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Glacial lakes and geomorphological evolution of Schirmacher Oasis, East Antarctica, during Late Quaternary

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ABSTRACT

Large former glacial lakes and their sediments are described from the Schirmacher Oasis region of East Antarctica. The water bodies were present during the Late Quaternary (~10–3 ka BP) and have reduced in size by negative water balance. This desiccation can possibly be attributed to the combined effect of recession of glaciers feeding them, low melt water, low precipitation and strong winds. Seven representative sections from five dry lake beds have been studied using loss-on-ignition (LOI) and Magnetic Susceptibility (MS). The LOI indicates a very low organic content, while MS enables assumptions to be made about the reconstruction of changing detrital input. Detailed study of sediment profiles was used to reconstruct the evolution of the Schirmacher Oasis from 13 ka BP to the present. These lacustrine sediments are a very important source of information on the Quaternary geological history of the Schirmacher Oasis.

1. Introduction

Lakes in the ice free regions of Antarctica are typically covered by ice for 6–8 months per year, which minimizes wind generated currents and reduces light penetration, as well as restricting sediment deposition in the lake. These are modern-day analogs of paraglacial and periglacial lakes that were common during glacial periods at temperate latitudes with extremely low sedimentation rates. Such lacustrine sediments record changes to the lakes and their catchments and can be particularly good palaeoenvironmental archives. Ice free areas in East Antarctica include the Dry Valleys of Victoria Land, Bunger Hills, Vestfold Hills, Larsemann Hills and Schirmacher Oasis (Fig. 1 A). Schirmacher Oasis (SO) is a 35 km^2 area in Central Queen Maud Land with ~118 permanent lakes and ponds (Bormann and Fritzsche, 1995; Richter and Bormann, 1995; Fig. 1 B-D). This region has few large coastal oases, and as a result any palaeoenvironmental information from SO is particularly valuable. Much of the valley floors of SO consist of lacustrine sediments (Fig. 2) which may contain palaeoenvironmental information. The lakes exhibit evidence of ongoing reduction in area, leaving behind a rich sedimentary record. In this work, the late Quaternary evolution of Schirmacher Oasis will be reconstructed via a consideration of the sedimentology (grain size, Magnetic Susceptibility, Loss-on-ignition) and radiocarbon chronology from a range of palaeolakes which existed over the past 13 ka.

2. Location, geology and geomorphology

The SO, an ice free 35 sq km area situated in the Queen Maud Land (East Antarctica) between 70° 43′ 50″ and 46′ 40″ S; 11° 22′ 40″ and 54′ 20″ E (Fig. 1), was sampled for this study. The region is located between the margin of the ice sheet and the shelf ice. SO has low lying hills, up to 228 m asl with an average altitude of 100 m, and contains 118 interspersed glacial lakes that are classified as proglacial, landlocked and epishelf lakes (Bormann and Fritzsche, 1995; Ravindra, 2001) (Fig. 2). A majority of the lakes in SO lie in glacially eroded bedrock basins. However, lakes dammed by moraines or ice are also common (Bormann and Fritzsche, 1995). On the north side towards the ice shelf, the oasis is bordered by steep cliffs of more than 100 m, whereas on the southern side it is mostly overridden by the inland ice sheet. Extensive debris cover, moraine deposits, hillocky relief and former lakes form a part of the present day landscape. The oasis is a recent periglacial region that is unaffected by anthropogenic activity (Krause et al., 1997). The Precambrian crystalline basement of SO forms a part of the East Antarctic craton (Sengupta, 1986, 1988; Paech and Stackebrandt, 1995) and shows polymetamorphic character. The rocks are strongly and repeatedly deformed under granulite and amphibolite facies conditions. The rock types consist of charnockites, enderbites, garnet-sillimanite gneisses, garnet-biotite gneisses,

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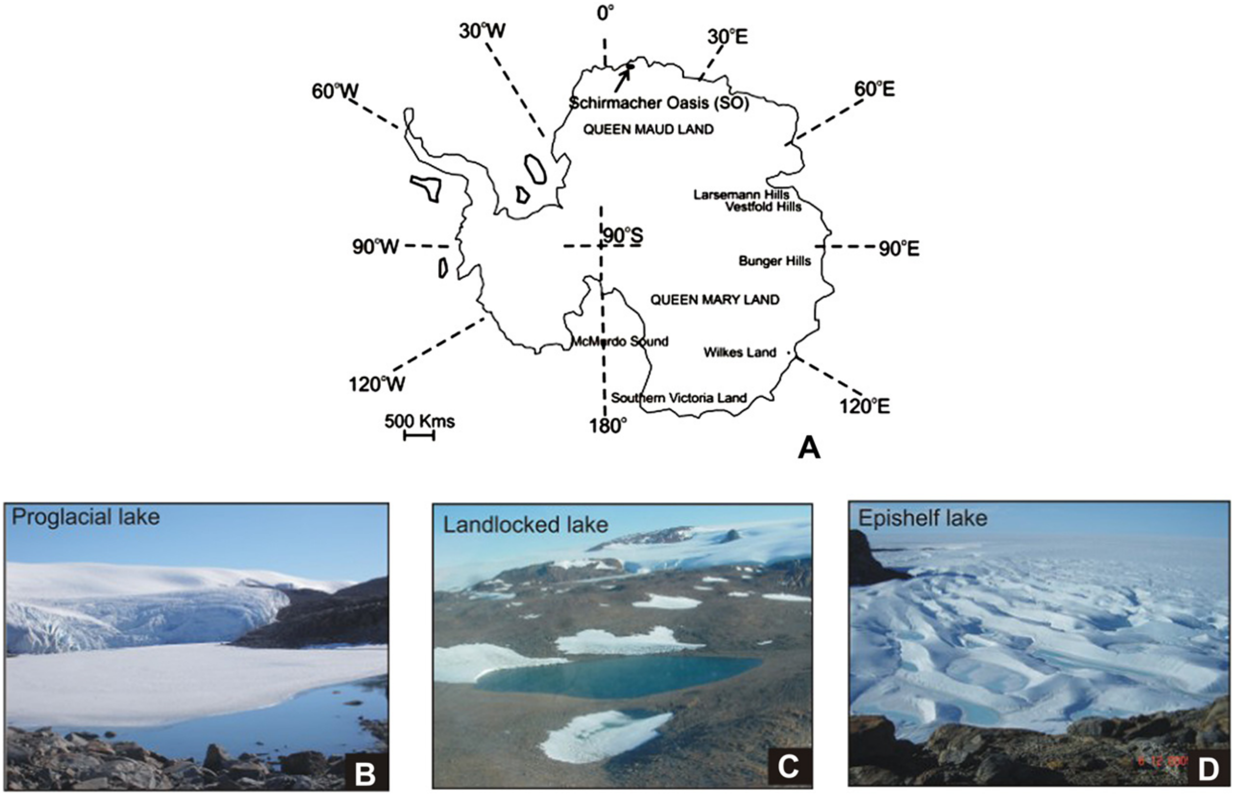

Fig. 1. (A) The ice sheet surface of Antarctica showing the ice free areas in East Antarctica which include the Dry valleys of Victoria Land, Bunger Hills, Vestfold Hills and Schirmacher Oasis (B–D) Photographs showing proglacial, landlocked and epishelf lakes in the Schirmacher Oasis, where 118 such lakes exist today (Bormann and Fritzsche, 1995; Ravindra, 2001).

quartzo-feldspathic augen gneisses with some foliated lamprophyres, amphibolites, dolerite, metagabbro and metabasalt (Sengupta, 1986, 1988). The rock suites dominantly fall under Grenvillean (1000 Ma) and Pan-African (550 Ma) events.

3. Present day climate of the study area

Climate in the SO has predominantly continental characteristics. Much of the Oasis, which is characterized by an absence of continental ice, experiences a dry polar climate. The Oasis is subjected to the influence of the peripheral area of the Antarctic High that forms clear frosty weather with katabatic winds. Annual temperatures range between +7.4 and −34.8 °C with a mean of −10.2 °C. Winter (April–September) is mild in general but with strong winds, frequent storms and snowstorms. Atmospheric pressure is greatest, and the absolute humidity least during the winter. In spring (October–November), atmospheric pressure decreases sharply, winds attenuate and both air temperature and humidity increase considerably leading to active evaporation and the commencement of thaw. Winds reach 90–95 knots with a mean annual wind speed of 18 knots. In mid-October, above zero temperatures on snow-free soil surfaces are recorded. In summer (December–January), atmospheric pressure, air temperatures and air humidity are greatest, winds are comparatively weak, snowfalls are rare and precipitation is insignificant. There is rapid melting of snow and ice and intense drainage of melt water from the Oasis to the ice shelf. Autumn (February–March) is characterized by decreasing air temperature and humidity. Atmospheric pressure decreases slightly compared with the summers, melt water in the Oasis freezes, and ice cover forms on the lakes. The warming influence of the Oasis is expressed in a higher air temperature equal to −11.0 °C, i.e. higher than at the nearest coastal stations and the average temperature oscillations from year-to-year are insignificant, within 1 °C (http://south.aari.nw.ru/stations/lazarev/lazarev_en.html). During the summers of 2005–06 and 2006–07, sediment cover >30 cm thickness was studied over the entire 35 km^2 of the SO (Figs. 1 and 2) to reconstruct palaeolakes that are now either completely dry or have been reduced in size.

4. Sampling and chronology

Seven vertical profiles were recovered, using either pit or channel sampling or cores taken by manual corer (PVC pipes), along an east–west transect. The SO region was subdivided into two sections for convenience in studying the distribution of the dry lakes; Section 1 comprises the eastern side, and Section 2 the western side (Fig. 2). Vertical profiles were sub-sampled at 1–2 cm intervals for lithological character, magnetic susceptibility and Loss-on-ignition. Eleven radiocarbon dates were obtained (by Accelerator Mass Spectrometer technique); seven from (A1, A2, A3, B1, C1, A7 and A8) Silesian University of Technology, Gliwice, Poland (calibrated using the SHCal04 southern hemisphere atmospheric curve; McCormac et al., 2004) and four from NOSAMS, USA (AS01, AS02, AS03 and AS04), with ages following the convention of Stuvier and Polach (1977). Standard sample preparation methods were adapted in the respective laboratories to make graphite targets which were analyzed by mass accelerator along with primary and secondary standards and process blanks. Bulk sediments were dated, as it was very difficult to separate the organic carbon from the organically poor sediment. Details of the AMS chronologies are in Table 1.

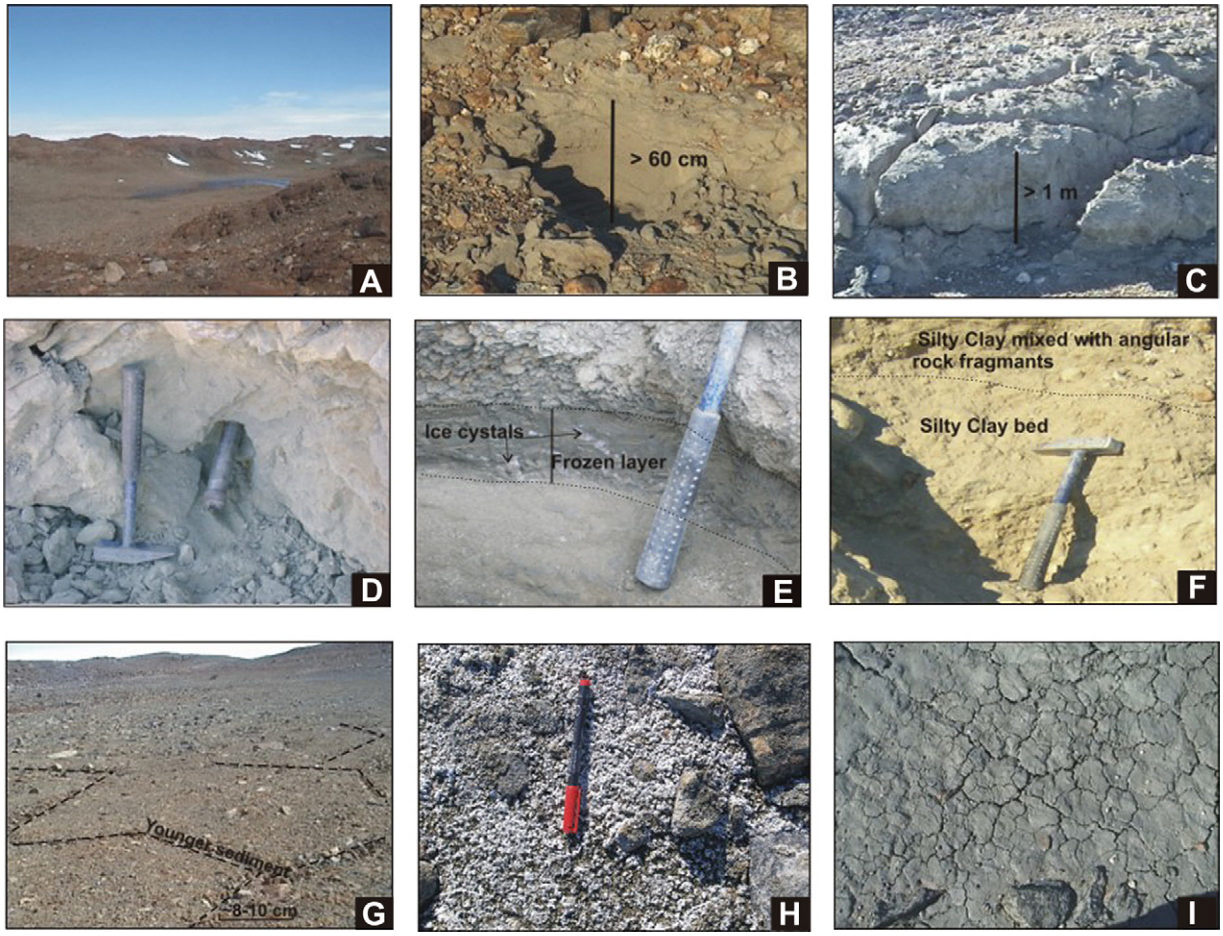

Fig. 2. Photo plate- (A) A drying lake which is reduced to a pond and the sediment is exposed. (B) Sediment fill (C) Clay beds ~1m thick entrapped in the moraine (D) Sampling in the exposed section (E) A pit section; ice crystals are seen in the lower bed (F) A clay bed overlain by angular debris (G) Frost sorted polygons formed on the dry lake surface (H) Salt deposit on the lake surface (I) Mud cracks forming on the surface of the drying lake surface.

5. Magnetic susceptibility (MS)

MS investigates changing inputs of magnetic minerals and has been used to successfully reconstruct Late Pleistocene and Holocene climatic variations (Bloemendal et al., 1988; Maher and Thompson, 1992; Evan and Heller, 1994; Verosub and Roberts, 1995; Williamson et al., 1999; Digerfeldt et al., 2000; Phartiyal et al., 2003). The MS was measured on 282 samples from seven profiles, using a MS2 Bartington Susceptibility meter and Dual Frequency Sensor (noise level 3×10^{-9} m^3/kg), operating at 0.47 kHz. MS is a concentration dependent parameter used for determining changing detrital input which results mostly due to climatic variations. During colder phases (glacial regimes), coarse grained material is deposited in the basins which enhances the MS values, while during the comparatively warmer periods fine grained material with low sedimentation rates lowers MS values. Thus higher MS values correspond to cold conditions and low susceptibilities to comparatively warmer climatic conditions.

6. Loss-on-ignition (LOI) percentages

Sixty eight selected samples from five profiles were chosen for sequential loss-on-ignition (LOI) which is used to estimate the combined weight of organic matter, carbonate minerals and waters of formation in some minerals in sediments using linear relations between LOI values and organic and inorganic carbon content. This method is widely used for palaeoenvironmental investigations (Korsman et al., 1999; Dodson and Ramrath, 2001; Bendell-Young et al., 2002). The methodology involves 5 gm air dried samples were heated at 110 °C for 12 h, 550 °C for 2 h, 950 °C for 2 h respectively in three steps and the weight loss observed after each step represented the moisture present, the total organic carbon and the inorganic carbon present in the samples respectively. The loss of ignition in the samples was then calculated by adding all the weight loss and taking out its percentage.

7. Results

7.1. Geomorphological observations

The SO is the only ice free area at the northern margin of Queen Maud Land. The region comprises rocky hills and sediment-draped valleys with altitudes ranging from 0 to 228 m asl. The southern portion of the oasis abuts the ice sheet whereas the northern margin is an escarpment in contact with Novolazarevskaya Ice Shelf. The landscape is dominated by bare rock slopes. Prominent features include deglaciated valleys, rounded hills, glacial sediment, patterned ground and numerous lakes. Erosional landforms (hills, valleys, cliffs, escarpments, striated surfaces and roches moutonnée) and depositional landforms (glacial sediments, patterned ground, lake terraces) are commonplace (Fig. 2). Most lakes are fed by glaciers flowing northwards from the ice sheet

Table 1
Details of AMS Chronology (bulk sediment organic carbon was dated). Samples A1, A2, A3, B1, C1, A7 and A8 were dated at Silesian University of Technology, Gliwice, Poland and AS01, AS02, AS03 and AS04 were dated at NOSAMS, USA.

No.	Sample name	Lab. No.	Calibrated age range 68%	Calibrated age range 95%	Age ^{14}C (BP)
1	A1	GdA-1236	11022BC (68.2%) 10881BC	11093BC (95.4%) 10812BC	12900 ± 70
2	A2	GdA-1237	10702BC (68.2%) 10561BC	10773BC (95.4%) 10492BC	12580 ± 70
3	A3	GdA-1238	6205BC (3.4%) 6192BC 6183BC (3.0%) 6171BC 6159BC (3.9%) 6143BC 6104BC (54.3%) 5982BC 5942BC (3.6%) 5928BC	6226BC (95.4%) 5894BC	7230 ± 80
4	B1	GdA-1239	6372BC (55.5%) 6207BC 6188BC (0.8%) 6185BC 6169BC (2.0%) 6161BC 6141BC (10.0%) 6106BC	6412BC (95.4%) 6071BC	7430 ± 80
5	C1	GdA-1240	5711BC (51.4%) 5606BC 5596BC (16.8%) 5560BC	5742BC (95.4%) 5484BC	6770 ± 80
6	A7	GdA-1470	5644BC (37.3%) 5608BC 5594BC (30.9%) 5562BC	5701BC (0.5%) 5696BC 5673BC (94.9%) 5530BC	6690 ± 40
7	A8	GdA-1471	10656BC (34.7%) 10504BC 10459BC (14.3%) 10394BC 10372BC (17.1%) 10288BC 10251BC (2.1%) 10239BC	10705BC (95.4%) 10173BC	10450 ± 60
8	AS01	OS-69329	7952BC (91.8%) 7782BC 7773BC (8.2%) 7755BC	8180BC (7.3%) 8113BC 8090BC (0.7%) 8007BC 8061BC (1.2%) 8043BC 7998BC (90.8%) 7657BC	8790 + −45
9	AS02	OS-69330	1424BC (85.82%) 1382BC 1334BC (14.18%) 1324BC	1435BC (74.46%) 1367BC 1362BC (25.54%) 1314BC	3110 + −25
10	AS03	OS-69331	11147BC (100%)10975BC	11181BC (100%) 10817BC	11100 + −50
11	AS06	OS-69332	9443BC (9.2%) 9423BC 9417BC (90.8%) 9272BC	9661BC (9.8%) 9571BC 9558BC (90.2%) 9246BC	9890 + −70

towards the coast. Glacial debris is very common. Weathering and frost action show strong effects on the bedrock and exfoliation is seen in exposed rocks. The northwestern part of SO is a large depression draped with lacustrine sediments (Fig. 2).

7.2. Sedimentology and chronology of lacustrine deposits

7.2.1. Section I

This section contains large and small lakes, including lakes Dlinnoye (No. 29), Zub (No. 45) and Glubokoye (No. 61) (Fig. 3). A major part of this section is occupied by lacustrine sediments. Five profiles of these sediments were sampled, namely SD (40 cm), PDL (30 cm), MBL (165 cm), TS (210 cm) and DLL (70 cm) (Figs. 3–5). PDL and DLL were cores; the remainders were from pits. The sediments are sandy, intercalated with silty sand and clay, with angular rock fragments. The nature of the five profiles is more or less the same. Clay was encountered below 30 cm, whereas sand and silt dominate at shallower depths. The base of most of the sediment sections is not exposed except for DLL section (near Dlinnoye Lake) which has bedrock at the base. The presence of permafrost between 60 and 80 cm restricted further digging or coring but the sediments are almost certainly deeper in the permafrost. The PDL core gives an AMS date of 7430 ± 80 BP (GdA-1239) at the base level while the uppermost clays date to 3110 ± 25 BP (OS-69330). MBL yields a date of 9890 ± 70 BP (OS-69332) at 125 cm depth; however an older date of 11,100 ± 50 BP

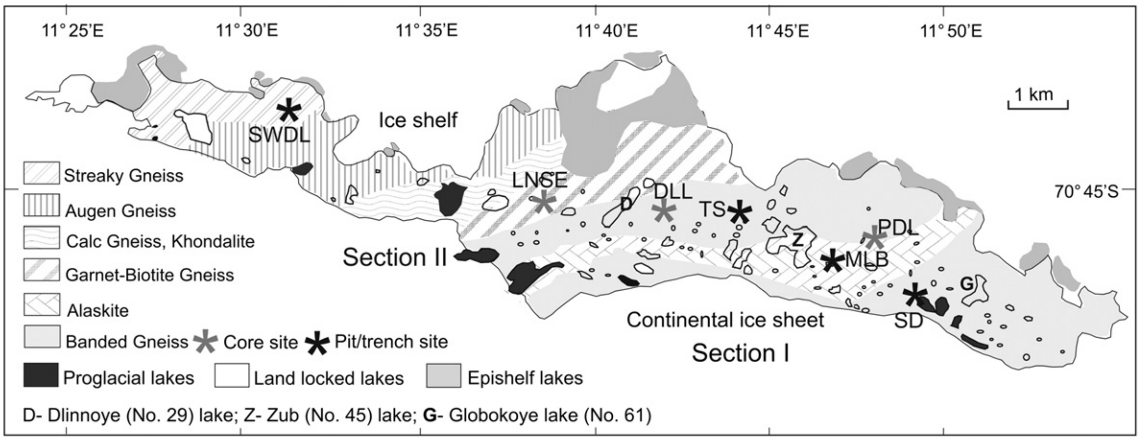

Fig. 3. Geological and geomorphological map of Schirmacher Oasis showing the present day lake distribution (modified after Sengupta, 1988 and Ravindra, 2001). The sampling profiles are marked.

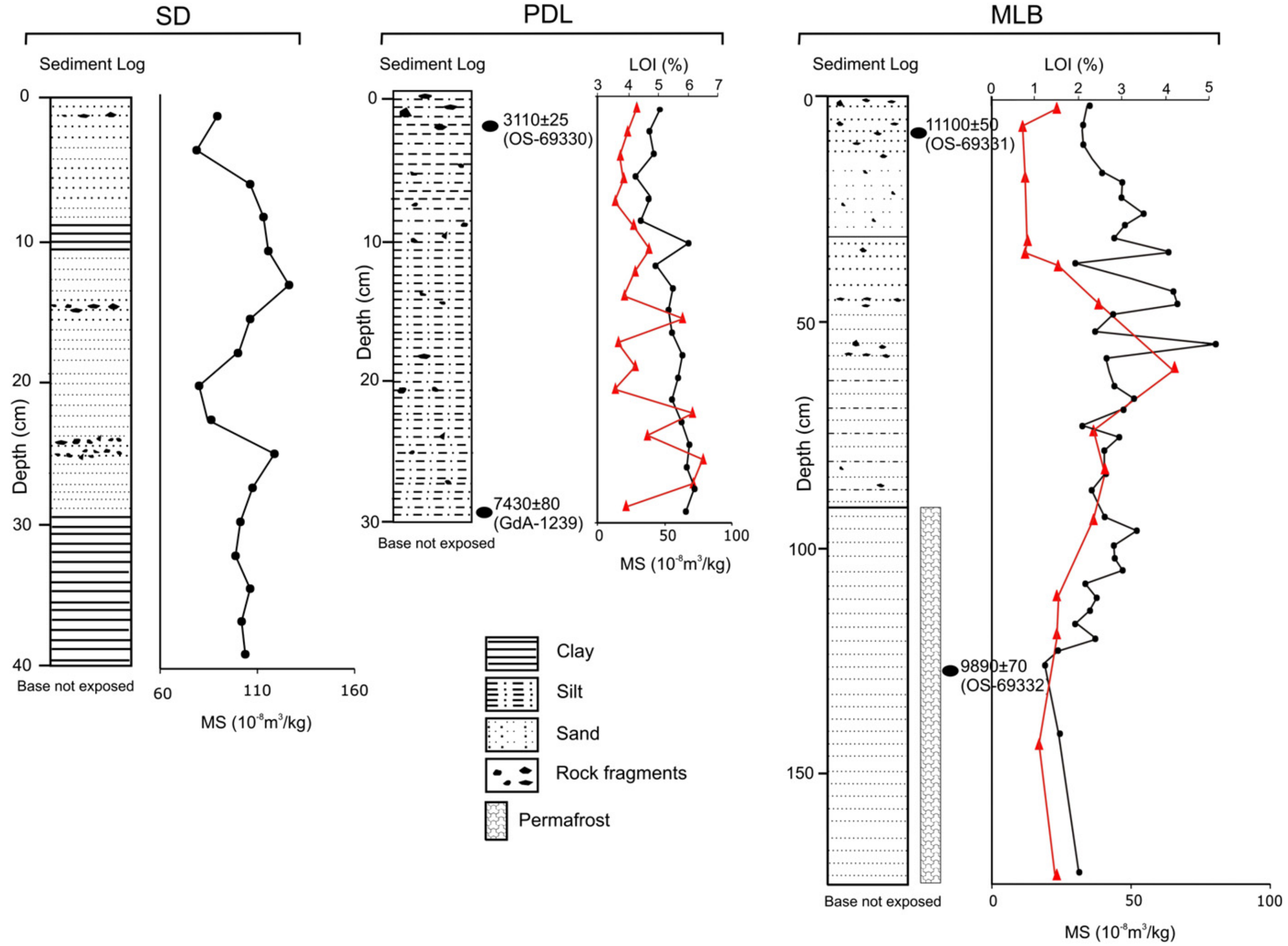

Fig. 4. (A) SD profile; (B) PDL core; (C) MLB profile plotted against their MS (circle) and LOI % (triangle).

(OS-69331) was found at 10 cm depth (Fig. 4), perhaps a result of periglacial cryoturbation. The DLL section gives a date of 12,900 ± 70 BP (GdA-1236) at 65 cm depth, 12,580 ± 70 BP (GdA-1237) at 52 cm depth and 7230 ± 90 BP (GdA-1238) in the upper 2 cm. Clay beds (~>1m thick) entrapped between moraines are seen; TS (Fig. 2D–E) is one such friable clay bed that was sampled (Fig. 5). The dry lake bed sediments are separated from other lake beds or flat areas of same altitude by rock fall in places or by small mounds or moraines. Rock slabs tens of metres wide are seen at places separating the former lake bodies; the whole system otherwise formed a single lake system in postglacial times. A 1 m thick clay bed, with sandy pockets embedded above present day lake levels may be indicative of recession of the lake. The new ^{14}C chronology indicates that these lakes existed from ~13 to 3 ka BP.

7.2.2. Section II

This section has only one large lake and a few small lakes and the ice free area is narrower than in Section I (Fig. 2). Here at a higher elevation the dry lake beds are exposed. Thick clay beds (~1 m) with a lateral extent of ~10 m are exposed (Fig. 3). LNSE (80 cm) and SWDL (30 cm) sediment cores were studied (Fig. 3). LNSE core gives an AMS age of 10450 ± 60 BP (GdA-1471) at the base while the top levels date to 6690 ± 40 BP (GdA-1470). The SWDL core gives an AMS age of 6770 ± 80 BP (GdA-1240) at 28 cm depth while at 2 cm depth an age of 8790 ± 45 BP (OS-69329) was found. This age inversion can be due to cryoturbation. Mud cracks are seen and blackish organic rich sediment is encountered in this part (Fig. 3). Clayey bands are present between the sand beds. The sediment is finer grained and thicker (>1 m) than in the eastern part of SO.

7.3. MS and LOI

MS is a concentration dependent parameter showing the bulk ferromagnetic content including the paramagnetic component. All seven lithosections were analyzed for MS; the values range from 20 to 200 $\times$ 10^{-8} m^3/kg. SD section shows a variation in the MS pattern, with the sand and rock fragment layers showing higher MS values than the finer sediment (clay, fine sand and silt). The PDL section shows a uniform lithology and consequently the variation is limited. The MS trend shows a decrease from the base to the top of the section indicating a trend of cold to comparatively warmer climatic conditions from ~7400 BP to 3000 BP. In the MLB section, the MS values fluctuate with the middle portion showing the maximum values. The TS and DLL are comparatively thicker sections and show a good correlation between sediment grain size and MS values (Fig. 5). Chronologically in the DLL section the basal part is ~13,000–12,500 BP; ~12–11.5 ka BP and 9.5–5 ka BP shows cold climatic conditions reflected in the high MS values at 55–70 cm, 40–45 cm and 0–20 cm depths respectively. In the LNSE, core higher values are encountered at the lower and the upper levels (~10 ka BP and ~7 ka BP) while the middle part

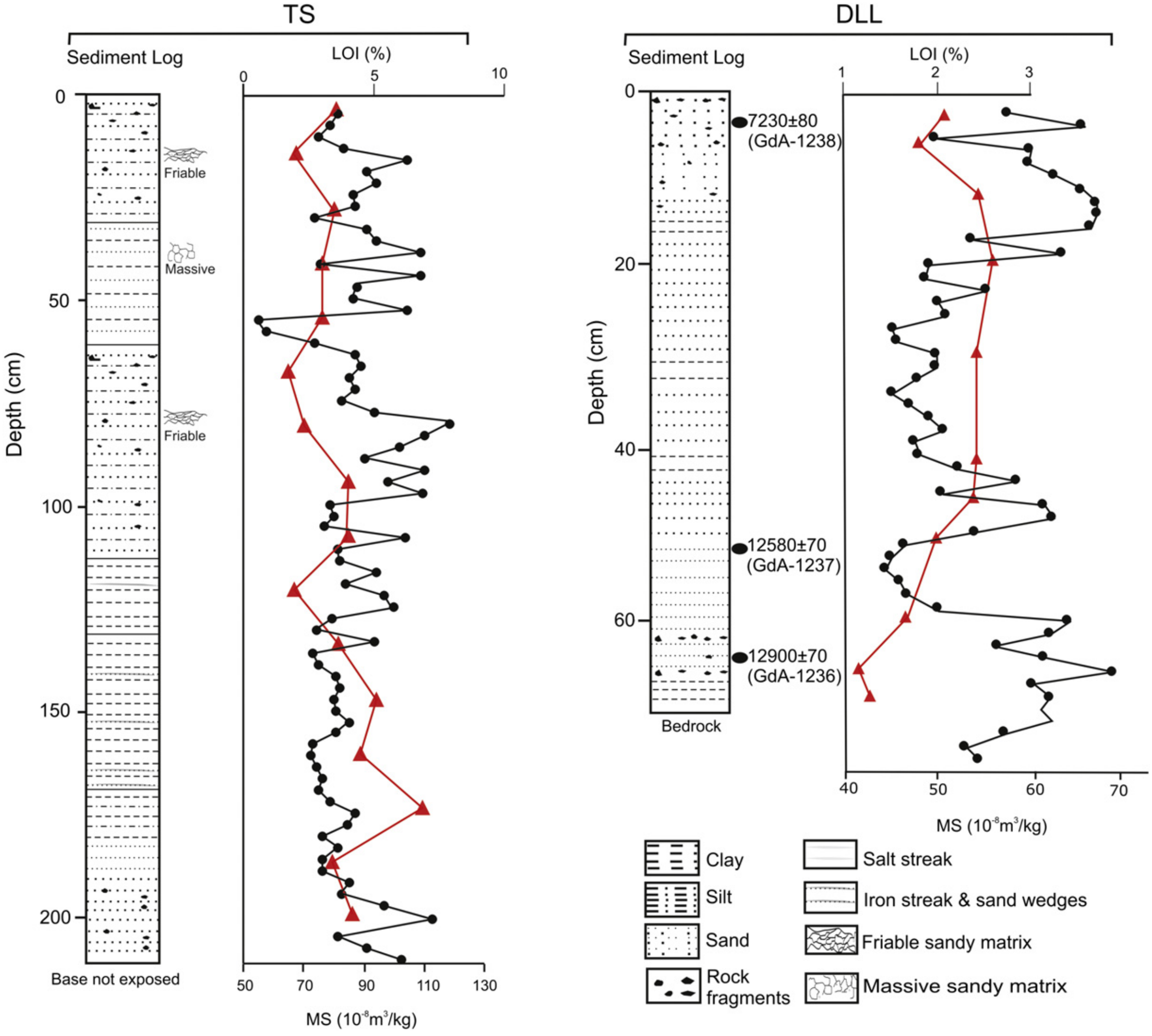

Fig. 5. (A) TS profile; (B) DLL core; plotted against their MS (circle) and LOI % (triangle).

(between ~10 and 7 ka BP) shows minor fluctuations in the low MS range indicating a warmer climatic trend. The SWDL shows a variation in MS values though it had a uniform lithology. Representative samples from PDL, MLB, TS, DLL and LNSE were analyzed for LOI. LOI is <8% in all the sections, however, a small fluctuation is noticed in the samples. There is no clear relationship in the LOI and the MS of the samples, however the clayey (finer grained) parts of the sediment sections show higher values.

8. Discussion and conclusion

The presence of >1 m thick, lacustrine sediment fills shows that the oasis hosted large lakes in the past. The present lakes are remnants of these larger water bodies which once occupied the oasis. According to the available AMS chronology as indicated in the Age-Depth model (Fig. 7), the PDL, DLL and LNSE sections represent a climatic history form ~13 ka-3 ka BP. The mean sedimentation rate is ~0.69 mm/year for the PDL core, ~0.019 for the LNSE core, and 0.132 mm/year for the DLL core, previous studies showing a comparable rate of 0.124 mm/year from the Priyadarshani (Zub) lake (Bera, 2004). In general, a sedimentation rate of 0.004–1.1 mm/year is observed in general from lacustrine sediments in Antarctica (Shen et al., 1998). The studied sediment distribution in the SO indicate the existence of five major lakes in the Holocene (Fig. 3), and the AMS ages and sediment parameters allowed a reconstruction of the landscape evolution during this period (Fig. 8). From 13 to 12.5 ka BP, the whole area may have been dominated by glaciers with the landlocked lakes of today as glacial lakes. With the onset of Holocene warming ~11.5 ka BP, the glaciers may have retreated, giving way to five large proglacial lakes occupying the low lying valleys of SO (Fig. 8. B). This is similar to Larsemann Hills where between 11.5 and 9.5 ka BP the lakes became ice free and an early Holocene optimum has been inferred (Verleyen et al., 2003, 2004a, 2004b; Hodgson et al., 2004). This warming also coincides with the beginning of the Holocene deglaciation of other East Antarctic oases (Ingólfsson et al., 1998; Gore et al., 2001; Hodgson et al., 2001; Kirkup et al., 2002). This is probably an Antarctic-wide phenomenon as it is also detected in ice cores elsewhere in the continent (Masson et al., 2000; Hall et al., 2001; Vimeux et al., 2001; Bentley et al., 2005). The lakes in the Schirmacher Oasis existed until ~3 ka BP and showed climatic fluctuations as seen in the variation of the MS and LOI, with comparatively colder periods between 13 ka BP and 12.5 ka BP; ~12,000–11,500 BP and 9500–5000 BP. Sand units are more abundant than silt or clay in the profiles. Silt and clay fractions of the sediment profiles exhibit low MS values, possibly due to the smaller detrital inputs from the catchment and more stable lake conditions. Many of the present day lakes have reduced to small ponds of just 10 cm–60 cm deep, confined to the lowermost part of the depression of a once big lake system (Fig. 2 A). Late Holocene desiccation is also recorded from McMurdo Dry Valleys (Lyons et al., 1998). The palaeolake beds as seen today are flat areas ranging from one to several sq km, with frost sorting (Fig. 2 G) and mud cracking of sediments (Fig. 2 I). The mud cracks indicate that the lake had recently dried as it has black, wet sediment indicative of recent water influence. The salt deposits on their surfaces (Fig. 2 H) today may be linked with a slightly negative moisture balance during the neoglacial cooling that commenced at ca. 2460 to 1800 BP and is continuing to the present (Taylor et al., 2001; Brachfeld et al., 2002; Taylor and McMinn, 2002; Cremer et al., 2003 and Verleyen et al., 2004a, 2004b). Soil formation in the oasis is negligible, but thin (mm to cm scale) dark clay organic layers are encountered in many of the sections although the LOI shows a range (2–8%) however variation in the pattern is noticed. The larger amplitude in LOI may be related to greater seasonal variability with carbonate being precipitated during the comparatively warmer periods. During the colder phases coarser material may have been deposited in the lakes thereby enhancing the values that are correlated with the stable and comparatively warmer lake phases. In the DLL section (Fig. 5), comparatively warmer phase and stable lake conditions may be inferred from sediments at 20–40 cm and 48–54 cm depths with low MS values. These warm phases correspond to the age of ~10–8 ka BP and around 12.5 ka BP. Lakes in the Larsemann Hills show productive periods between ~7 ka BP and 5 ka BP and between 3 ka BP and 2 ka BP (Hodgson et al., 2004).

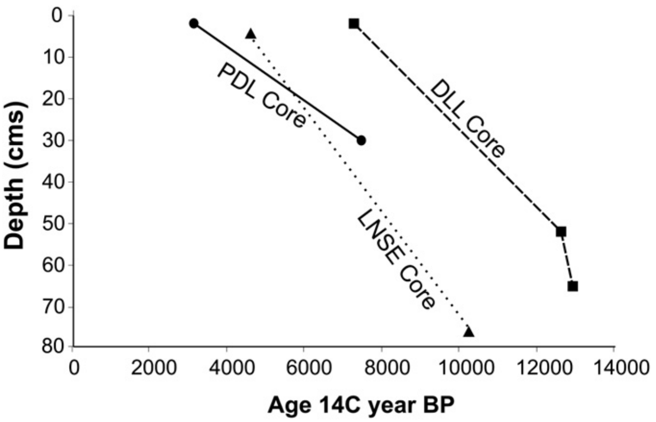

Fig. 7. Age-Depth model of the PDL, DLL and LNSE cores.

In LNSE section high MS values are seen at the base and at 8–15 cm levels (Fig. 6) corresponding to the ~10.5 ka and around 8 ka BP colder episodes. Older OSL ages from the moraines in the eastern side of Schirmacher Oasis date to ~70 ka BP and 50 ka BP (Krause et al., 1997), to the beginning of the Marine Isotope Stage 3 (Lorius, 1985) have been reported. Lake Dlinnoye shows a chronology of 23–7 ka BP (Krause et al., 1997) and DLL profile which is at the vicinity of the core dated by Krause et al. (1997) also shows dates of ~13–7 ka BP. All these ages signify the presence of glacial

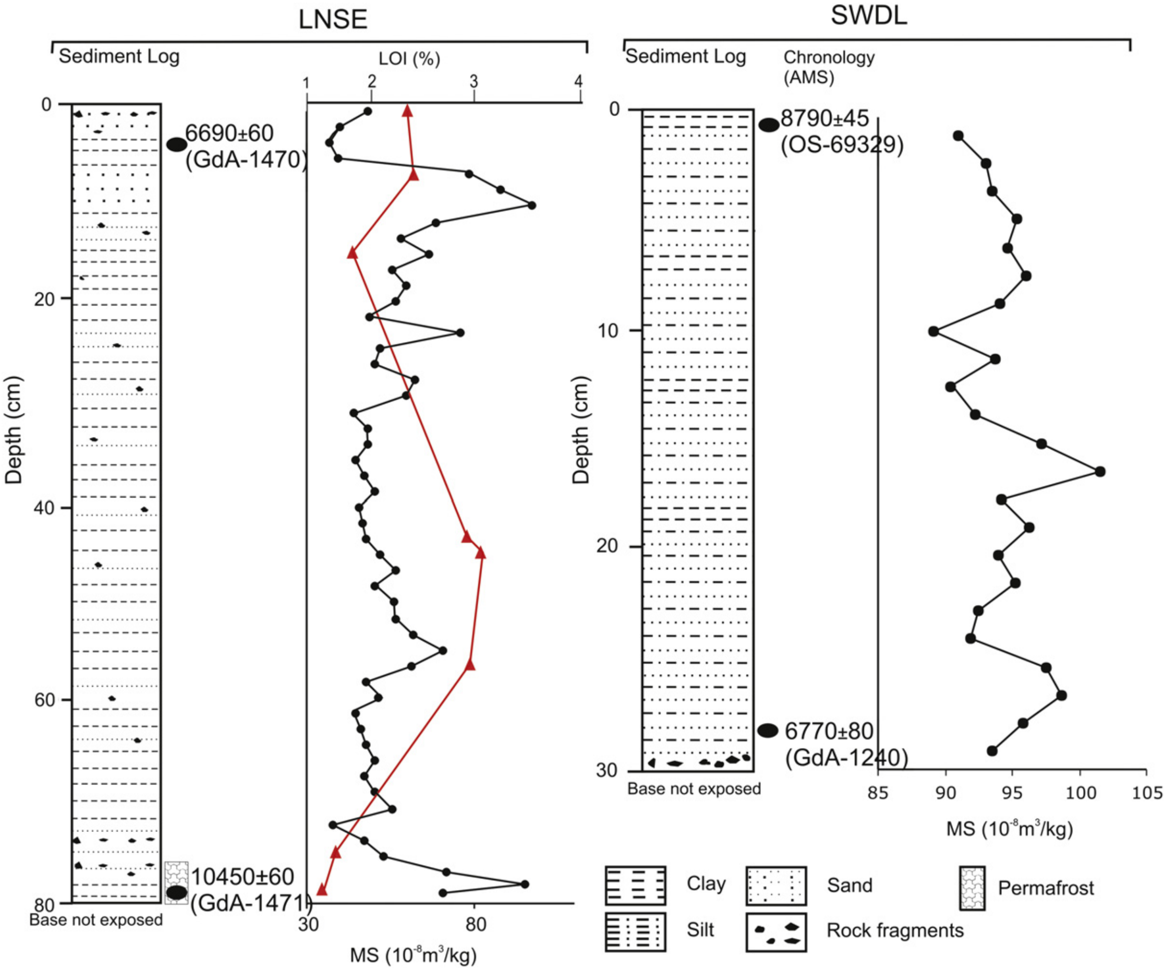

Fig. 6. (A) LNSE core; (B) SWDL profile; plotted against their MS (circle) and LOI % (triangle).

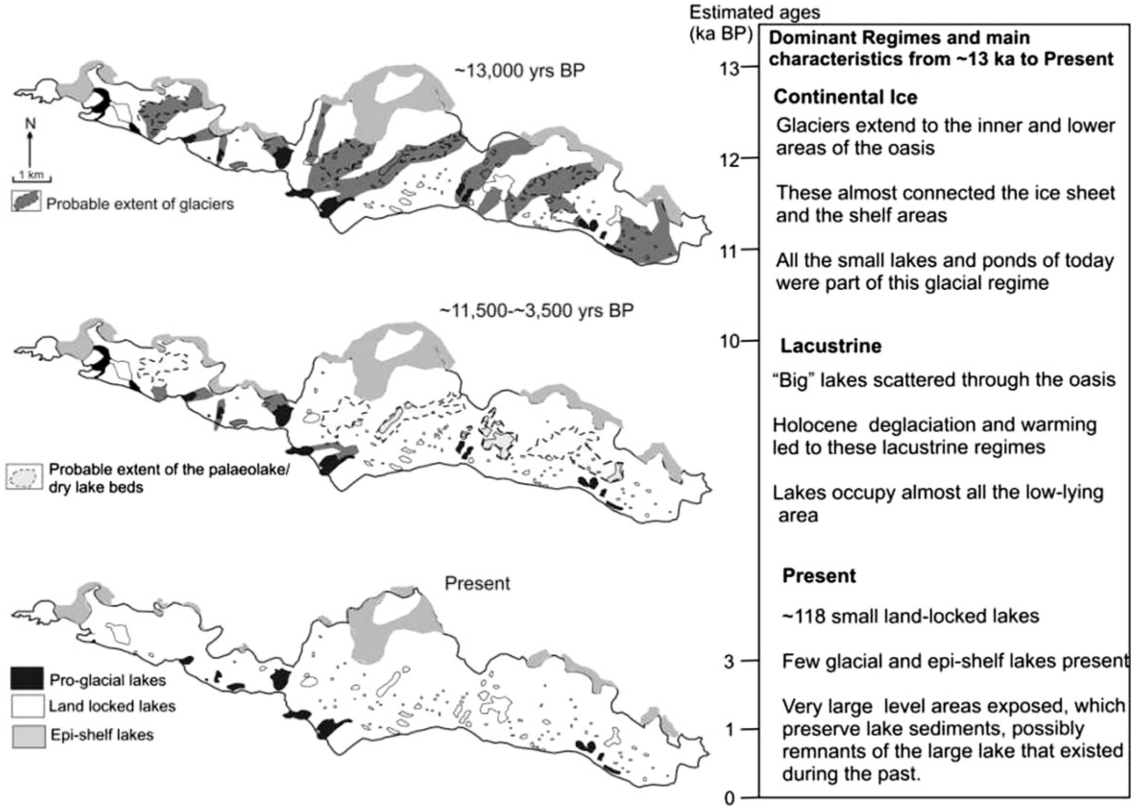

Fig. 8. Reconstruction of the lacustrine regime in the SO; >13,000 to 10,000 BP, 10,000–3000 BP and present.

and lacustrine episodes prior to 13 ka also in the SO. The drying of these landlocked lakes may be attributed to a number of factors-the glacier recession in the area depriving these lakes with regular supply of water during summer months; reduced precipitation or snow accumulation, less melt water, strong winds and sublimation of the lake due to ice cover, may be the reasons which have led to the drying of these lakes. On the other hand, proglacial and the epishelf lakes have a continuous source of melt water from the continental ice sheet and the ice shelf respectively. Although the cause of the lowering of water levels for these palaeolakes is not clear, they could serve as an important source of information for Quaternary researchers.

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