Antarctic Science 19 (1), 125–128 (2007) © Antarctic Science Ltd Printed in the UK DOI: 10.1017/S095410200700017X

Indications of Holocene sea-level rise in Beaver Lake, East Antarctica

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Abstract: A 100 cm long sediment sequence was recovered from Beaver Lake in Amery Oasis, East Antarctica, using gravity and piston corers. Sedimentological and mineralogical analyses and the absence of micro and macrofossils indicate that the sediments at the base of the sequence formed under glacial conditions, probably prior to *c.* 12 500 cal. yr BP. The sediments between *c.* 81 and 31 cm depth probably formed under subaerial conditions, indicating that isostatic uplift since deglaciation has been substantially less than eustatic sea-level rise and that large areas of the present-day floor of Beaver Lake must have been subaerially exposed following deglaciation. The upper 31 cm of the sediment sequence were deposited under glaciomarine conditions similar to those of today, supporting geomorphic observations that the Holocene was a period of relative sea-level highstand in Amery Oasis.

Received 8 May 2006, accepted 27 July 2006

Key words: deglaciation, sea-level change, sediment

Introduction

Beaver Lake in Amery Oasis, East Antarctica, is the largest Antarctic lake (Wand *et al.* 1987). It is located in a horseshoe-shaped basin, here called 'Beaver basin', which captures a glacier tongue from Nemesis Glacier to the north (Fig. 1). As Beaver Lake is hydrologically connected to the ocean beneath Nemesis Glacier and Amery Ice Shelf, it is a tidal lake or so-called epishelf lake. The absence of emergent marine terraces or beaches around Beaver Lake, and the presence of extremely well developed ventifacts just above present day sea-level indicate that the Holocene has been a period of relative sea-level highstand (cf. Adamson *et al.* 1997). Additional evidence for a lower relative sea-level in the past consists of a submerged channel with a v-shaped cross section, which extends across the lake floor for at least 7 km from the mouth of Pagodroma Gorge and to at least 235 m water depth. It is possible that erosive density currents from Radok Lake have contributed to the formation of this channel. However, the v-shape of the channel suggests that it has been mainly formed by fluvial erosion during lower lake levels (Adamson *et al.* 1997). It has been suggested that local ice expansion onto Amery Oasis during the Last Glacial Maximum (LGM) was relatively modest, with ice extents perhaps similar to that of today (cf. Adamson *et al.* 1997, Hambrey & McKelvey 2000). In contrast, marine cores from Prydz Bay indicate that the Lambert Glacier/Amery Ice Shelf system was significantly extended during the LGM, and grounded half way across Prydz Bay (e.g. Domack *et al*. 1998, Whitehead *et al*. 2006 and references therein). Retreat of Lambert Glacier/Amery Ice Shelf at 12–11 ka BP (O'Brien & Harris 1996, Taylor & McMinn 2001, 2002) was contemporaneous with the deglaciation of several basins in Amery Oasis between 20 and 10 ka BP (Wagner *et al.* 2004, Fink *et al.* 2006). The absence of shorelines leads to the prediction that the isostatic rebound due to shrinking of the glaciers after the LGM was less than eustatic global sea-level rise of about 120 m (Fairbanks 1989), and therefore presently underwater areas of Beaver Lake must have been subaerially exposed since deglaciation.

In the summer of 2001/2002, bathymetric measurements were carried out at ice-covered Beaver Lake along a transect from the shore to the distal part (Fig. 1). Two sediment cores (Lz1013-1; 0–31 cm and Lz1013-2; 19–100 cm) were recovered from a subaquatic terrace at 54 m water depth (Fig. 1) with a gravity and piston corer, respectively (UWITEC Co; Wagner 2003). Cores were opened lengthwise in the laboratory, documented, and subsampled in 1–2 cm intervals. Sedimentological and mineralogical analyses were carried out on selected bulk sediment samples using standard methods described in Diekmann & Kuhn (1999) and Wagner *et al.* (2004). Micro and macrofossils such as diatoms and foraminiferas were completely absent in the core sequences recovered (cf. Cremer *et al*. 2004), consistent with the observation that Beaver Laker is the most depauperate epishelf lake in Antarctica so far known (Laybourn-Parry *et al*. 2001). The absence of fossils and the presence of very finely disseminated coal fragments from coal-bearing Permo-Triassic sediments to the west of the lake prevented the use of carbon isotopes as a proxy for paleoenvironmental information. The same coal fragments precluded

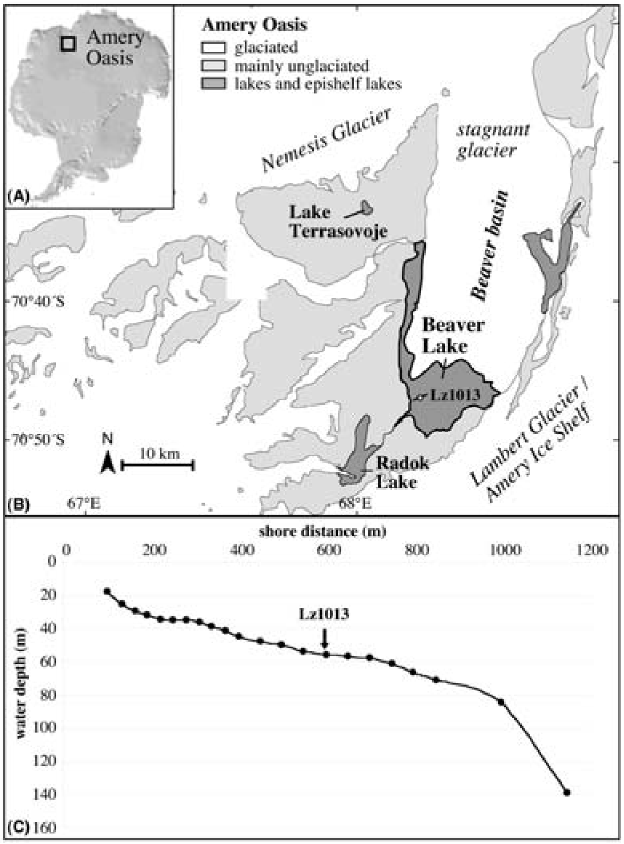

Fig. 1.a. Map of Antarctica showing the location of Amery Oasis. **b.** Location of Beaver Lake in Amery Oasis. The black line in the south-western part of Beaver Lake indicates the location of the bathymetric profile. The dot on the line shows the location of coring site Lz1013 at 54 m water depth. **c.** Bathymetric profile from the shore to the distal part of south-western Beaver Lake, based on spot measurements (black dots).

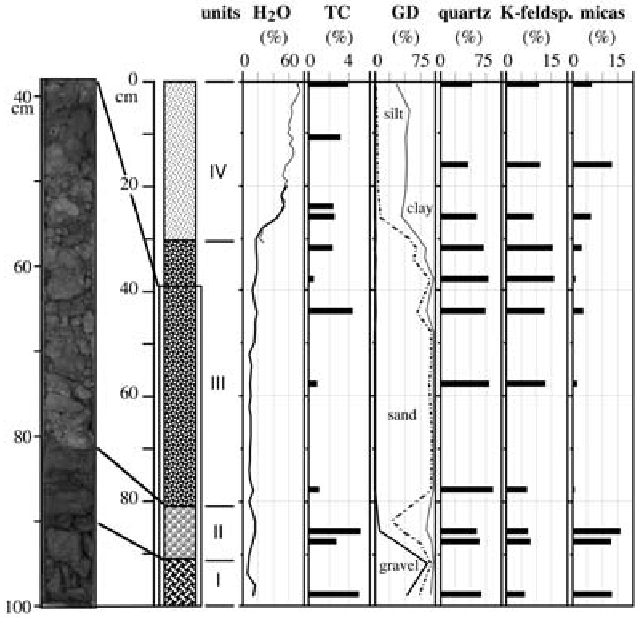

Fig. 2. Lithology, water and total carbon (TC) content, cumulative grain-size distribution (GD), and quartz, feldspar, and mica contents of core sequence Lz1013 from south-western Beaver Lake. The two overlapping curves in the water content indicate cores Lz1013-1 and Lz1013-2, respectively. The photography shows the lowermost 62 cm of the sequence, which is composed mainly of coarse gravel.

radiocarbon dating of the sediments, which would have produced erroneous bulk carbon ages. Dating of the surface sediments via the ^{210}Pb method failed, probably because the recent atmospheric input of ^{210}Pb into the lake was insufficient to obtain reliable ages. Finally, dating via optically stimulated luminescence (OSL/IRSL) was not attempted, because bleaching of feldspars and quartz particles is often insufficient in Antarctic glacial lakes (Krause *et al.* 1997).

Results and discussion

Macroscopic core description, water and carbon contents, grain-size distributions, and mineralogical analyses revealed that four sedimentary units can be distinguished in the sediment sequence at site Lz1013 from Beaver Lake (Fig. 2).

Unit 1, spanning from 100 to 91 cm, is characterized by mainly coarse to very coarse clastic material with low water contents and dominating quartz, mica, and K-feldspar. Due to the occurrence of coal particles, total carbon (TC) contents are relatively high. The angular to sub-angular shape of the gravel suggests sedimentation in either glacial or subaerial settings.

Unit 2 spans from 91 to 81 cm. Water and TC contents and the mineralogical composition are similar to unit 1. However, the grain-size distribution is characterized by significantly greater amounts of the fine fraction (< 63 µm), leading to poor sorting, and the consistency of the sediment is very stiff. These characteristics imply that unit 2 is a glacial diamicton, probably deposited during an advance of the glacier in 'Beaver basin'.

The overlying unit 3 spans from 81 to 31 cm. Low water contents and sandstone clasts up to several centimetres in diameter dominate throughout this unit, which is also reflected in high contents of quartz and K-feldspar. The sandstone clasts correspond in colour and mineralogy with the Permo-Triassic sediments outcropping to the west of the lake. As these clasts were poorly lithified or strongly weathered, they disaggregated during the grain-size analyses and thus were assigned to the sand fraction (Fig. 2). Fluvial or glacial transport and sedimentation of these clasts, or deposition following melting through an ice cover on Beaver Lake, would almost certainly have led to clast rounding, disaggregation, and a greater proportion of fine grain material in the sediment, and thus these depositional settings can be excluded as unlikely.

Glaciomarine sedimentation can also be discounted due to the relative absence of the fine fraction. Variable amounts of TC within this unit can be traced to the occurrence of coal fragments of different sizes (Fig. 2). Sediments with similar composition, structure, and clast strength are widespread on the subaerially exposed slopes to the west of Beaver Lake. These sediments were either emplaced by mass movement processes from the slopes above, or were created by the *in situ* subaerial weathering of older glacial and colluvial sediments. Present-day aeolian activity deflates the surface, removing fine grains and maintaining the coarse texture of the surface sediment. Due to the similarities between the sediments found onshore today and those in unit 3, we believe that unit 3 was most likely emplaced under subaerial conditions. A decrease in occurrence of the clasts along with an increase in sand and fines toward the top of unit 3 (Fig. 2) probably marks the onset of nearshore marine sedimentation and a gradual transition to the overlying unit 4.

Unit 4 comprises the uppermost 31 cm of core Lz1013 and is characterized by high water and TC contents, dominating silt and clay, and a mineralogical composition, which due to finer grain sizes differs from the underlying units by lower quartz and K-feldspar contents and higher mica contents (Fig. 2). Clasts are completely absent. As significant changes in sediment composition cannot be observed throughout unit 4, which includes the surface sediment, the complete unit most likely represents glaciomarine deposition similar to that of today, with a low-energy environment and limited supply of coarse-grained Permo–Triassic sandstones either from glacial transport or areas to the west of the lake.

Interpretation

Following a period of glacial or subaerial setting (unit 1), the coring site Lz1013 in south-western Beaver Lake was overrun by continental ice (unit 2). Coring site Lz1013 is located only *c.* 3 km in front of the present-day glacier tongue entering 'Beaver basin' from the north, where the main branch of Nemesis Glacier flows. During the last glacial cycle, Nemesis Glacier was at least 150 m higher than today, intruding the Lake Terrasovoje basin in the northern part of Amery Oasis (Fig. 1; Wagner *et al.* 2004). The retreat of ice from Lake Terrasovoje and the onset of biogenic sedimentation there at 12 500 cal. yr BP, are contemporaneous with rapid retreat of the Lambert Glacier/Amery Ice Shelf system, and the deglaciation of Radok Lake (to the south-west of the coring site, Fig. 1) around 20–11 ka BP deduced from ^{10}Be and ^{26}Al *in situ* cosmogenic exposure ages (Fink *et al.* 2006). The thickened Nemesis Glacier would also have occupied larger parts of 'Beaver basin' during the local glacial maximum, and it is likely that deglaciation at the coring site, and thus the cessation of deposition of unit 2, also occurred around 12 500 cal. yr BP during the Late Glacial regional deglaciation. Much younger deglaciation of the coring location Lz1013 is also possible, since fluctuations of the glacier front may have occurred since the regional deglaciation.

Deglaciation of the coring site was followed by subaerial conditions (unit 3), indicating that the coring site at 54 m water depth today was not immediately inundated by a marine transgression. Significantly lower relative sea-levels in 'Beaver basin' are also indicated by the presence of subaquatic terraces in the bathymetric profile (Fig. 1), although further bathymetric profiles are needed for confirmation of the extent of these terrace features. Neglecting isostatic uplift, the coring location at 54 m water depth today should have been flooded by the eustatic sea-level rise at *c.* 10 ka BP (Fairbanks 1989, Milne *et al.* 2005), several millenia after deglaciation. Studies in Larsemann Hills (Verleyen *et al.* 2005) and Vestfold Hills (Zwartz *et al.* 1998) indicated that the relative sea-level at *c.* 10 ka BP was about 5–8 m higher there than today, implying an istostatic uplift of *c.* 60–65 m since then. Much thicker ice load in Amery Oasis during the LGM is likely to have caused significantly higher isostatic uplift here (cf. Huybrechts 2002) and the thickened Nemesis Glacier may have prevented that sea water from entering 'Beaver basin', which is at its entrance some 600 m deep (Adamson *et al.* 1997). There are no data presently available on Holocene or present day uplift velocities, so it is hard to determine from eustatic and isostatic changes, when the coring location in Beaver Lake was flooded.

Glaciomarine sedimentation similar to that of today is indicated in the uppermost 31 cm of core Lz1013. Without better chronological constraints, we only can speculate about the period comprised in unit 1 and about the timing of the onset of the marine transgression. Sedimentation rates in epishelf lakes can vary significantly depending on their proximity to the glacier front, meltwater inlets or hydrological conditions. This was shown, for example, in sediment cores from Bunger Hills and the Antarctic Peninsula, where postglacial sedimentation rates in epishelf lakes varied between about 0.1 and 1.3 mm yr^{-1} (Melles *et al.* 1997, Bentley *et al.* 2005). According to these sedimentation rates and the presumed period of deglaciation, the marine transgression could have occurred at any time during the Holocene.

Despite the uncertainties in chronology, our results support Adamson *et al.* (1997), who suggested that the Holocene has been a period of relative sea-level high stand in Amery Oasis. We have found indications that large areas in lateral Beaver Lake have been subaerially exposed after deglaciation and that subaquatic terraces were probably formed during the subsequent marine transgression. It seems that the total isostatic uplift since deglaciation has been substantially less than the eustatic sea-level rise, consistent with the low uplift rates of 1–3 mm a^{-1} proposed by Colhoun *et al.* (1992).

Acknowledgements

The project was funded by the German Research Foundation (Grant ME1169/4 and HU378/10), the Australian Antarctic Science Advisory Committee (ASAC1071) and the Australian Research Council (DP0556728). Special thanks are due to Martin Klug, Gerald Müller, Andy Cianchi, Margie Jenkin and Rob Ferguson for their assistance in the field. The manuscript benefitted from comments of the reviewers Dominic Hodgson and Ian Goodwin.

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