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Were the Larsemann Hills ice-free through the Last Glacial Maximum?

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Abstract: Lake sediments in the Larsemann Hills contain a great diversity of biological and physical markers from which past environments can be inferred. In order to determine the timing of environmental changes it is essential to have accurate dating of sediments. We used radiometric (^{210}Pb and ^{137}Cs), radiocarbon (AMS ^{14}C) and uranium series (^{238}U) methods to date cores from eleven lakes. These were sampled on coastal to inland transects across the two main peninsulas, Broknes and Stornes, together with a single sample from the Bolingen Islands. Radiometric dating of recent sediments yielded ^{210}Pb levels below acceptable detection limits. However, a relatively well-defined peak in ^{137}Cs gave a date marker which corresponds to the fallout maximum from the atmospheric testing of atomic weapons in 1964/65. Radiocarbon (AMS ^{14}C) measurements showed stratigraphical consistency in the age-depth sequences and undisturbed laminae in some cores provides evidence that the sediments have remained undisturbed by glacial action. In addition, freshwater surface sediments were found to be in near-equilibrium with modern $^{14}CO_2$ and not influenced by radiocarbon contamination processes. This dating program, together with geomorphological records of ice flow directions and glacial sediments, indicates that parts of Broknes were ice-free throughout the Last Glacial Maximum and that some lakes have existed continuously since at least 44 ka BP. Attempts to date sediments older than 44 ka BP using ^{238}U dating were inconclusive. However, supporting evidence for Broknes being ice-free is provided by an Optically Stimulated Luminescence date from a glaciofluvial deposit. In contrast, Stornes only became ice-free in the mid to late Holocene. This contrasting glacial history results from the Dålk Glacier which diverts ice around Broknes. Lakes on Broknes and some offshore islands therefore contain the oldest known lacustrine sediment records from eastern Antarctica, with the area providing an ice-free oasis and refuge for plants and animals throughout the Last Glacial Maximum. These sediments are therefore well placed to unravel a unique limnological sequence of environmental and climate changes in East Antarctica from the late Pleistocene to the present. This information may help better constrain models of current climate changes and ensure the adequate protection of these lakes and their catchments from the impacts of recent human occupation.

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Introduction

The Larsemann Hills (69°23'S, 76°53'E), Prydz Bay, is an ice-free polar oasis on the Ingrid Christensen Coast, Princess Elizabeth Land, East Antarctica, located approximately midway between the eastern extremity of the Amery Ice Shelf and the southern boundary of the Vestfold Hills (Fig. 1). The region consists of two main peninsulas (Stornes and Broknes), together with a number of scattered offshore islands. At 50 km², the Larsemann Hills is the second largest of only four major ice-free oases found along East Antarctica's 5000 km of coastline. The closest significant ice-free areas are the Bolingen Islands, 25 km to the west-south-west, and the Rauer Islands 60 km to the north-east (Fig. 1). The highest elevations are around 180 m above sea level (ANARE 2000). The hills are dissected by steep valleys lying between the ice sheet and the coast. Many valley floors are filled with multi-year ice but those that are ice-free contain a complex geomorphological history preserved in erosional features, including glacial striae and tafoni,

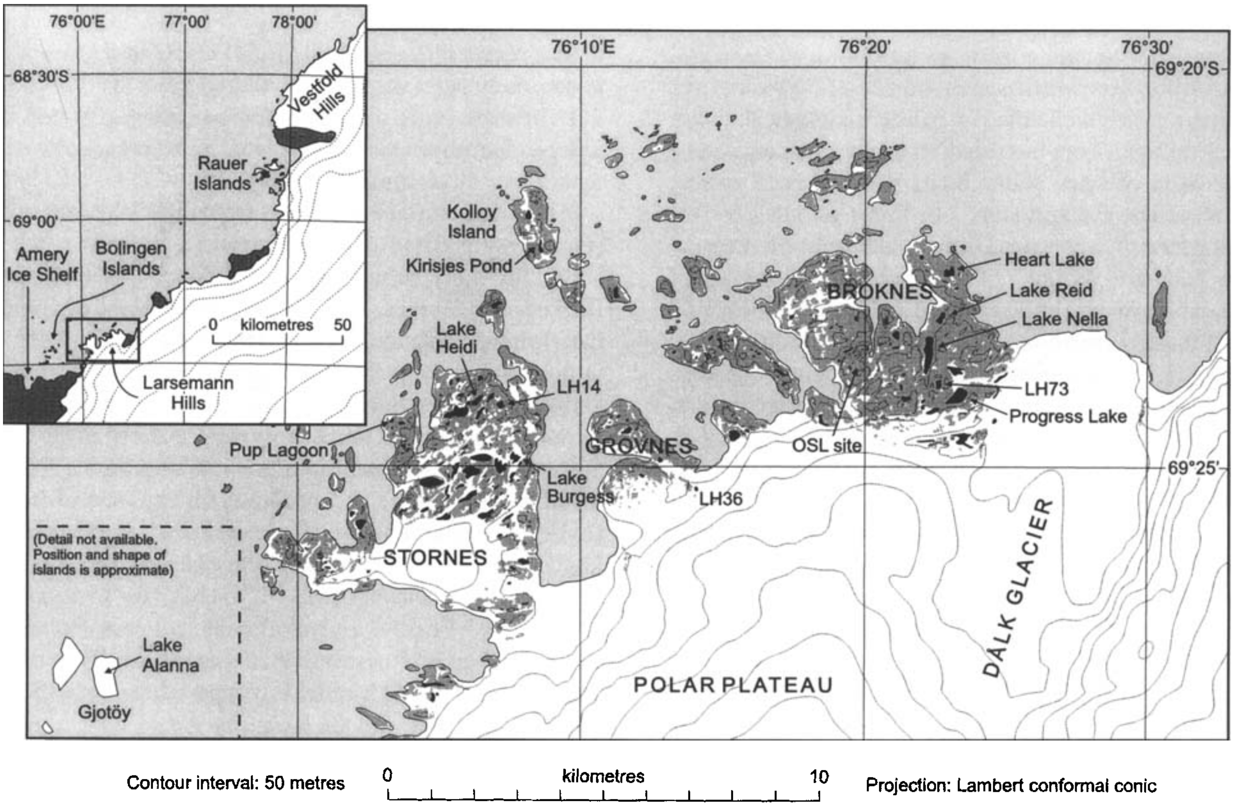

Fig. 1. Map showing sampling locations in the Larsemann Hills (courtesy of the Australian Antarctic Data Centre).

glacial and glaciofluvial sediments (Stuwe *et al.* 1989). The shape of the land surface is controlled by the lithology and shape of geological structures, particularly joints and lineaments, as well as erosion by ice, water and salt. Salt weathering, in particular exerts, a strong control on the land. Hills near the ice sheet are significantly higher than those by the sea where there has been extensive weathering from sea salt and periods of marine immersion (ANARE 2000). This pattern of salt weathering and lowered relief near the coast is also found in the nearby Vestfold Hills (Gore & Colhoun 1997).

More than 150 freshwater lakes are found in the hills (Gillieson *et al.* 1990) ranging from small ephemeral ponds to large water bodies such as Progress Lake (10 ha and 38 m deep). Some of these water bodies are briefly ice-free or partially ice-free in the summer months when their temperatures increase rapidly; surface water in some of the shallower ones reaches +8°C. For the remainder of the year (8–10 months) they are covered with *c.* 2 m of ice. Some lakes have evidence of past shorelines which are up to 2 m above present levels (e.g. LH73, Fig. 1) but do not exhibit the highly elevated salinities associated with lakes in the Rauer Islands (Hodgson *et al.* 2001) and Vestfold Hills (Roberts & McMinn 1996). Lake systems are typically closed and contained in steep-sided V-shaped valleys normally around 50–100 m deep and less than 1 km long. These valleys dissect the area and provide a conduit for summer meltwater streams between the few lake systems that are open. During December, January and February the daily air temperature frequently exceeds +4°C and has been known to reach +10°C (ANARE 2000). Mean monthly winter temperatures are between -15°C and -18°C. Precipitation occurs as snow and is unlikely to exceed 250 mm water equivalent annually. Strong, katabatic winds blow most mornings.

Were the Larsemann Hills ice-free during the Last Glacial Maximum? The timing of deglaciation in the Larsemann Hills is not known. Gillieson (1991) proposed that the continental ice sheet receded from the off-shore islands around 9500 years ago, with the peninsulas being exposed some 4500 years ago. This is comparable with some other Antarctic sites, particularly the Vestfold Hills which have a minimum deglaciation age of 13–12 ka BP (Fabel *et al.* 1997, Roberts & McMinn 1999). However, a single date of 24 950 ± 710 ^{14}C yr BP (ANU 8826, Burgess *et al.* 1994), on moss fragments found in a lake shore moraine, has hinted at a longer period of exposure for some areas of the Larsemann Hills. Burgess' new date, coupled with a very strongly weathered rock surface over most of Broknes, allows us to propose that at least parts of the hills remained ice-free throughout the last glaciation. If accurate, then the lakes may contain some of the oldest, continuous lacustrine sediment and palaeoenvironmental records from the eastern Antarctic and will be an invaluable tool with which to examine past climate changes.

Preliminary studies by McMinn & Hodgson (unpublished) and Ellis-Evans *et al.* (1998) have revealed that lakes in the Larsemann Hills contain a great diversity of biological and physical markers from which past environments can be inferred. They are particularly well suited for palaeolimnological studies as there is no significant bioturbation of the sediments and a limited season of open water when wind-induced mixing might encourage resuspension. In order to interpret the historical information contained in these sediments it is essential to have accurate dating. This enables the timing of palaeoclimatic events to be determined and permits meaningful comparison and correlation amongst different stratigraphical records (e.g. lake cores, marine cores and ice cores). This has been demonstrated in recent studies of the Antarctic mid-Holocene warm period (Ingólfsson *et al.* 1998, Jones *et al.* 2000) and late Holocene East Antarctic climate trends (Roberts *et al.* 2001).

There are a number of problems associated with dating lacustrine deposits which can result in inaccurate chronologies. These include ^{14}C contamination from surface or groundwater, from soils or from the marine environment, recycling of old carbon, and reduced gas exchange with the atmosphere under ice cover. These are reviewed in Björck *et al.* (1991) and Ingólfsson *et al.* (1998). In particular, where marine sources contaminate freshwater sediments, dates can be influenced by the Antarctic marine reservoir effect which yields older radiocarbon dates due to ^{14}C depletion in Southern Ocean water masses (Omoto 1983). There are, however, several ways to constrain these dating problems. For example, using radiocarbon dating it is possible to estimate marine reservoir effects by dating surface sediments and checking for stratigraphical consistency in the dated sequence. Sampling precision may also be improved by using Accelerator Mass Spectrometry (AMS) to date small fragments of material of known origin, for example aquatic moss (Jones *et al.* 2000). Another approach is to compare sediment ages using different dating technologies, for example ^{210}Pb, and ^{137}Cs can be used to date recent sediments and the $^{230}Th/^{234}U$ series can be used to date carbonates from a few hundred years to 400 000 years old. In some cases dates can also be cross-calibrated using independent physical stratigraphical markers such as volcanic tephra (e.g. Hodgson *et al.* 1998).

In this study surface sediments from three lakes on Broknes (Fig. 1) were dated using radiometric methods (^{210}Pb and ^{137}Cs). Secondly, surface and basal sediments from 10 lakes on Broknes and Stornes, and one lake on the island of Gjotöy in the Bolingen Islands, were dated using AMS (AMS ^{14}C) radiocarbon dating. This was to establish whether reservoir correction factors should be applied and to determine the onset of sedimentation (not necessarily deglaciation) in the region. Some near basal sediments were also dated using the $^{230}Th/^{234}U$ method. Selected cores from lakes on transects of Broknes (Lake Reid, Heart Lake and Progress Lake), and Stornes (Pup Lagoon and Kirisjes Pond on Kolloy Island) were then dated at multiple levels using AMS ^{14}C to check for stratigraphical consistency. Finally, a glaciofluvial sediment deposit on a valley floor on Broknes was dated using Optically Stimulated Luminescence (OSL) in order to compare a terrestrial sediment age determination with the lacustrine data.

Table I. Location, altitude, coring depth and core length for lakes on the Broknes and Stornes transects, and the Bolingen Islands. Lake codes follow Gillieson *et al.* (1990).

Lake	Latitude	Longitude	Altitude (m a.s.l.)	Coring depth (m)	Core length (cm)
Broknes transect					
Heart Lake, LH 68	76°23'	69°23'	5	4.5	361
Lake Reid, LH 70	76°23'	69°23'	30	3.8	110
Lake Nella, LH 72	76°22'	69°24'	15	18	26
Lake 73, LH 73	76°23'	69°24'	85	4	138
Progress Lake, LH 57	76°24'	69°24'	65	34	58
Stornes transect					
Kirisjes Pond, LH 34	79°09'	69°22'	5	9	159
Pup Lagoon, LH 23	76°03'	69°25'	5	4.6	302
Lake Heidi, LH 10	76°06'	69°24'	60	5	48
Lake 14, LH 14	76°07'	69°24'	60	4.7	24
Lake Burgess	76°08'	69°25'	40	16	34
Bolingen Islands					
Lake Alanna	75°46'	69°25'	20	4	40

Methods

In the Antarctic summer of 1997/98, sediment cores were extracted from selected lakes in the Larsemann Hills (Fig. 1). Eleven sampling sites were selected on the basis of the diversity of their fossil biomarkers and depth of sediment deposits from a survey of 70 lakes in the region (see Hodgson *et al.* 2001). The sites were on coastal to ice-sheet transects across the two main peninsulas (Broknes and Stornes) with an additional sample from the Bolingen Islands (Table I). Surface to supposed basal sediment cores were extracted from the deepest part of the lakes using a combination of a Glew gravity corer for surface sediments and a Livingstone corer for intermediate to basal sediments. Basal sediment depths were confirmed with an augured Hiller corer in some lakes. Samples for dating were collected from distinct stratigraphical boundaries, placed in sterile 'Whirlpack' bags and stored at -40°C.

Radiometric dating

Three cores from the Broknes transect (Progress Lake, Lake Reid and Heart Lake) were analysed for ^{210}Pb, ^{226}Ra and ^{137}Cs by direct gamma assay using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby *et al.* 1986). ^{210}Pb was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and 352 keV γ-rays emitted by its daughter isotope ^{214}Pb following three weeks storage in sealed containers to allow radioactive equilibration, ^{137}Cs was measured by its emissions at 662 keV. The absolute efficiencies of the detectors were determined

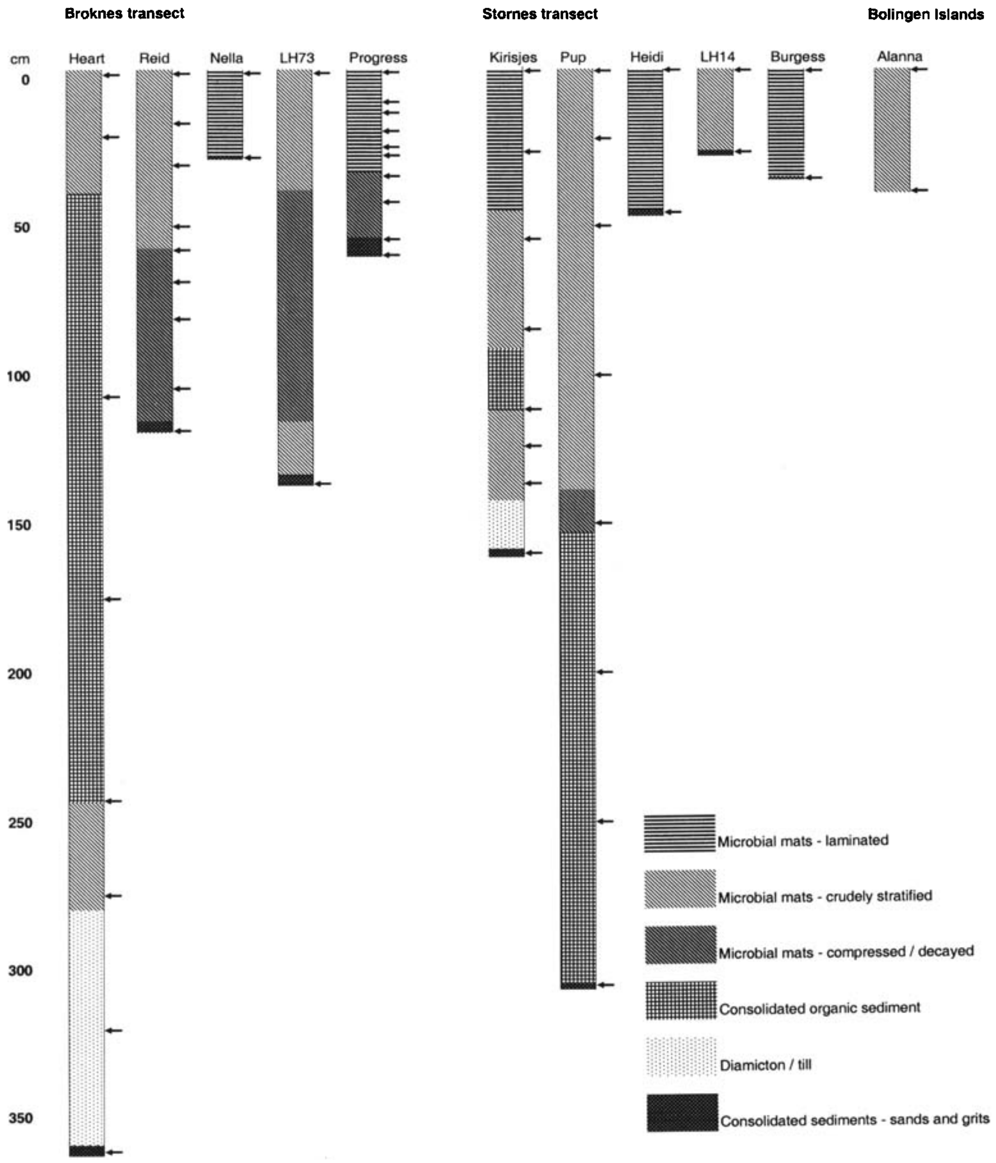

Fig. 2. Simplified lithologies of sediment cores from the Larsemann Hills. Small arrows indicate the depths of samples used in radiocarbon analyses. For clarity, minor lithological features are excluded. These include sub-mm sand layers in some cores which are thought to be derived from wind-blown material.

using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low energy γ-rays within the sample (Appleby *et al.* 1992).

Radiocarbon dating

Where possible, discrete biological remains were dated. These were derived from benthic filamentous cyanobacterial mats with interstitial algal communities. Samples were digested with 2M HCl (80°C, 10 hours), rinsed free of mineral acid with distilled water, dried and homogenized. Graphite targets for ^{14}C analysis by AMS were prepared in East Kilbride, UK, by quantitative recovery of carbon from pre-treated sample material in a sealed quartz tube followed by cryogenic separation of CO_2 (Boutton *et al.* 1983). Aliquots of CO_2 were converted to an iron/graphite mix by Fe/Zn reduction (Slota *et al.* 1987). A sub-sample of CO_2 was used to measure ^{13}C using a dual-inlet mass spectrometer (VG OPTIMA) in order to normalize ^{14}C data to -25‰ ^{13}CPDB. Graphite was sent for ^{14}C analysis by AMS to either the NSF-AMS Facility University of Arizona (Donahue 1990), or the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, University of California (Southon *et al.* 1990). In keeping with international practice the results are reported as conventional radiocarbon years BP (relative to AD 1950) and % modern ^{14}C, both expressed at the 1% level for overall analytical confidence. Results > 100% modern are also reported as absolute % modern, which involves a mathematical adjustment to account for ongoing radioactive decay of the international reference standard (oxalic acid) since AD 1950 (Stuiver & Polach 1977).

Uranium series dating

Six near-basal samples were submitted for analysis, from Lake Reid, 91–92 cm, 94–95 cm, and 92–94 cm, and from Progress

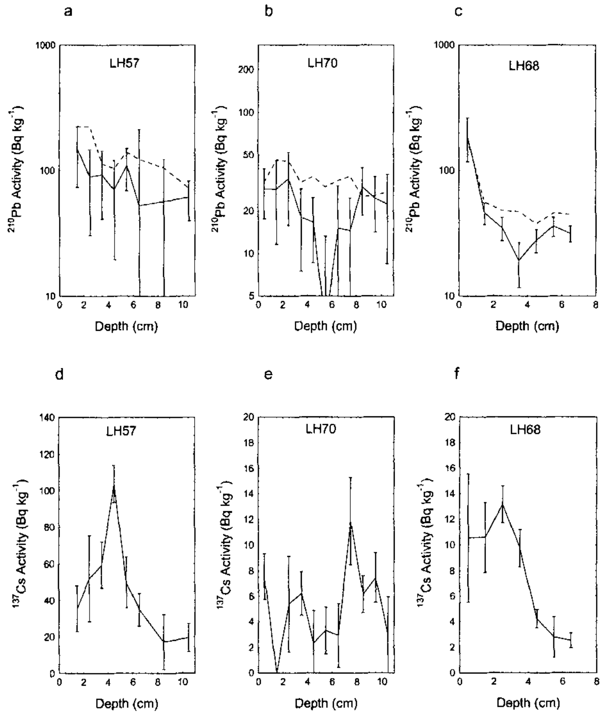

Fig. 3. ^{210}Pb and ^{137}Cs concentrations vs depth in sediment cores from the Larsemann Hills. **a.** & **d.** Progress Lake, **b.** & **e.** Lake Reid, **c.** & **f.** Heart Lake. Upper graphs show total ^{210}Pb (solid line) and supported ^{210}Pb (dashed line).

Table II. ^{210}Pb and ^{137}Cs concentrations together with radiometric parameters and mean post-1964 sedimentation and accumulation rates for the three lakes.

Depth cm	Depth g cm^{-2}	^{210}Pb Total Bq kg^{-1}	±	^{210}Pb Supported Bq kg^{-1}	±	^{137}Cs Bq kg^{-1}	±
Progress Lake (LH57)							
1.5	0.12	149.6	76.3	225.8	16.0	35.6	12.7
2.5	0.22	88.9	58.4	225.2	21.6	51.8	23.6
3.5	0.33	92.7	51.8	113.0	12.5	59.4	12.7
4.5	0.48	69.9	50.2	104.0	10.8	103.6	10.2
5.5	0.63	109.5	40.7	140.9	14.7	49.9	13.9
6.5	0.79	52.5	161.2	122.8	12.8	34.8	9.0
8.5	1.08	56.6	67.0	105.1	17.2	17.1	15.0
10.5	1.34	61.1	21.2	72.2	6.8	19.5	7.7
Lake Reid (LH70)							
0.5	0.06	28.7	11.1	31.9	2.6	7.5	1.8
1.5	0.18	28.5	16.9	46.2	4.4	0.0	0.0
2.5	0.33	33.9	18.1	44.9	4.4	5.4	3.8
3.5	0.47	18.1	10.6	31.8	2.7	6.2	1.7
4.5	0.59	16.7	8.1	35.1	2.5	2.3	2.5
5.5	0.72	3.1	10.2	29.5	2.4	3.3	1.8
6.5	0.85	15.1	15.0	32.9	3.1	2.9	2.5
7.5	0.99	14.6	10.0	35.3	3.3	11.9	3.4
8.5	1.13	29.6	10.9	25.5	2.0	6.2	1.5
9.5	1.27	24.5	10.4	25.7	2.2	7.5	1.9
10.5	1.42	22.4	13.9	27.3	3.3	3.0	3.0
Heart Lake (LH68)							
0.5	0.03	191.4	73.5	176.4	18.0	10.6	10.9
1.5	0.15	46.1	9.0	55.9	2.9	10.6	2.7
2.5	0.40	35.0	7.4	48.0	1.8	13.2	1.4
3.5	0.73	19.2	7.6	46.9	1.9	9.8	1.4
4.5	1.07	28.0	5.8	37.7	1.1	4.2	0.7
5.5	1.40	36.2	6.5	45.9	2.0	2.8	1.6
6.5	1.74	31.5	4.6	44.8	1.2	2.5	0.6

	Mean ^{226}Ra activity Bq kg^{-1}	Weapons ^{137}Cs inventory Bq m^{-2}	±	Depth of ^{137}Cs peak cm	g cm^{-2}	Sedimentation & accumulation rate cm yr^{-1}	g cm^{-2} yr^{-1}
Progress L.	112	570	64	4.5	0.48	0.14	0.015
Lake Reid	27	74	10	7.5	0.98	0.23	0.030
Heart Lake	60	128	13	2.5	0.40	0.08	0.012

Lake 55–56 cm, 54–55 cm and 56–58 cm. Pre-treatment with HNO_3 was used to dissolve and remove carbonates and HF, HNO_3, HCl and $HClO_4$ to dissolve the residual silicate and organic material. Once the silicate and organic phases were completely dissolved and all the HF driven off the initial carbonate solution was pooled. All steps were carried out quantitatively. There was no perceptible fizzing with HNO_3 on initial dissolution indicating a low carbonate content.

Samples (typically < 100 mg) were totally dissolved and spiked with a mixed ^{229}Th/^{236}U standard. Uranium and thorium fractions were separated on 2 ml anion exchange columns (Edwards *et al.* 1986), loaded onto graphite coated Re filaments and analysed using a Finnigan MAT262 mass spectrometer with a retarding potential quadrupole and secondary electron multiplier (described by van Calsteren & Schwieters 1995). A dynamic peak switching routine was employed measuring ^{234}U/^{236}U and ^{235}U/^{236}U (a proxy for ^{238}U, assuming a ^{238}U/^{235}U natural ratio of 137.88) and ^{230}Th/^{229}Th and ^{232}Th/^{229}Th. Although ^{232}Th abundance is not required for the age calculation it was measured in order to monitor detrital Th input and consequently correct for its presence if practicable. Total procedure blanks for ^{238}U and ^{232}Th were 47pg and 84pg respectively for total dissolutions.

Optically Stimulated Luminescence dating (OSL)

A hummocky sand deposit mantled thinly by pebbles covers 1 ha of a valley floor on south-western Broknes (Fig. 1). A 0.7 m deep pit dug in the side of one mound revealed a fine to coarse sand with fine laminae and truncated cross-bedding that confirmed a glaciofluvial origin, with south-westerly (down valley) palaeodrainage. No glaciotectonic deformation of the fine laminations or other sedimentary structures was apparent. Sediment was collected for quartz OSL at a depth of 0.45 m. Sample preparation at the Department of Geography, Royal Holloway, University of London, was based on standard quartz separation techniques for glacigenic sediments (Rhodes & Bailey 1997). The 125–180 mm fraction was dry sieved from the bulk sample and the alkali feldspar fraction was isolated using a heavy liquid (sodium polytungstate, density 2.62 g cm^{-3}) separation. The remaining sample was etched in 40% HF for 40 min and the quartz fraction was then isolated by another heavy liquid separation (2.68 g cm^{-3}). The sample

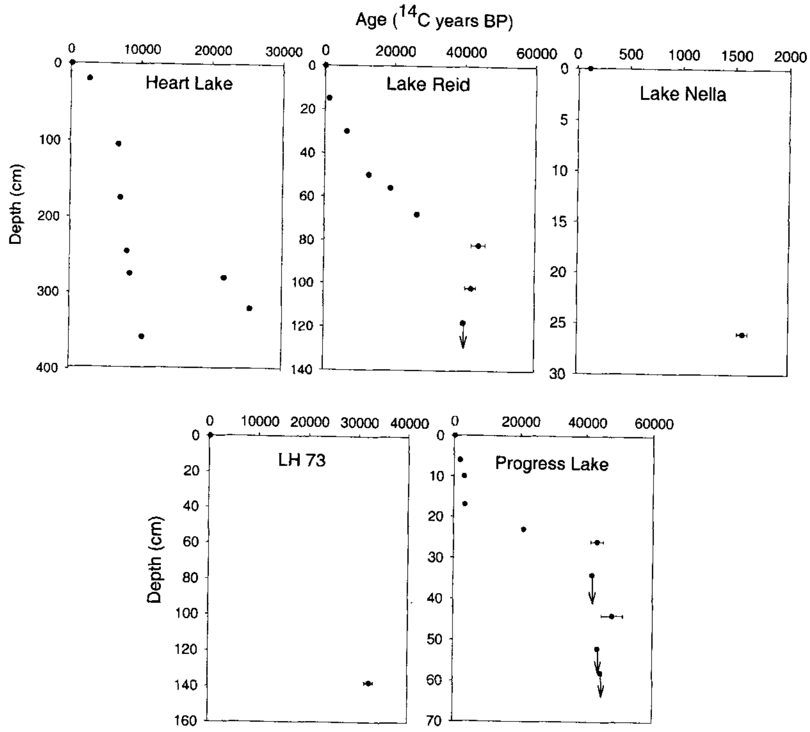

Fig. 4. AMS ^{14}C age-depth sequences for lakes on Broknes.

was sieved a second time before being attached to aluminium discs using a silicone based glue. The age estimate was based on multiple aliquot OSL measurements, which were performed in a Risø reader equipped with a green filtered halogen lamp attachment (excitation filter pack, 3 x GG-420, interference filter and heat absorbing filter) detecting emission in the ultraviolet region (2 x U340). Each OSL measurement was preceded by a preheat of 220°C for 5 min (Rhodes 1988, Smith *et al.* 1986, 1990) and a 25 s infrared-stimulated luminescence (IRSL) measurement to test for feldspar contamination. Each OSL measurement consisted of a single 25 s exposure at ambient temperature, which typically reduced the OSL signal

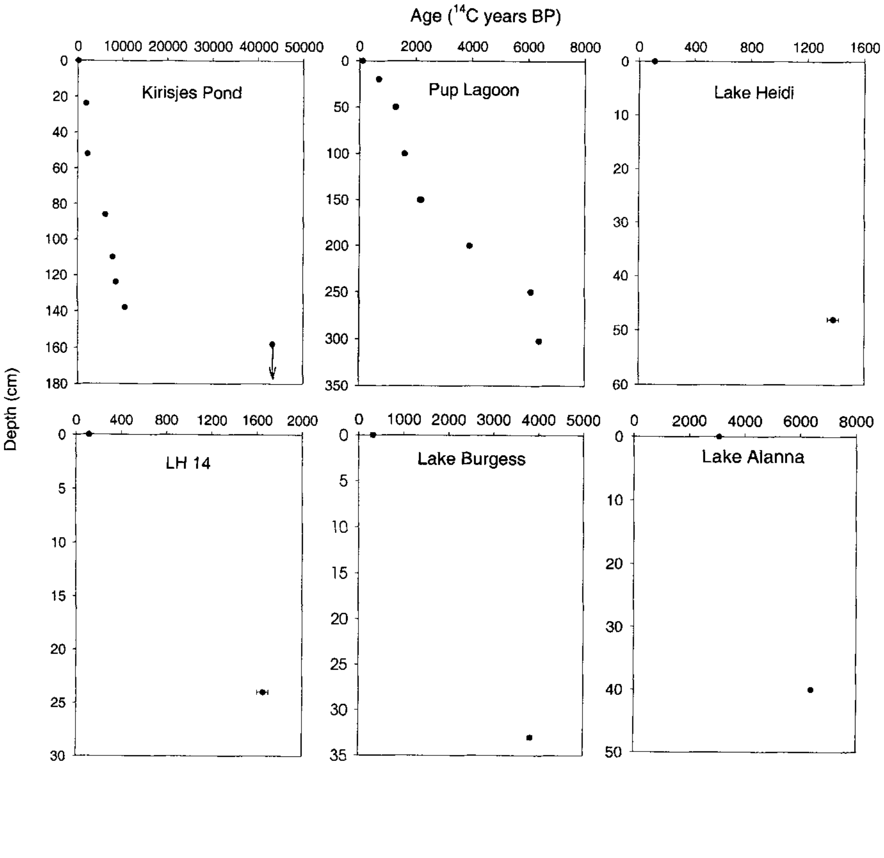

Fig. 5. AMS ^{14}C age-depth sequences for lakes on Stornes and the Bolingen Islands.

Table III. AMS ^{14}C dating of lake sediments from the Larsemann Hills.

Sediment depth (cm)	Lab. code	Sample material	^{14}C enrichment (%modern ± 1σ)	^{14}C Enrichment (%modern absolute ± 1σ)	Conventional radiocarbon age (yr BP ± 1σ)	Carbon content# (% by wt)	$\delta^{13}C_{PDB}$ (‰ ± 0.1)
Broknes transect: Heart Lake							
0	AA-35716	C	109.80 ± 0.55	109.15 ± 0.55	modern	22	-16.9
20	AA-35736	C DE	72.16 ± 0.39		2620 ± 45	1.7	-13.2
105	AA-35737	O DE	42.91 ± 0.29		6795 ± 55	0.6	-20
175	AA-35738	O DE	41.26 ± 0.28		7110 ± 55	1.7	-20.5*
245	AA-35739	O DE	36.63 ± 0.33		8070 ± 75	3	-20.9
275	AA-41164	O DE	34.68 ± 0.26		8508 ± 59	9.3	-10
280	AA-35740	D	6.64 ± 0.14		21 780 ± 160	0.04	-20.5*
320	AA-35741	D	4.20 ± 0.12		25 460 ± 230	0.05	-23.3
356-360**	AA-41633	O DE S	27.7 ± 0.23		10 314 ± 65	0.3	-18.8
Lake Reid							
0	AA-35720	C	101.97 ± 0.49	101.37 ± 0.49	modern	25.0	-12.1
15	AA-35722	C DE	87.19 ± 0.44		1100 ± 40	18.0	-11
30	AA-35723	C DE	46.39 ± 0.31		6170 ± 55	8.0	-10.1
50	AA-35724	C DE	20.95 ± 0.2		12 555 ± 75	2.6	-12.4
56	AA-35725	O DE	9.64 ± 0.15		18 790 ± 120	0.8	-15.1
68	AA-35726	O DE	3.68 ± 0.12		26 520 ± 260	1.5	-14*
82	AA-35727	O DE	0.43 ± 0.11		43 800 ± 2000	2.8	-13.8
102	AA-35728	O DE	0.55 ± 0.1		41 800 ± 1500	1.8	-20.2
116-118	CAMS-50381	O DE S	***		>39 700	1.8	-20.5
Lake Nella							
0	AA-35713	C	113.78 ± 0.61	113.11 ± 0.61	modern	18.2	-13.4
26	CAMS-50382	C DE S	82.28 ± 0.48		1570 ± 50	3.5	-22.9
LH73							
0	AA-35719	C	98.07 ± 0.51		155 ± 40	24.0	-13.7
136-138	CAMS-50383	C DE	1.81 ± 0.2		32 220 ± 880	0.4	-17.3
Progress Lake							
0	AA-35721	C	113.33 ± 0.53	112.66 ± 0.53	modern	21.0	-9.6
6	AA-35754	C	80.54 ± 0.43		1740 ± 40	1.1	-17.7
10	CAMS-64374	C	68.82 ± 0.25		3000 ± 30	0.5	-16.2
17	AA-35755	C	65.93 ± 0.38		3345 ± 45	1.9	-18.8
22-24	AA-41165	C	7.39 ± 0.14		20 920 ± 150	1.2	-26
26	AA-35756	C S	0.46 ± 0.11		43 200 ± 1900	0.3	-25.8
34	AA-35757	C S	< 0.55		> 41 800	0.5	-26
44	AA-35758	C S M	0.26 ± 0.11		47 800 ± 3300	0.8	-26
52	AA-35759	C S M	< 0.45		> 43 400	2.3	-27.2
56-58	CAMS-50384	C S M	***		> 44 400	1	-29.0
Stornes Transect: Kirisjes Pond							
0	AA-35717	C	107.35 ± 0.51	106.72 ± 0.51	modern	7.4	-15.8
24	AA-35742	C	80.39 ± 0.42		1755 ± 40	2.8	-19.9
52	AA-35743	C DE	77.12 ± 0.43		2085 ± 45	1.7	-20.0*
86	AA-35744	C DE	46.19 ± 0.3		6205 ± 50	34	-14.6
110	AA-35745	O DE	37.76 ± 0.32		7825 ± 70	11	-23
124	AA-35746	C DE	34.51 ± 0.26		8545 ± 60	7.6	-17
138	AA-35747	C DE O S	27.4 ± 0.23		10 400 ± 65	11	-16.5
156-158	CAMS-50376	O S	***		> 43 200	0.7	-25
Pup Lagoon							
0	AA-35718	C	104.45 ± 0.51	103.83 ● 0.51	modern	21	-13.1
20	AA-35748	C DE	91.93 ± 0.46		675 ± 40	36	-13.9
50	AA-35749	C DE	85.39 ± 0.44		1270 ± 40	26	-13.8
100	AA-35750	C DE	82.02 ± 0.49		1590 ± 45	8.2	-14.9
150	AA-35751	O DE	76.53 ± 0.41		2150 ± 45	13	-19.3
200	AA-35752	O DE	61.42 ± 0.36		3915 ± 45	6.4	-21.6
250	AA-35753	O DE S	46.88 ± 0.3		6085 ± 50	0.06	-19.5
300-302	CAMS-50377	O DE S	45.17 ± 0.25		6380 ± 50	0.7	-20.7
Lake Heidi							
0	AA-35714	C	111.66 ± 0.59	111.00 ± 0.59	modern	24	-16.7
46-48	CAMS-50379	C DE S	84.23 ± 0.4		1380 ± 40	24	-12.9
Lake LH14							
0	AA-35715	C	111.34 ± 0.55	110.68 ± 0.55	modern	29	-20.7
22-24	CAMS-50378	C DE S	81.41 ± 0.47		1650 ± 50	12	-20.5
Lake Burgess							
0	AA-35711	C	96.29 ± 0.55		305 ± 45	5.3	-24.9
33-35	CAMS-50380	C DE S	62.13 ± 0.35		3820 ± 50	4.4	-24.5
Bolingen Islands: Lake Alanna							
0	AA-35712	C	68.23 ± 0.43		3070 ± 50	11.5	-15.5
38-40	CAMS-50385	C DE	45.29 ± 0.32		6360 ± 60	15.2	-12.6
Reference data: Dec 1991 atmosphere†				113 ± 0.5			

Sample material: C = filamentous cyanobacteria, O = unknown organic fraction, S = silts, sands, M = moss layers, D = diamicton, DE = degraded. †Cape Grimm, Tasmania (Zwartz *et al.* 1998), * estimated $\delta^{13}C$ value - insufficient sample material for an independent $\delta^{13}C$ measurements, ** being retested, *** indistinguishable from background at 2 s d, Results reported as > conventional radiocarbon age and/or < ^{14}C enrichment were indistinguishable from background at 2 s d – results are quoted at 2σ lower limits. #carbon content of dried, pre-treated material to ~7% of its initial value. Different properties of the OSL signal were used to provide an indication of the degree of signal zeroing by light exposure prior to burial, including the degree of scatter (Rhodes & Pownall 1994, Huntley & Berger 1995), the shine plateau (Huntley *et al.* 1985, Rhodes 1988) and the magnitude of a thermal transfer signal (Rhodes & Pownall 1994, Rhodes & Bailey 1997).

Ice flow directions and glacial sediments

The distribution of striae and their orientations were measured on Broknes and Stornes. Each site was examined carefully for crosscutting relationships that might reveal the history of ice flow direction. Aerial photography and satellite imagery was examined for flow lines that reveal contemporary ice flow directions, and the surface slope of the ice sheet was also recorded.

Results

Lithology

Surface sediments in all cores are composed of well-preserved, structured and in some cases, finely laminated microbial mats comprizing 50–80% organic matter (Fig. 2). In the short cores (< 50 cm) these persist to the bottom where over-consolidated sediments are encountered. The longer sediment sequences from inland lakes (Lake Reid, LH73, both > 25 m above sea level (a.s.l)) also contain microbial mats which gradually transition down core into compressed, structurally decayed.and crudely laminated microbial mats. In Progress Lake (proximal to the ice sheet) similar units are present but with a more distinct transition. The coastal cores (Heart Lake, Kirisjes Pond, Pup Lagoon, all < 10 m a.s.l.) have a more complex lithology. Surface sediments of microbial mats gradually change down core becoming more structurally decayed. These overlie a consolidated organic sediment. In Kirisjes Pond and Heart Lake this is followed, down core, by crudely stratified microbial mats, an inorganic diamicton and finally a unit of over consolidated sands and grits (Fig. 2). In all cores (except Lake Alanna) penetration of the corers was arrested by these consolidated sediments.

Radiometric dating

In the three cores selected for radiometric analyses, measured total ^{210}Pb activity was less than or equal to the ^{226}Ra activity and unsupported ^{210}Pb, from atmospheric fallout, was below limits of detection (Table II, Fig. 3). In consequence, dating these cores by ^{210}Pb was not possible. However, the ^{137}Cs activity versus depth profile had a relatively well-defined peak (Fig. 3). The depths of these peaks were used to calculate mean post-1964 sediment accumulation rates for each core (Table II). Progress Lake and Heart Lake had very similar accumulation rates (0.012–0.015 $g\,cm^{-2}\,yr^{-1}$). The value in Lake Reid was twice as high (0.030 $g\,cm^{-2}\,yr^{-1}$). The ^{137}Cs inventories (radionuclide fluxes) of the Lake Reid, Progress Lake and Heart Lake cores are shown in Table II.

Radiocarbon dating

Radiocarbon enrichments in freshwater surface sediments (microbial mats) are close to those for modern atmospheric $^{14}CO_2$, with the notable exception of Lake Alanna in the Bolingen Islands (Table III). On the Broknes transect, basal dates indicate a relatively young age for Lake Nella and late Pleistocene ages for the remaining lakes (Table III). Lake Reid and Progress Lake yielded ^{14}C ages beyond statistically acceptable detection limits indicating ages in excess of 39 700 and 44 400 ^{14}C yr BP respectively. Both cores were stratigraphically dated. Lake Reid has a conformable sequence in its age depth profiles up to the limit of detection. Progress Lake has a conformable Holocene sequence, a period of very slow sedimentation (or a discontinuity), below which there is a compressed laminated unit yielding a series of late Pleistocene dates (Fig. 4). Heart Lake also has a conformable sequence up to 275 cm sediment depth followed by late Pleistocene dates in the glacial till layer. The basal date for this core shows a reversal and is being retested. On the Stornes transect basal dates are all less than 6000 yr BP with the exception of Kirisjes Pond, which is on an island and further from the present ice sheet margin (Table III, Fig. 5). This has a conformable sequence of dates up to a detection limit of > 43 200 ^{14}C yr BP. On western Stornes, Pup Lagoon has a conformable sequence of dates to 6380 yr BP (Table III, Fig. 5).

Uranium series dating

The U/Th ratio in the late Pleistocene sediments from Lake Reid and Progress Lake is *c.* 0.1 (comparable with the local granitic geology). This indicates a carbonate signature totally swamped by silicate. ^{230}Th/^{232}Th ratios range from 0.2–0.8 which are typical silicate values. In general, samples are considered to be 'detritally contaminated' if their ^{230}Th/^{232}Th ratios are < 100. With an insufficient signature from either the carbonate or organic material fractions there is no authigenic signature, or authigenic phase that can be dated in these sediments.

Optically Stimulated Luminescence dating

The date for the sand deposit on south-western Broknes was 20 710 ± 1769 yr BP. The intrinsic characteristics of this sample (primarily low OSL sensitivity) limited analytical precision to 12%. While this error seems large, it is similar to errors associated with cosmogenic isotope determinations, and it is particularly important in a context where chronological control on terrestrial sediments is otherwise absent.

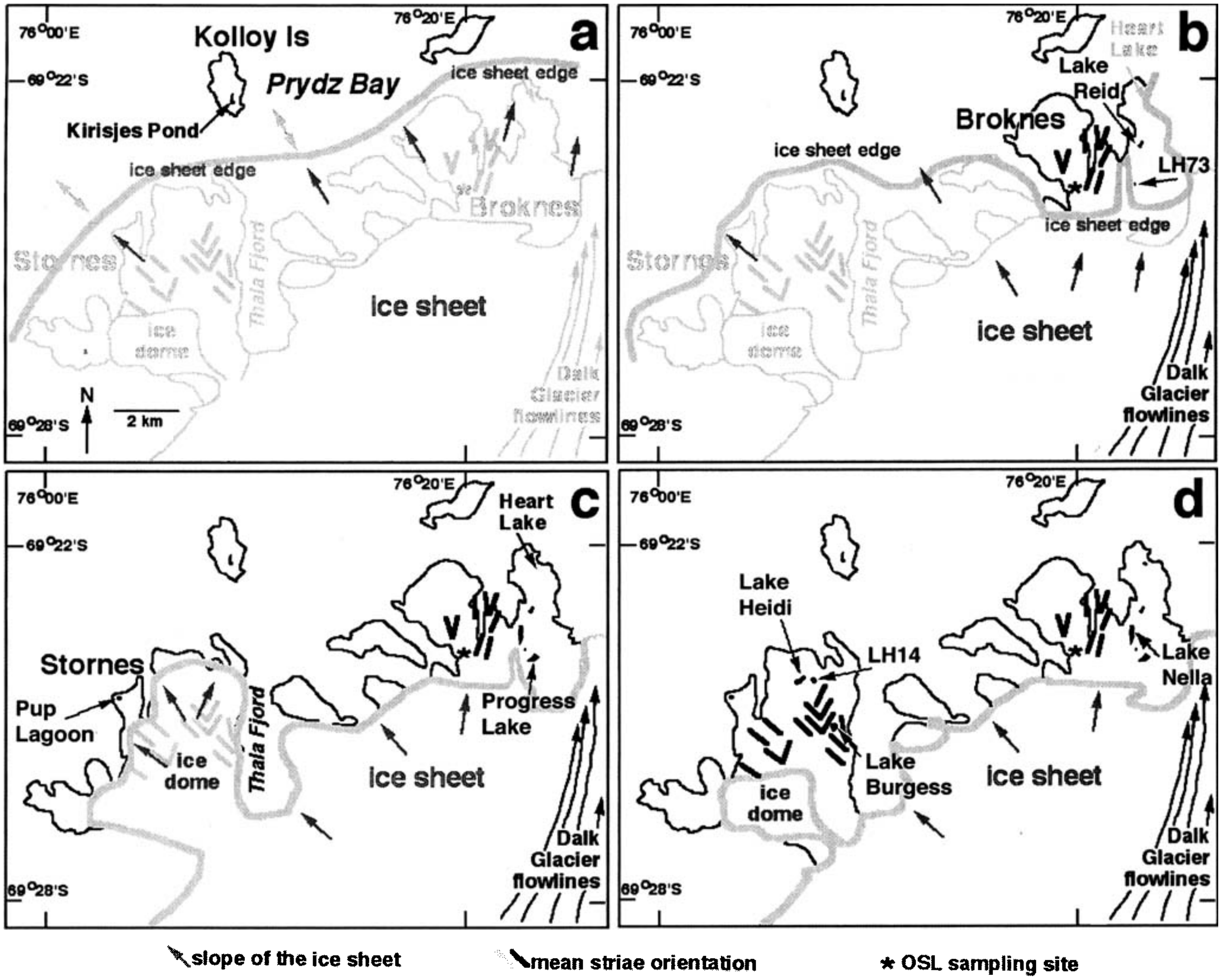

Fig. 6. Interpretive deglaciation history of the Larsemann Hills. **a.** Sometime preceding 40 ka BP the ice sheet covered both peninsulas, we are uncertain of the location of the ice edge and the timing of the advance is unknown. Ice advanced across Thala Fjord, deriving fossiliferous Pliocene marine muds and smearing them across Stornes. **b.** At some time preceding 40 ka BP and lasting until at least 20 ka BP, an expanded ice sheet covered most of Stornes. Islands to the north were exposed. Broknes remained largely free of ice with a minor encroachment of the Dålk Glacier to the northeast and a minor readvance of the ice sheet margin in the vicinity of Progress Lake until sometime after 20.9 ka BP. A lobe of stagnant ice lay in the Lake Nella basin. **c.** By ~6 ka BP the ice sheet had receded from Stornes, leaving the periphery of the peninsula exposed, but with most of the area covered by an ice dome which exhibited radial flow. On Broknes, the Lake Nella ice lobe receded (after 6.6 ka BP, or 1.6 ka BP) and the ice sheet margin in the vicinity of Progress Lake was similar to that of today. **d.** 4–0 ka BP. On Stornes there was irregular melt-out of the outer Peninsula and the remnants of the Stornes ice dome now occupy a minority of the area.

Ice flow indicators

Glacial striae were measured at eight sites on Broknes and 11 sites on Stornes (Fig. 6). The distribution of striae on Broknes was limited to areas illustrated in Fig. 6: further north and east, striae were absent from the strongly weathered rock surfaces. Former ice flow directions were northerly, with occasional alignment of striae consistent with the orientation of adjacent valleys. On Stornes, two ice flow directions were apparent. The most abundant and best-developed striae reflect a north-westerly ice flow, while striae formed from north-easterly ice flow were fainter and less common. Faint crosscutting relationships demonstrate that the north-westerly flow preceded the north-easterly flow. The present day ice flow lines of the Dålk Glacier show that flow occurs to the north or just east of north, broadly consistent with striae on Broknes. The surface slope of the ice sheet adjacent to Broknes is presently to the north while, inland of Stornes, the ice sheet slopes to the northwest. The slope of the ice sheet adjacent to the peninsulas is coincident with the orientation of striae on them.

Discussion

Dating/chronology

Radiometric dating using ^{210}Pb has proved unsuited to dating deposits in the Larsemann Hills. Small sample sizes made accurate determinations of ^{210}Pb in the surficial samples very difficult and the measured values of ^{210}Pb may underestimate the true values. In general ^{210}Pb from atmospheric fallout around continental Antarctica is extremely low and accounts for difficulties with ^{210}Pb dating (Appleby & Oldfield 1992). Despite this, ^{210}Pb has been used successfully in the Maritime Antarctic at Signy Island (Appleby *et al.* 1995), the nearby Vestfold Hills (Bird *et al.* 1991, McMinn *et al.* 1994, 1997) and elsewhere. In a study by the same laboratory of lake sediments from Signy Island, where precipitation is 268 mm yr^{-1}, atmospheric fallout of radionuclides was estimated to be 5.5 $\pm$ 2 Bq m^{-2} yr^{-1} of ^{210}Pb corrected to 1991 (Appleby *et al.* 1995). Since the mean annual precipitation in the Larsemann Hills is thought unlikely to exceed 250 mm yr^{-1} water equivalent (Gillieson *et al.* 1990), radionuclide fluxes are likely to be lower than measurements from Signy Island. Assuming a ^{210}Pb flux of 5 Bq m^{-2} yr^{-1}, and using the mean post-1964 sedimentation rates, the surficial unsupported ^{210}Pb activities are estimated to be: Progress Lake ~30 Bq kg^{-1}; Lake Reid ~16 Bq kg^{-1}; Heart Lake ~42 Bq kg^{-1}. Since these values are a little higher than the 'theoretical' detection limits it is possible that sedimentation rates have increased in recent years, diluting the very weak atmospheric signal. This could also be a function of the surface sediments being less compressed.

In contrast, ^{137}Cs activity showed a relatively well-defined peak that presumably records the 1964/65 fallout maximum from the atmospheric testing of atomic weapons. Similar activities have also been measured in the Vestfold Hills where an exposed lacustrine sediment from a small proglacial lake yielded a total ^{137}Cs activity of 38.4 mBq cm^{-2} (Payne 1988, p. 50) and the Rauer Islands (Fig. 1) where a sand dune on Hop Island yielded a total ^{137}Cs activity of 138.0 $\pm$ 13.3 mBq cm^{-2}. At Signy Island 16 mBq cm^{-2} of ^{137}Cs decay, corrected to 1991, has been measured in lake sediments (Appleby *et al.* 1995). Again, values are generally higher at Signy Island on account of the greater precipitation (268 mm yr^{-1}) compared with the Larsemann Hills (< 250 mm yr^{-1}). The ^{137}Cs inventories of the Lake Reid and Heart Lake cores are consistent with other measurements in the region. The radionuclide inventory of the Progress Lake core, however is substantially higher, by a factor of more than 3 (Table II). This could be due to two reasons, sediment focussing, or inputs of catchment radionuclides during the summer thaw (cf. Appleby *et al.* 1995). Although all these values are lower than mid-latitude southern hemisphere sites there is sufficient ^{137}Cs activity in the Antarctic environment to use it as a dating tool in palaeolimnological and geomorphological studies.

^{14}C in modern freshwater surface sediments in the Larsemann Hills is in near equilibrium with modern atmospheric CO_2 (Table III). Values greater than 100% modern absolute (in all but three of the surface sediment samples) unequivocally indicate the presence of atomic bomb-derived ^{14}C (i.e. post-1950). However, values > 98% but < 100% could be as young as 1950 because of the 'Suess effect', caused by the distribution of ^{14}C in the atmosphere due to CO_2 emissions from fossil fuels (this can apply to the Antarctic as the CO_2 mixing in the upper atmosphere is rapid). This suggests that, if a ^{14}C reservoir effect is present, it is of considerably less significance than at other sites in eastern Antarctica and consistently less than in marine samples (see Gordon & Harkness 1992). It is therefore likely that, at least in the recent past, annual melt (often only taking the form of a peripheral melting of the lake ice) will have permitted CO_2 exchange and maintained a well-mixed carbon pool in equilibrium with atmospheric CO_2. This equilibrium has also been measured in freshwater algae from the Vestfold Hills (Zwartz *et al.* 1998), in stream and near shore microbial mats in the McMurdo Dry Valleys (Doran *et al.* 1999), and (near-equilibrium) in two lakes in the Bunger Hills (Melles *et al.* 1994). It suggests that these sites are isolated from sources of ancient ^{14}C, formerly trapped as bubbles in the ice sheet and subsequently entrained in glacial meltwater as proposed for some areas of Antarctica (*sensu* Domack *et al.* 1989, Gore 1997). It also indicates the importance of summer melting in maintaining a ^{14}C equilibrium. In the Larsemann Hills most of the lakes are not presently receiving meltwater from the ice sheet. Progress Lake, closest to the influence of glacial meltwater, yields a 'modern' surface radiocarbon age and does not demonstrate any impact (Table III).

Despite this it is possible that a reservoir effect, such as supply of ^{14}C depleted CO_2 from glacier ice, may have been significant in the past but it is not possible to determine this (Andrews *et al.* 1999). During isostatic and sea level changes some of the coastal lakes will have been inundated (e.g. Heart Lake) and a reservoir correction of *c.* 1300 yr can be applied to these marine sediments following recent conventions in the Vestfold Hills (Adamson & Pickard 1986). However, in the freshwater sediments, the reservoir correction of 984 yr for lacustrine systems calculated in the nearby Vestfold Hills (Roberts *et al.* 1999) need not be applied.

Basal dates provide minimum ages for the onset of sedimentation in the lakes. On Broknes they confirm previous hypotheses (Burgess *et al.* 1994) that in some of the lakes (Heart Lake, Progress Lake, Lake Reid and LH73) there are sediments that pre-date the Last Glacial Maximum and indeed, in the higher altitude lakes (Progress Lake, Lake Reid), the dates indicate the existence of the lakes since at least the late-Pleistocene. Kirisjes Pond, on Kolloy Island, also contains sediments of a similar age. Analyses of fossil pigments and diatoms in these sediments indicates autochthonous (aquatic) carbon sources (Hodgson, unpublished data). This suggests that these late Pleistocene dates are not influenced by an allochthonous supply of ^{14}C depleted carbon from soils or weathered carbon bearing rocks (cf. Melles *et al.* 1997). Again, we cannot exclude the possibility that ^{14}C depleted carbon may have been supplied in meltwater from glacier ice in the past even though it does not occur today.

In contrast, basal dates from Stornes indicate that this peninsula has only become ice-free in the mid to late Holocene with ages for inland lakes ranging from 3.8 ka BP (Lake Burgess) to 1.6–1.3 ka BP (LH14 and Lake Heidi respectively). This age distribution is discussed below with respect to glacial history. Extensive multi year snow and ice persists on Stornes even during late summer. The lakes have extremely low conductivities, indicating that only a limited time has elapsed for ions to accumulate through evaporation (cf. Hodgson *et al.* 2001). Both these observations support the young ^{14}C ages. As only a short sediment core was retrieved from Lake Alanna (Bolingen Islands) the lowermost date can only be used to confirm that the island of Gjotöy was ice-free after 6.3 ka BP.

A primary control for the reliability of dates is stratigraphical consistency in the dated sequence. The higher altitude lakes (e.g. Lake Reid) have consistent age-depth profiles but extremely low accumulation rates during the glacial periods on account of lower temperatures, reduced light (from ice cover) and low nutrient supply from surface or groundwater sources. The stratified core from Progress Lake has a Pleistocene sediment (all dates in excess of the radiocarbon method) overlain by a dateable consistent Holocene sequence with biogenic production being low to non existent during the glacial period. The absence of a distinct inorganic unit in the core indicates that an active ice sheet was not present over the site at this time.

The lower altitude lakes (e.g. Pup Lagoon and Kirisjes Pond) have consistent age-depth profiles and similarly low accumulation rates during the glacial periods. Again, the absence of sand layers or a distinct inorganic unit argue against a complete discontinuity in organic production at this time. Heart Lake has two inconsistent dates which are discussed below.

In general, the consistent age-depth profiles in the Larsemann Hills are similar to those found in microbial mats in Lake Hoare in the McMurdo Dry Valleys (Doran *et al.* 1999), but without a recent reservoir effect.

Neither ^{210}Pb or ^{238}U dating could be used here to corroborate the AMS ^{14}C dates. However, the peak in ^{137}Cs in the uppermost sediment is useful and would permit a direct comparison if ^{14}C dates were available from identical levels. The levels that have been dated suggest a faster linear sedimentation rate in the uppermost sediments based on ^{137}Cs than that derived from a linear extrapolation of the surface and first ^{14}C date (which covers a much longer period). This is consistent with the progressive sediment compression of moribund cyanobacterial mats down the cores.

There is, however, evidence from the terrestrial sedimentary record that supports the late-Pleistocene to Holocene dates measured in the lake sediments. The OSL date from Broknes confirms glaciofluvial sediment deposition was occurring around the Last Glacial Maximum, and the 24 950 ± 710 ^{14}C radiocarbon date of Burgess *et al.* (1994) confirms that moss was growing somewhere near the shore of Lake Nella at this time. The rarity and poor preservation of glacial striae and ice polished pavements also indicates a substantial period of subaerial weathering since the retreat of a much earlier Pleistocene ice sheet (cf. Gore & Colhoun 1997).

Palaeolimnology

In the Larsemann Hills, many of the lakes have up to 3 m sediment thickness of finely-layered benthic cyanobacterial mats. Similar organic remains in sediment cores from Lake Hoare in the McMurdo Dry Valleys have been extremely valuable in palaeolimnological studies but have suffered from problems using radiocarbon dating as a method (Squyres *et al.* 1991, Ingólfsson *et al.* 1998, Doran *et al.* 1999). There, the radiocarbon dates are correct, but the source ^{14}C is not in equilibrium with the atmosphere. This is expressed as very old ages for surface sediments (varying between 2000 and 6000 ^{14}C yr) with samples obtained from depth in the cores yielding similar or younger ages than the surface material. In the Larsemann Hills, these problems have not occurred and the sediments are consequently of great interest for palaeoecological and palaeoclimatological studies.

Preliminary analyses of the cores indicates that the higher altitude lakes, proximal to the ice sheet, contain an entirely lacustrine record. Progress Lake (closest to the ice sheet) contains a possible discontinuity between Holocene and Pleistocene sediments. However, initial sedimentological observations indicate that the sediments were not scoured out at this time but that the lake was under a snow and ice field or a 'passive' lobe of the ice sheet (*sensu* Gore 1997). Other high altitude lakes (e.g. Lake Reid) have a slightly more consistent sedimentation rate with long limnological records containing information on the onset of basin sedimentation, the colonization by Pleistocene microbial communities, and their succession to the present. Rapid recruitment of microbial communities is evidenced by the colonization of ephemeral meltwater pools by cyanobacteria each summer. In the lower altitude coastal lakes the sediments contain alternations between lacustrine and marine deposits (Heart Lake, Pup Lagoon and Kirisjes Pond). These will be studied in more detail and will permit the emergence of these basins and relative sea level to be reconstructed with high precision (cf. the methodology of Zwartz *et al.* 1998).

There are additional features in the ^{14}C dated sequences that are of interest. For example, in Heart Lake there is evidence that the inorganic unit dated at 280 and 320 cm (Fig. 2) is a homogenous, over-consolidated (< 25% water content) diamicton. We tentatively interpret this as a deposit from beneath a grounded ice mass (Melles *et al.* 1997). If accurate, this till can only have reached the site by extension and thickening of the Dålk Glacier tongue. At 5 m a.s.l. and only 2–3 km from the present tidewater terminus, Heart Lake would be prone to subglacial debris from a modestly extended and thickened Dålk Glacier. More research is being carried out to clarify this. While we do not yet know the history of glacioisostasy of the Larsemann Hills, we do know that the Last Glacial Maximum was a period of eustatic sea level lowstand (e.g. Chappell *et al.* 1996), and it is generally believed that a lower sea level allows ice advance and, conversely, that rising sea level forces ice retreat (e.g. Ingólfsson *et al.* 1998). For example, by the LGM the Amery Ice Shelf nearby had extended only a few hundred km north of its present position (O'Brien & Harris 1996, Domack *et al.* 1998). The basal date of the Heart Lake core, which has a low carbon content, will be retested.

Another anomaly is the Lake Nella core, which has a basal age and accumulation rate similar to some of the lakes on Stornes. Our dating of Lake Nella returned modern at the surface and 1.6 ka BP at 26 cm depth (Table III). In contrast, the dating of the Lake Nella sediments by Gillieson *et al.* (1990, p. 159) shows a chronologic inversion, with an age of 6.6 ka BP in the upper 10 cm with 1.9 ka BP between 20–30 cm. There are two issues here: explaining the inversion and the young ages compared with surrounding lake basins. Gillieson's chronologic inversion can be explained by contamination or by sediment disturbance. With conventional radiocarbon dating, it is possible for a small amount of 'dead' carbon to become incorporated in the bulk sediments that are dated, leading to a falsely 'old' radiocarbon age and the appearance of an age inversion. A second explanation is that there may have been slumping, or disturbance and overturning by fluvial activity such as occurs during snow or ice dam release (cf. Gore 1992, Burgess *et al.* 1994). Which of these scenarios is accurate depends on whether the core is considered to be undisturbed (the former interpretation) or disturbed (in which case the latter applies). Whichever explanation is correct it is likely that it only applies to the specific coring site used by Gillieson as our photographic evidence (see cover of this issue) shows a finely laminated core with no evidence of sediment disturbance.

The second issue is how Lake Nella commenced sedimentation as late as the mid to late-Holocene, in comparison with Broknes lakes to the east and north. We believe that the basin hosted a remnant lobe of ice sheet ice that persisted until the mid Holocene (see below). This lobe of ice did not surmount the moraine that divides Lake Nella from Lake Reid. That it did not enter the catchment of Lake Reid is supported by the older dates from Lake Reid together with moss fragments from the foot of the Lake Reid moraine, near the shore of Lake Nella, which have been dated at 24 950 ± 710 ^{14}C yr BP by Burgess *et al.* (1994).

Ice flow and glacial history

Measurements of the present and former ice flow indicators, coupled with the dating program, permit us to present one possible scenario for the glacial history of the Larsemann Hills (Fig. 6).

First, glacially eroded surfaces and glacial sediments testify to ice having covered all of the Larsemann Hills at some time though we are uncertain of the location of the ice edge and the timing of the advance. The late Pliocene foraminifer *Ammoelphidiella* (Quilty *et al.* 1990) recovered from basal till on the eastern side of Stornes, shows that a Pleistocene ice sheet advanced northwest across Thala Fjord, deriving the Pliocene marine muds and smearing them across Stornes. The age of these muds has been constrained to between 4.5 Ma to 3.5 Ma (McMinn & Harwood 1995) but the extent and timing of the ice sheet advance(s) that moved them remains unknown. The reconstructed north-westerly ice flow across Stornes is consistent with the present day slope of the ice sheet in this area. Similarly, on Broknes, striae orientations indicate that a former ice flow was northerly, consistent with the present day slope of the ice there. The consistency between the former ice flow directions indicated by the striae, and the present ice flow directions indicated by the slope of the ice sheet, is strong evidence for little change in the geography of the ice sheet around the Larsemann Hills over long periods.

The second stage is that at some time preceding 40 ka BP and lasting until at least 20 ka BP, an expanded ice sheet flowing to the northwest covered Stornes, although islands to the north (including Kirisjes Pond) were exposed. In contrast, Broknes remained largely free of ice, with the ice sheet lying only 0–2 km north of its present day margin. The low altitude Heart Lake in the northeast of Broknes, was possibly influenced by subglacial deposits from the grounded ice of an expanded Dålk Glacier between 25–8 ka BP and more research is being carried out to clarify this. Progress Lake has a distinct discontinuity in its sediment sequence with a Pleistocene sediment (> 40 ka BP) overlain by a late Pleistocene to Holocene sediment with an extremely slow biogenic sedimentation from 20–3 ka BP, indicating at least a minor (~0.5 km?) readvance of the ice sheet margin in this area after 20.9 ka BP. This was probably a 'passive lobe' of remnant ice sheet ice, fed by snow drift which would account for the low bulk sedimentation during this period. While the high (85 m a.s.l.) LH73 lake basin appears to have remained free of ice throughout this period, the low lying (15 m a.s.l.) Lake Nella basin nearby also hosted a long lasting lobe of remnant ice sheet ice, probably fed by snow drift much in the same way as long lived domes or lobes of ice elsewhere around East Antarctica (Gore 1997) and exemplified by the 2 km diameter ice dome on Stornes.

The third stage was the start of recession of the ice sheet on Stornes from ~6 ka BP, exposing the periphery of the peninsula (e.g. Pup Lagoon), and leaving a remnant mass of ice that formed a local ice dome that, albeit smaller, persists to the present day. The dome, flowing radially, created fine striae which cross-cut the older north-westerly ice sheet striae. On Broknes, the Lake Nella catchment contained a remnant lobe of ice sheet ice. The recommencement of biogenic sedimentation in Progress Lake indicates that the ice sheet had retreated to south-eastern Broknes.

The fourth stage involved continued recession of the ice dome on Stornes and irregular melt out of the remaining parts of the peninsula spanning the last 4 ka. Striae in north-east and central Stornes suggest that the dome retreated towards the south-west, leaving behind it the scratches of its former north-easterly ice flow. On Broknes, Lake Nella was exposed after 6.6 ka BP if the Gillieson *et al.* (1990) dates are correct, or 1.6 ka BP as indicated in this study. An increase in the biogenic sedimentation rate in Progress Lake suggests that the ice sheet had reached its present position after 3.3 ka BP. Undisturbed sediments, in at least some parts of the Lake Nella basin, indicate that the ice sheet attained its present margin in south-central Broknes at around 1.6 ka BP.

We believe the reasons for the contrasting glacial history of Broknes and Stornes can be attributed to the action of the Dålk Glacier. The coincidence of the glacial striae (and reconstructed former ice flow) and the present day slope of the ice sheet (and inferred ice flow) in the immediate hinterland south of the Larsemann Hills indicates that flow of the ice sheet in this area is rather feeble. The Dålk Glacier exhibits strong flow lines and, judging from the drawdown of the ice surface around the glacier outlet, flows in a deep trough. The glacier also calves frequently, indicating a rapid mass flux. As a consequence of ice sheet diversion into the Dålk Glacier, the ice sheet between the Larsemann Hills and the glacier is shallow and possibly also stagnant or almost so. Broknes, closest to the outlet of the Dålk Glacier, is closest to this effect and has been exposed from the ice continuously since at least 40 ka BP. In contrast, Stornes is more distant from the Dålk Glacier and deglaciated during the mid to late-Holocene. During the last glacial cycle, including the Last Glacial Maximum, ice would have diverted around Broknes onto the continental shelf, thus allowing the peninsula to remain ice-free.

Conclusions

The dating program in this paper indicates that parts of Broknes have been ice-free continuously since at least 40 ka BP. The present ice sheet margin to the south of Broknes is stagnant or almost so, and has fluctuated by only 0.5–2 km over the last 20 ka. In contrast, Stornes deglaciated largely during the Holocene although Kirisjes Pond on Kolloy Island to the north of Stornes, has been exposed continuously since at least 40 ka BP. The ice dome on Stornes retreated from 6–1.3 ka BP, leaving fine striae that lie normal to the former flow direction of the ice sheet. A four stage model incorporating the dating and geomorphological evidence, describes how the glacial history of the Larsemann Hills is based on its physiographic relationship with the Dålk Glacier, which diverted ice around Broknes allowing it to remain an ice-free refuge for plants and animals throughout the Last Glacial Maximum.

While these records indicate older dates than have been recorded from other eastern Antarctic oases, the Antarctic Peninsula and the sub-Antarctic, they do not pre-date lakes in the Dry Valleys whose earliest exposures are proposed between 4.6 and 9 Ma BP (see review in Doran *et al.* 1994). However, substantial changes in the precipitation/evaporation balance in this latter area has resulted in repeated lake water level variations (*c.* 224 m for Lake Vanda) including evaporation to dryness, resulting in sediment loss due to ablation and consequent discontinuities in the records. To date, diatom and isotope results suggest that the Larsemann Hills lakes have not evaporated to dryness, although a minority have evidence of former shorelines (e.g. lake LH73).

In combination, these lakes should therefore permit a detailed reconstruction of past climate-induced changes, providing information on both terrestrial as well as marine environments and on regional ice-sheet history, sea level and isostacy (Lambeck 1996, Quinlan & Beaumont 1982, Zwartz *et al.* 1998). We hope that information in this paper will help protect these lakes, their catchments and their valuable sediment archives from the impacts of recent human occupation which has resulted in changes to local drainage patterns (from road construction), chemical pollution (mostly petroleum products and waste water) and litter (Burgess *et al.* 1992).

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References

ANARE. 2000. Visitor's guide to the Larsemann Hills (http://www.antdiv.gov.au).

ADAMSON, D.A. & PICKARD, J. 1986. Cainozoic history of the Vestfold Hills. *In* PICKARD, J., *ed.* Antarctic oasis: terrestrial environments and history of the Vestfold Hills. Sydney: Academic Press, 63–98.

Andrews, J.T., Domack E.W., Cunningham, W.L., Leventer, A., Light, K.J., Jull, A.J.T., DeMaster, D.J. & Jenning, A. 1999. Problems and possible solutions concerning radiocarbon dating of surface marine sediments, Ross Sea, Antarctica. *Quaternary Research*, **52**, 206–216.

Appleby, P.G., Nolan, P.J., Gifford, D.W., Godfrey, M.J., Oldfield, F., Anderson, N.J. & Battarbee, R.W. 1986. ^{210}Pb dating by low background gamma counting. *Hydrobiologia*, **141**, 21–27.

Appleby, P.G. & Oldfield, F. 1992. Application of lead 210 to sedimentation studies. *In* Ivanovich, M. & Harmon, R.S., *eds. Uranium series disequilibrium, applications to earth, marine and environmental sciences* (2nd ed). Oxford: Oxford University Press, 731–778.

Appleby P.G., Richardson, N. & Nolan, P.J. 1992. Self-absorption corrections for well-type germanium detectors. *Nuclear Instruments & Methods in Physics Research*, **71**, 228–233.

Appleby, P.J., Jones, V.J. & Ellis-Evans, J.C. 1995. Radiometric dating of lake sediments from Signy Island (maritime Antarctic): evidence of recent climatic change. *Journal of Paleolimnology*, **13**, 179–191.

Bird, M.I., Chivas, A.R., Radnell, C.J. & Burton, H.R. 1991. Sedimentological and stable-isotope evolution of lakes in the Vestfold Hills, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **84**, 109–130.

Björck, S., Hjört, C., Ingólfsson, O. & Skog, G. 1991. Radiocarbon dates from the Antarctic Peninsula region - problems and potential. *Quaternary Proceedings*, **1**, 55–65.

Boutton, T.W., Wong, W.W., Hachey, D.L., Lee, L.S., Cabrera, M.P. & Klein, P.D. 1983. Comparison of quartz and pyrex tubs for combustion of organic samples for stable carbon isotope analysis. *Analytical Chemistry*, **55**, 1832–1833.

Burgess, J.S., Spate, A.P. & Shevlin, J. 1994. The onset of deglaciation in the Larsemann Hills, eastern Antarctica. *Antarctic Science*, **6**, 491–495.

Burgess, J.S., Spate, A.P. & Norman, F.I. 1992. Environmental impacts of station development in the Larsemann Hills, Princess Elizabeth Land, Antarctica. *Journal of Environmental Management*, **36**, 287–299.

Chappell, J., Omura, A., Esat, T., McCulloch, M., Pandolfi, J., Ota, Y. & Pillans, B. 1996. Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. *Earth and Planetary Science Letters*, **141**, 227–236.

Domack, E.W., Jull, A.J.T., Anderson, J.B., Linick, T.W. & Williams, C.R. 1989. Application of Tandem Accelerator Mass-Spectrometer dating to Late Pleistocene-Holocene sediments of the East Antarctic continental shelf. *Quaternary Research*, **31**, 277–287.

Domack, E., O'brien, P., Harris, P., Taylor, F., Quilty, P.G., De Santis, L. & Raker, B. 1998. Late Quaternary sediment facies in Prydz Bay, East Antarctica and their relationship to glacial advance onto the continental shelf. *Antarctic Science*, **10**, 236–246.

Donahue, D.J. 1990. Radiocarbon analysis by accelerator mass spectrometry. *International Journal of Mass Spectrometry and Ion Processes*, **143**, 235–245.

Doran, P.T., Wharton Jr., R.A. & Lyons, W.B. 1994. Paleolimnology of the McMurdo Dry Valleys, Antarctica. *Journal of Paleolimnology*, **10**, 85–114.

Doran, P.T., Berger, G.W., Lyons, W.B., Wharton Jr, R.A., Davisson, M.L., Southon, J. & Dibb, J.E. 1999. Dating Quaternary lacustrine sediments in the McMurdo Dry Valleys, Antarctica. *Palaeogeography Palaeoclimatology and Palaeoecology*, **147**, 223–239.

Edwards, L.R, Chen, J.H. & Wasserberg, G.J. 1986. ^{238}U–^{234}U–^{230}Th–^{232}Th systematics and the precise measurement of time over the past 500 000 years. *Earth and Planetary Science Letters*, **81**, 175–192

Ellis-Evans, J.C., Laybourn-Parry, J., Bayliss, P. & Perriss, S.J. 1998. Physical, chemical and microbial community characteristics of lakes of the Larsemann Hills, Continental Antarctica. *Archiv für Hydrobiologie*, **141**, 209–230.

Fabel, D., Stone, J., Fifield, L.K. & Cresswell, R.G. 1997. Deglaciation of the Vestfold Hills, East Antarctica: Preliminary evidence from exposure dating of three subglacial erratics. *In* Ricci, C.A., *The Antarctic region: geological evolution and processes.* Siena: Terra Antartica Publications, 829–834.

Gillieson, D., Burgess, J.S., Spate, A. & Cochrane, A. 1990. An atlas of the lakes of the Larsemann Hills, Princess Elizabeth Land, Antarctica. *ANARE Research Notes*, No. 74, 173 pp.

Gillieson, D.S. 1991. An environmental history of two freshwater lakes in the Larsemann Hills, Antarctica. *Hydrobiologia*, **214**, 327–331.

Gordon, J.E. & Harkness, D.D. 1992. Magnitude and geographic variation of the radiocarbon content in Antarctic marine life: implications for reservoir corrections in radiocarbon dating. *Quaternary Science Reviews*, **11**, 697–708

Gore, D.B. 1992. Ice damming and fluvial erosion in the Vestfold Hills, East Antarctica. *Antarctic Science*, **4**, 227–234.

Gore, D.B. 1997. Blanketing snow and ice: constraints on radiocarbon dating deglaciation in East Antarctic oases. *Antarctic Science*, **9**, 336–346.

Gore, D.B. & Colhoun, E.A. 1997. Regional contrasts in weathering and glacial sediments reflect long term subaerial exposure of the Vestfold Hills, East Antarctica. *In* Ricci, C.A., *ed. The Antarctic region: geological evolution and processes*. Siena: Terra Antartica Publications, 835–839.

Hodgson, D.A., Dyson, C.L., Jones, V.J. & Smellie, J. 1998. Tephra analysis of sediments from Midge Lake (South Shetland Islands) and Sombre Lake (South Orkney Islands), Antarctica. *Antarctic Science*, **10**, 13–20.

Hodgson, D.A., Vyverman, W. & Sabbe, K. 2001. Limnology and biology of saline lakes in the Rauer Islands, eastern Antarctica. *Antarctic Science*, **13**, 255–270.

Huntley, D.J. & Berger, G.W. 1995. Scatter in luminescence data for optical dating - some models. *Ancient TL*, **13**, 5–9.

Huntley, D.J., Godfrey-Smith, D.I. & Thewalt, M.L.W. 1985. Optical dating of sediments. *Nature*, **313**, 105–107.

Ingólfsson, Ó., Hjort, C., Berkman, P.A., Björck, S., Colhoun, E., Goodwin, I.D., Hall, B., Hirakawa, K., Melles, M., Möller, P. & Prentice, M.L. 1998. Antarctic glacial history since the Last Glacial Maximum: an overview of the record on land. *Antarctic Science*, **10**, 326–344.

Jones, V.J., Hodgson, D.A., & Chepstow-Lusty, A. 2000. Palaeolimnological evidence for marked Holocene environmental changes on Signy Island, Antarctica. *The Holocene*, **10**, 43–60.

Lambeck, K. 1996. Limits on the areal extent of the Barents Sea ice sheet in Late Weichselian time. *Global and Planetary Change*, **12**, 41–51.

McMinn, A., Heijnis, H. & Hodgson, D. 1994. Minimal effects of UV-B on Antarctic diatoms over the past 20 years. *Nature*, **370**, 547–549.

McMinn, A. & Harwood, D.M. 1995. Biostratigraphy and palaeoecology of early Pliocene diatom assemblages from the Larsemann Hills, eastern Antarctica. *Antarctic Science*, **7**, 115–116.

McMinn, A., Heijnis, H. & Hodgson, D. 1997. Temporal evidence against short term UV-B induced changes in Antarctic coastal diatom communities. *In* Battaglia, B, Valencia, J. & Walton, D.W.H., *eds. Antarctic communities, species structure and survival.* Cambridge: Cambridge University Press, 381–387.

Melles, M., Verkulich, S.R. & Hermichen, W.D. 1994. Radiocarbon dating of lacustrine and marine sediments from the Bunger Hills, East Antarctica. *Antarctic Science*, **6**, 375–378.

Melles, M., Kulbe, T., Verkulich, S.R., Pushina, Z.V. & Hubberten, H.-W. 1997. Late Pleistocene and Holocene environmental history of Bunger Hills, East Antarctica, as revealed by freshwater and epishelf lake sediments. *In* Ricci, C.A., *ed. The Antarctic region: geological evolution and processes.* Siena: Terra Antartica Publications, 809–820.

O'Brien, P.E. & Harris, P.T. 1996. Patterns of glacial erosion and deposition in Prydz Bay and the past behaviour of the Lambert Glacier. *Papers and Proceedings of Royal Society of Tasmania*, **130**, 79–85.

Omoto, K. 1983. The problem and significance of radiocarbon geochronology in Antarctica. *In* Oliver, R.L., James, P.R. & Jago, J.B., *eds. Antarctic earth science*. Canberra: Australian Academy of Science, 450–452.

Payne, R. 1988. *Some observations on the geomorphology of the south eastern Vestfold Hills, Antarctica*. BSc thesis, The University of Newcastle, Australia, 84 pp. [Unpublished]

Quilty, P.G., Gillieson, D., Burgess, J., Spate, A. & Pidgeon, R. 1990. Ammoelphidiella from the Pliocene of Larsemann Hills, East Antarctica. *Journal of Foraminiferal Research*, **20**, 1–7.

Quinlan, G. & Beaumont, C. 1982. A comparison of observed and theoretical post-glacial relative sea-level in Atlantic Canada. *Canadian Journal of Earth Science*, **18**, 1146–1163.

Rhodes, E.J. 1988. Methodological considerations in the optical dating of quartz. *Quaternary Science Reviews*, **7**, 395–400.

Rhodes, E.J. & Bailey, R.M. 1997. The effect of thermal transfer on the zeroing of the luminescence of quartz from recent glaciofluvial sediments. *Quaternary Science Reviews (Quaternary Geochronology)*, **16**, 291–298.

Rhodes, E.J. & Pownall, L. 1994. Zeroing of the OSL signal in quartz from young glaciofluvial sediments. *Radiation Measurements*, **23**, 581–585.

Roberts, D. & McMinn, A. 1996. Relationships between surface sediment diatom assemblages and water chemistry gradients in saline lakes of the Vestfold Hills, Antarctica. *Antarctic Science*, **8**, 331–341.

Roberts, D. & McMinn, A. 1999. A diatom-based palaeosalinity history of Ace Lake, Vestfold Hills, Antarctica. *The Holocene*, **9**, 515–520.

Roberts, D., Roberts, J., Gibson, J.A.E., McMinn, A.E. & Heijnis, H. 1999. Palaeohydrological modelling of Ace Lake, Vestfold Hills, Antarctica. *The Holocene*, **9**, 515–520.

Roberts, D., Van Ommen T.D., McMinn, A. & Roberts, J.L. 2001. Late Holocene East Antarctic climate trends from ice core and lake sediment proxies. *The Holocene*, **11**, 117–120.

Slota P.J., Jull A.J.T., Linick T.W. & Toolin L.J. 1987. Preparation of small samples for ^{14}C accelerator targets by catalytic reduction of CO. *Radiocarbon*, **29**, 303–306.

Smith, B.W., Aitken, M.J., Rhodes, E.J., Robinson, P.D. & Geldard, D.M. 1986. Optical dating: methodological aspects. *Radiation Protection Dosimetry*, **17**, 229–233.

Smith, B.W., Rhodes, E.J., Stokes, S. & Spooner, N.A. 1990. The optical dating of sediments using quartz. *Radiation Protection Dosimetry*, **34**, 75–78.

Southon, J.R., Caffee, M.W., Advise, J.C., More, T.L., Proctor, I.D., Schemata, B. & Vogel, J.S. 1990. The new LLNL AMS Spectrometer. *Nuclear Instruments and Methods in Physics Research*, **B52**, 301–305.

Squyres, S.W., Andersen, D.W., Nedell, S.S. & Wharton Jr, R.A. 1991. Lake Hoare, Antarctica: sedimentation through thick perennial ice cover. *Sedimentology*, **38**, 363–379.

Stuiver, M. & Polach, H.A. 1977. Discussion: reporting of ^{14}C data. *Radiocarbon*, **19**, 355–363.

Stuwe, K., Braun, H.-M. & Peer, H. 1989. Geology and structure of the Larsemann Hills area, Prydz Bay, East Antarctica. *Australian Journal of Earth Sciences*, **36**, 219–241.

Van Calsteren, P. & Schwieters, J.B. 1995. Performance of a thermal ionisation mass spectrometer with a deceleration lens system and post-deceleration detector selection. *International Journal of Mass Spectrometry Ionisation Processes*, **146/147**, 119–129.

Zwartz, D., Bird, M., Stone, J. & Lambeck, K. 1998. Holocene sea level change and ice sheet history in the Vestfold Hills, East Antarctica. *Earth and Planetary Science Letters*, **155**, 131–145.