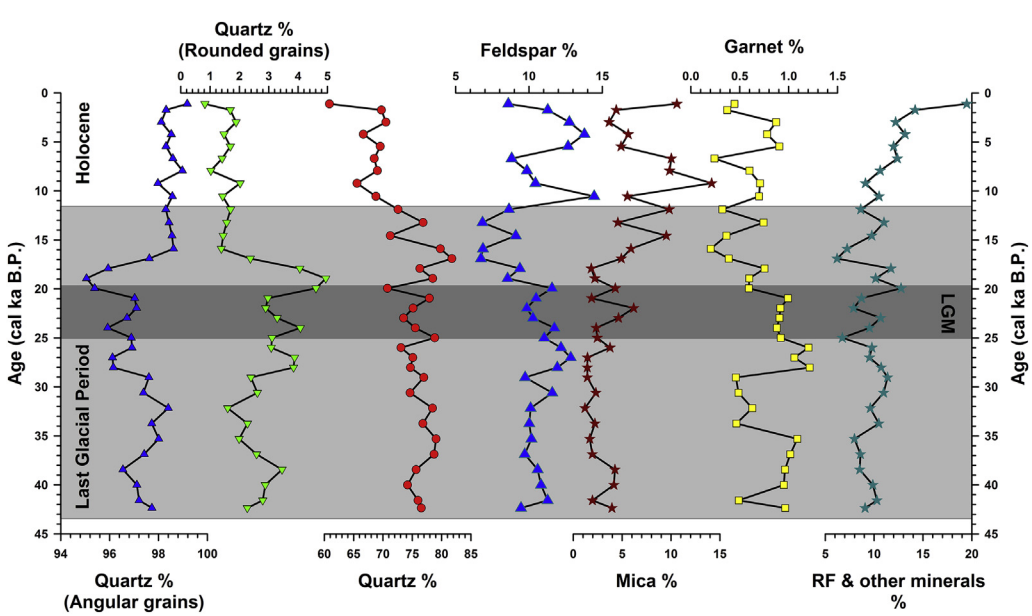

Fig. 5. Down-core variations of angular & rounded quartz grains, quartz, feldspar, mica, garnet and rock fragments & other minerals.

Grain outline describes the roundness or angularity of the grains and is controlled mainly by the mode and distance of transportation, time and particle size (Goudie and Watson, 1981; Kleesment, 2009; Costa et al., 2013). Rounded grains are often believed to represent aeolian mode of transportation (An et al., 2012; Damiani et al., 2006). Angular grains are characteristic of glacial regime wherein they are crushed due to high-energetic subaqueous environments with short transport distances, causing breakage of grains without rounding of edges (Helland and Holmes, 1997). Grains that lack pronounced cleavage directions develop curved and shell-like breakage patterns. These fractures are known as conchoidal fractures. These are produced due to the pressure generated due to a massive impact (Kragelskii, 1965; Margolis and Krinsley, 1974). These types of fractures are very common in quartz grains. According to Higgs (1979) and Mahaney (2002), the size of conchoidal fractures is a reflection of the energy involved during its formation.

The relief describes the surface roughness or smoothness of the grains in microscopic scale and is subdivided into low, medium and high relief depending on the topographic irregularities present on the surface (Higgs, 1979). The irregularities are either caused by collisions with other grains and/or alteration processes. High and moderate reliefs are usually diagnostic for freshly weathered grains or glacial activity, whereas low and medium reliefs are rather produced in diagenetic environments. Diagenetic quartz grains can be stored in ancient sediments or in paleosols (Beyer et al., 2000) and can be eroded and dropped near the core location by meltwater streams or moving glaciers (Damiani et al., 2006).

Figures 6–9 show the scanning electron micrographs of the 12 quartz grains representing different ages during the past 43 cal ka B.P. The quartz grains exhibit three different types of grain outline – angular, sub-angular and rounded. These outlines indicate their varied distance and time of transport (Narayana et al., 2010). The grain edges are sharp and show all the three types of relief – low, medium and high. The quartz grains show features representing mechanical breakage (Figs. 6–9). A large amount of quartz grains show angular to sub-angular (average = ~95%; Fig. 5) grain outline that are indicative of glacial action. Rounded grains are very few in terms of percentage (average = ~5%; Fig. 5) when compared with the angular grains hence suggesting that quartz grains deposited in the Sandy Lake sediments are primarily derived from within the catchment and suggestive of shorter distance of transport. Small

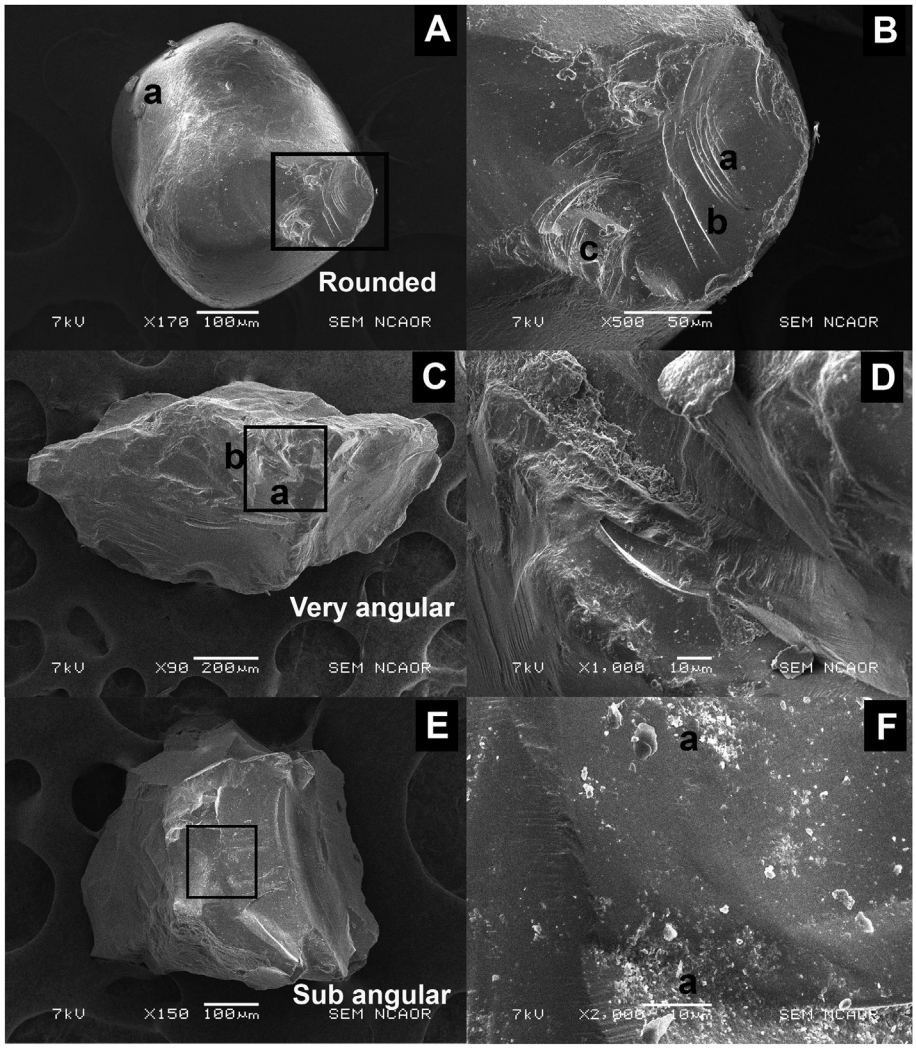

Fig. 6. Scanning electron micrographs of quartz grains from Sandy Lake sediment core. (A) Well-rounded (low relief) with broken surface and adhered particles[a] (0–1 cm depth). (B) Conchoidal fractures[a], step[b] and arcuate steps[c] (0–1 cm depth). (C) Very angular grain (high relief) with straight[a] and arcuate[b] steps (2–3 cm depth). (D) Minor upscaling of quartz, straight steps and mineral precipitation due to diagenesis (2–3 cm depth). (E) Sub-angular quartz grain showing moderate relief (6–7 cm depth). (F) Surface alteration seen in the form of surface etching[a] (6–7 cm depth).

scale conchoidal fractures, broken surfaces, adhered particles, straight and arcuate steps, mineral precipitation, surface alteration in the form of surface etching, upturned plates, collision pits etc. are other significant micro-textures that can be seen in the quartz grains of Sandy Lake. Arcuate steps/grooves and straight steps/grooves (Figs. 6B, 7E and 8A, 8B, 8D, 9B, 9F) are the commonly observed features on quartz grains indicative of glacial origin. Between the curved conchoidal fractures, we can see meandering ridges (Fig. 9B) which traverse across the grain surface in a form of intersection line (Krinsley and Donahue, 1968). Chemical action also seems to have played a significant role as evident in the form of mineral precipitation, leading to the adherence of minute particles. Silica precipitation is also high in few of the quartz grains suggesting cold climatic conditions (Narayana et al., 2010). Fig. 8F shows the presence of circular to sub-circular droplets of silica globules on quartz grains formed due to its precipitation. As explained above, these diagenetic features may have been originated from older sediments and paleosols in the catchment area (Beyer et al., 2000; Damiani et al., 2006). Upturned plates (Fig. 7D) are a series of thin, parallel plates which are oriented at an angle with respect to the grain surface (Margolis and Krinsley, 1974). According to Krinsley et al. (1976), these plates are formed due to shattering of quartz grains during high-energy collision and hence are indicative of eolian and glacial environment. Parallel striations (Fig. 9C, D and F) are also seen in the quartz grains which are the diagnostic microtecture of glacial environment. They occur as a series of parallel lines on quartz surfaces and are formed due to the movement of sharp edges against the grain involved (Krinsley and Donahue, 1968). The features observed on the quartz grains of Sandy Lake sediments indicate that they are primarily derived due to actions of glacier movement, meltwater streams and aeolian activity. They reflect short distance of transport and fast rate of deposition (Damiani et al., 2006) and most of the quartz grains are sourced from the gneissic terrain of Schirmacher Oasis.

4.3. Palaeoclimatic implications

From the results discussed above, the sediments deposited in Sandy Lake during the last glacial period are generally fine grained and they are poorly to very poorly sorted (Fig. 3). They are platykurtic in nature and their skewness is symmetrical. This is probably due to the decreasing intensity of erosional process in the catchment. Sediment mean grain size is an useful indicator of energy conditions referring to the intensity of water current or turbulence

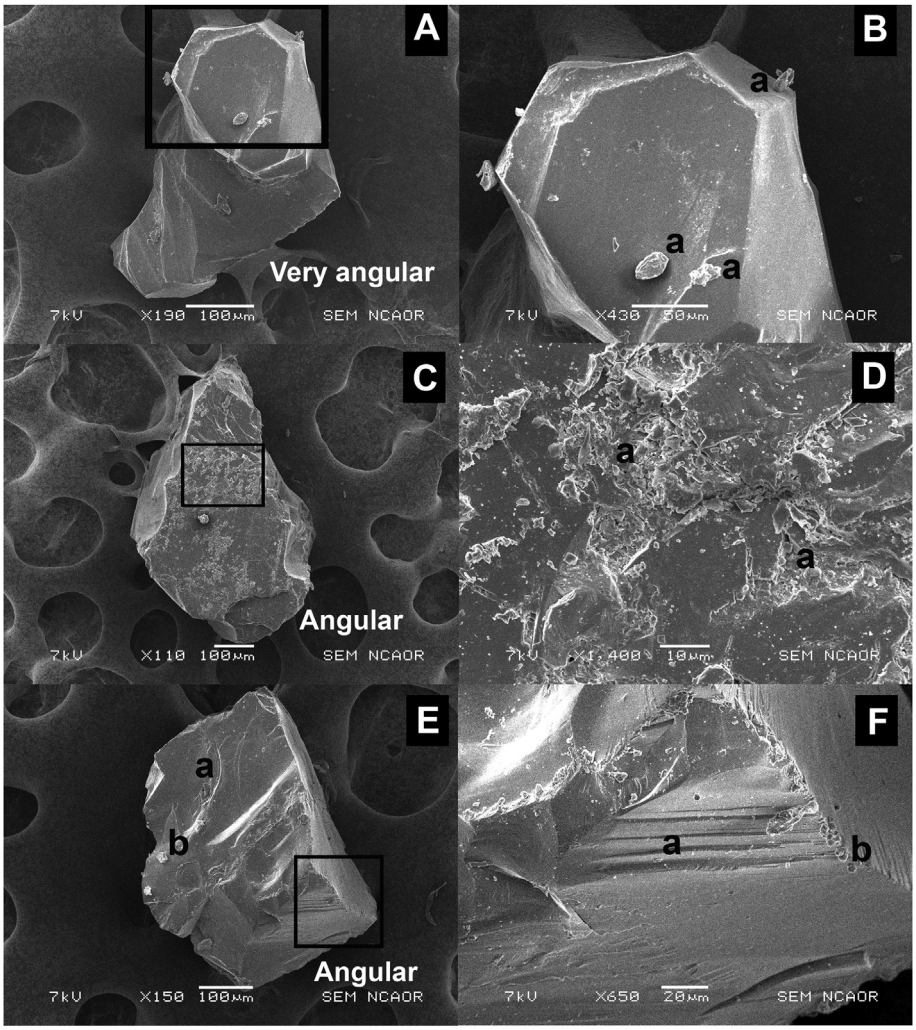

Fig. 7. Scanning electron micrographs of quartz grains from Sandy Lake sediment core. (A) Very angular grain showing high relief (16–17 cm depth). (B) Adhered[a] particles seen on the quartz grain (16–17 cm depth). (C) Angular grain showing moderate relief with surface alteration and conchoidal cleavage (18–19 cm depth). (D) Chemical alteration[a] seen in the form of upturned plates (18–19 cm depth). (E) Angular grain showing moderate relief, conchoidal cleavage[a] and adhered particles[b] (32–33 cm depth). (F) Straight steps[a] and collision pits[b] are also seen (32–33 cm depth).

level (Folk, 1966) and water depth (Campbell, 1998), wherein fine (coarse) grained sediments are deposited in a lower (higher) energy condition. The mean grain size data for Sandy Lake sediments suggests that low-energy conditions prevailed from 43 cal ka B.P. to ~24 cal ka B.P. as seen by the low values (Figs. 3 and 10). During the same period, the percentile particle sizes (D_{10}, D_{50} and D_{90}) were low (Fig. 3), further adding evidence to the cold climatic conditions. However, it is interesting to note that the MGS value shows a peak at 38 cal ka B.P. and 32 cal ka B.P. indicating relatively warmer conditions during these time periods during the last glacial period (Fig. 10). The peak during the 38 cal ka B.P. period may be linked to the Antarctic Warming Event – A1, which is one of the seven warming events reported in the southern hemisphere (Blunier and Brook, 2001). This warming event is also documented in oxygen isotopic data for ice-cores from Byrd (Blunier and Brook, 2001) and EPICA Dronning Maud Land (EDML; EPICA Community Members, 2006) and lake sediments of Schirmacher Oasis (Warrier et al., 2014). Several other peaks in the MGS data (35.29, 33.73, 32.16, 28.52, 22.45 and 13.89 cal ka B.P., respectively) are also correlatable with the Antarctic Isotope Maximum events (7, 6, 5, 3, 2 and 1, respectively) recorded in the EPICA ice-core data (Fig. 10). It is also interesting to note that for most dominant part of the last glacial period, the rounded quartz grains show a relatively higher percentage when compared with angular quartz grains (Fig. 10). This could be attributed to the peak in aeolian activity. We have compared the dust flux data obtained from EPICA ice-core (Lambert et al., 2012) with the rounded % quartz data (Fig. 10). There is broad correlation between the dust flux data and the rounded quartz data indicating that aeolian activity was high during the last glacial period, which would have transported the rounded quartz grains from distant regions and would have deposited them near the vicinity of Sandy Lake due to a drop in the wind velocity. The rounded quartz data is of very coarse correlation and the dust data from the ice core is of very high resolution, however, the general trend between the two suggests that the presence of rounded quartz grains in the Sandy Lake sediments is due to aeolian activity. Occurrences of aeolian quartz grains have been reported in polar sediments (Rex et al., 1970; Damiani et al., 2006; Hodel et al., 1988). These grains could have formed under arid climatic conditions and carried by the wind. As the wind intensity reduces, the load would have been dropped on to the lake-ice and as the ice melts, these grains percolate through the water column and get deposited in the sediments. However, it may also be noted that there is a high percentage of angular quartz grains in the Sandy Lake sediments

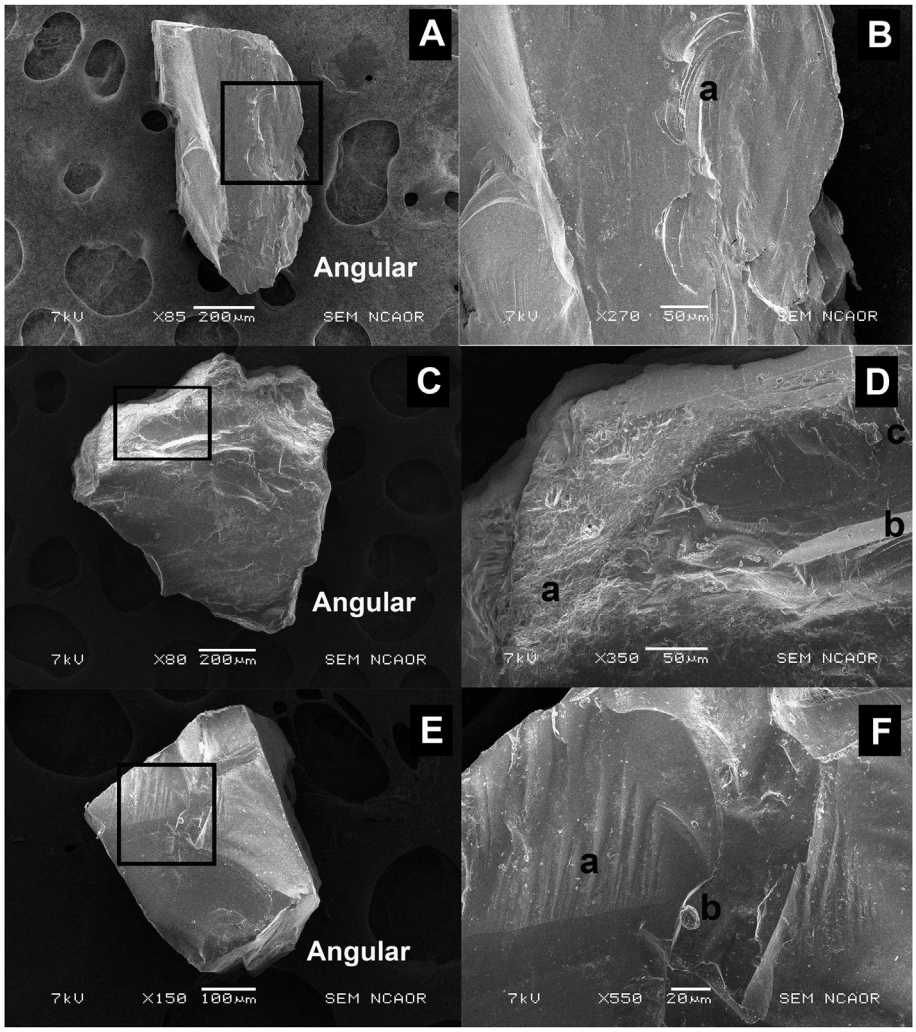

Fig. 8. Scanning electron micrographs of quartz grains from Sandy Lake sediment core. (A) Angular grain showing medium relief (40–41 cm depth). (B) Conchoidal fracture[a] (40–41 cm depth). (C) Angular grain showing medium relief (46–47 cm depth). (D) Abrasive surface[a] along with straight steps[b] and adhered particles[c] (46–47 cm depth). (E) Angular grain showing medium relief with straight and arcuate steps[a] (50–51 cm depth). (F) Close up of straight and arcuate steps[a], adhered particle appears to be silica globule[b] (50–51 cm depth).

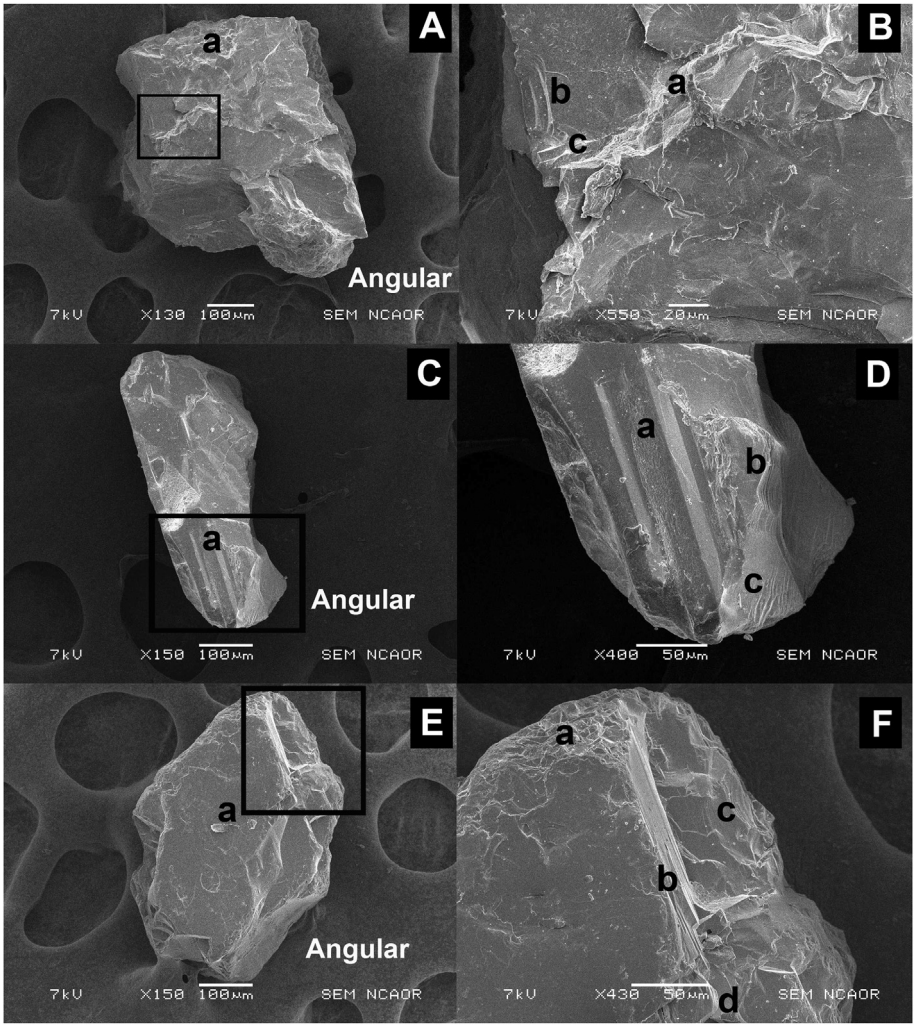

Fig. 9. Scanning electron micrographs of quartz grains from Sandy Lake sediment core. (A) Angular grain showing high relief and abrasive surface[a] (52–53 cm depth). (B) Meandering ridges[a], conchoidal fracture[b] and straight steps[c] are also seen (52–53 cm depth). (C) Angular grain showing medium relief with parallel striations[a] (60–61 cm depth). (D) Close up of parallel striations[a], arcuate[b] and straight steps[c] (60–61 cm depth). (E) Angular grain showing medium relief and adhered particles[a] (66–68 cm depth). (F) Abrasive surface[a], striations[b], conchoidal fracture[c] and arcuate steps[d] are also seen (66–68 cm depth).

suggesting that these grains are sourced from the catchment area of the lake and glaciers being the major carrier of these angular grains. The temporal variations between the angular and rounded quartz grains also give an indication of the interplay between aeolian and glacial mode of transportation. During the last glacial period, there are records of high percentage of mineral dust being deposited in the ice-cores which have been attributed to peak in aeolian activity (Lambert et al., 2012; Albani et al., 2012). After the last glacial maximum, all the sedimentological and mineralogical parameters show an increase in their respective values towards the core-top (Figs. 3, and 10), indicating a shift in climatic conditions in the Schirmacher Oasis. The mean grain size values show an increase in their values and the sediments are poorly sorted and finely skewed. This increase in the mean grain size suggests an increase in the intensity of the transporting medium i.e., melt-water streams originating from the melting of the polar ice-sheet and glaciers. This increase in the influx of melt-water streams indicates that deglaciation in the Schirmacher Oasis occurred after the LGM, i.e., from ~19 cal ka B.P. According to Stenni et al. (2011), the first stage of deglaciation is believed to have synchronously begun all over Antarctica at 18.2 ± 0.7 kyr BP (Termination 1). Magnetic susceptibility data from the same sediment core also showed that deglaciation in the SO began at around 19 cal ka B.P. (Warrier et al., 2014). As stream velocity which is a function of sediment discharge increases, larger proportion of coarse-grained sediments can be transported in the stream's suspended load and debouched into the lake bed (Campbell, 1998). During the Holocene warming period, enhanced melting of the glaciers brought in a large proportion of coarse-grained sediments from the catchment into the Sandy Lake. The mean grain size values show a cyclic variability suggesting that during the Holocene period, Schirmacher Oasis was characterised by alternating periods of relatively warm and cold climatic conditions which is also evident in other lake sediment records from Schirmacher Oasis (Phartiyal et al., 2011; Phartiyal, 2014) and other ice-free regions (Verleyen et al., 2004, 2011; McMinn, 2000; Wagner et al., 2004; Hodgson et al., 2005) in East Antarctica.

5. Conclusions

The sediment grain size data and scanning electron microscopic observations of quartz grains from Sandy Lake sediments of Schirmacher Oasis, East Antarctica, enable us to draw the following

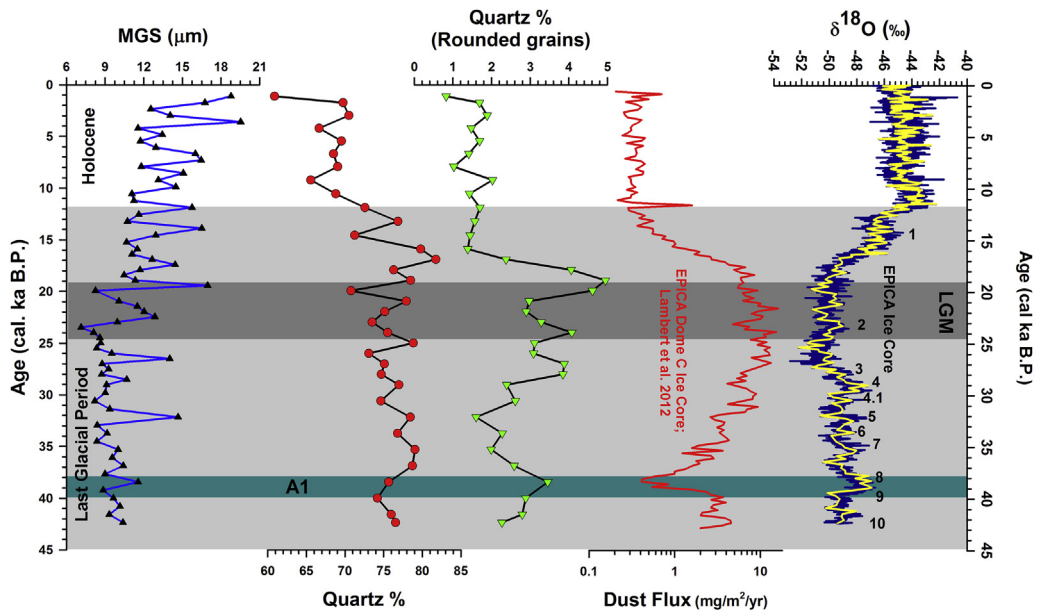

Fig. 10. Comparison of mean grain size, % quartz, and % rounded quartz grains with dust flux (Lambert et al., 2012) and oxygen isotopic data (EPICA Community Members, 2006) from EPICA ice-core data.

conclusions:

- The statistical parameters of grain size data (sorting, skewness, kurtosis, mean grain size, D_{10}, D_{50}, D_{90} and SPAN index) indicate that the sediments are primarily deposited due to glaciofluvial activity. However, certain periods during the Last Glacial period, aeolian activity was responsible for the transport of Sandy Lake sediments.
- Different modes of grain size distribution (unimodal, bimodal, trimodal and polymodal) indicate that the sediments are transported by different erosive agents.
- The sediments have a poor textural maturity as they are poorly sorted and supported by the fact that a range of grain size classes are present.
- SEM studies of selected quartz grains and the analyses of various surface textures indicate that glacigenic conditions must have prevailed at the time of their transport to the lake basin.
- The quantitative analyses of sediments indicate a mixed population of mineralogy of grains with quartz being the dominant mineral. High concentrations of quartz over other minerals indicate that the sediments are compositionally mature.
- High relative percentage of rounded quartz grains data during the last glacial period indicates a peak in aeolian activity in the Schirmacher Oasis.
- There is a major shift in climatic conditions from the LGM into the Holocene as evident by increase in sedimentological and mineralogical parameters.
- The study reveals the different styles of physical weathering and erosive signatures, most of them characteristic of glacial environment which affected these quartz grains before final deposition as lake sediments.
- The study shows that sediment mean grain size can be used as a suitable proxy for past climate reconstruction in high-latitude lakes.

Acknowledgements

We are grateful to the Secretary, Ministry of Earth Sciences and Director, ESSO-NCAOR for their constant encouragement and support under the project Past Climate and Oceanic Variability. We are grateful to the Antarctic Logistics Division, ESSO-NCAOR and Members of the 28th Indian Scientific Expedition to Antarctica for their help. We thank Dr. John Kurian, ESSO-NCAOR, for kindly providing access to the Laser Diffraction Particle Size Analyser facility. We thank the two anonymous reviewers and the guest editor for critically reviewing the earlier version of the manuscript and helping us improve the same. This is ESSO-NCAOR contribution no. 1/2016

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