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Holocene sea-level change and ice-sheet history in the Vestfold Hills, East Antarctica

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Abstract

A new Holocene sea-level record from the Vestfold Hills, Antarctica, has been obtained by dating the lacustrine–marine and marine–lacustrine transitions that occur in sediment cores from lakes which were formerly connected to the sea. From an elevation of ~7.5 m 8000 yr ago, relative sea-level rose to a maximum ~9 m above present sea-level 6200 yr ago. Since then, sea-level has fallen monotonically until the present. The precision of the new record makes it suitable for constraining the recent history of the ice sheet in that region, using numerical models of glacio-hydro-isostasy. Simplified regional models suggest that the ice-sheet margin has retreated 30–40 km since the last glacial maximum, with 600–700 m of thinning occurring at the present coastline. © 1998 Elsevier Science B.V.

Keywords: sea-level changes; glacial rebound; numerical models; Vestfold Hills; Antarctica

1. Introduction

Determining the extent of the Antarctic ice sheet at the last glacial maximum is a major problem in climate and global change studies. Published estimates of the Antarctic contribution to eustatic sea-level rise since that time (Table 1) vary by an order of magnitude, indicating that ice-sheet history in this region introduces the greatest unknown in the study of global ice balance. Constraints on the former size of the ice sheet have been obtained using a diverse range of methods, including terrestrial and marine geology, ice core analysis and numerical modelling (refs. in Table 1). Although considerable progress has been made, many of these methods suffer from the localised applicability of their results. Since large areas of Antarctica have yet to be studied in detail, methods which constrain ice-sheet history over a wide region will be particularly useful in developing an adequate model.

Table 1
Published estimates of Antarctic ice volume change since the LGM

Reference	e.s.l. (m)
Nakada and Lambeck [1]	37
Hughes et al. [2]	25–30
Peltier [3]	22
Huybrechts [4]	12–16
Colhoun et al. [5]	0.5–2.4

Volume change is expressed in terms of the amount of eustatic sea-level rise caused.

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One such method is the study of glacio-hydro-isostasy: the Earth's isostatic response to ice-sheet and ocean-volume changes causes predictable sea-level change at a specified site. Because of the damping effect of the lithosphere, these isostatic movements are responses to changes in the ice sheet over areas of hundreds of kilometres. Precise sea-level records can therefore be used to infer regional ice-sheet history, as has been achieved for example in the Barents Sea [6] and North America [7]. Sea-level predictions for the Antarctic region have been made using a speculative ice-sheet reconstruction [8,9] but no comparison was made with sea-level observations. This paper documents a new Holocene sea-level record from the Vestfold Hills, East Antarctica (Fig. 1), which will be used to constrain ice-sheet reconstructions.

The record of Holocene sea-level change around

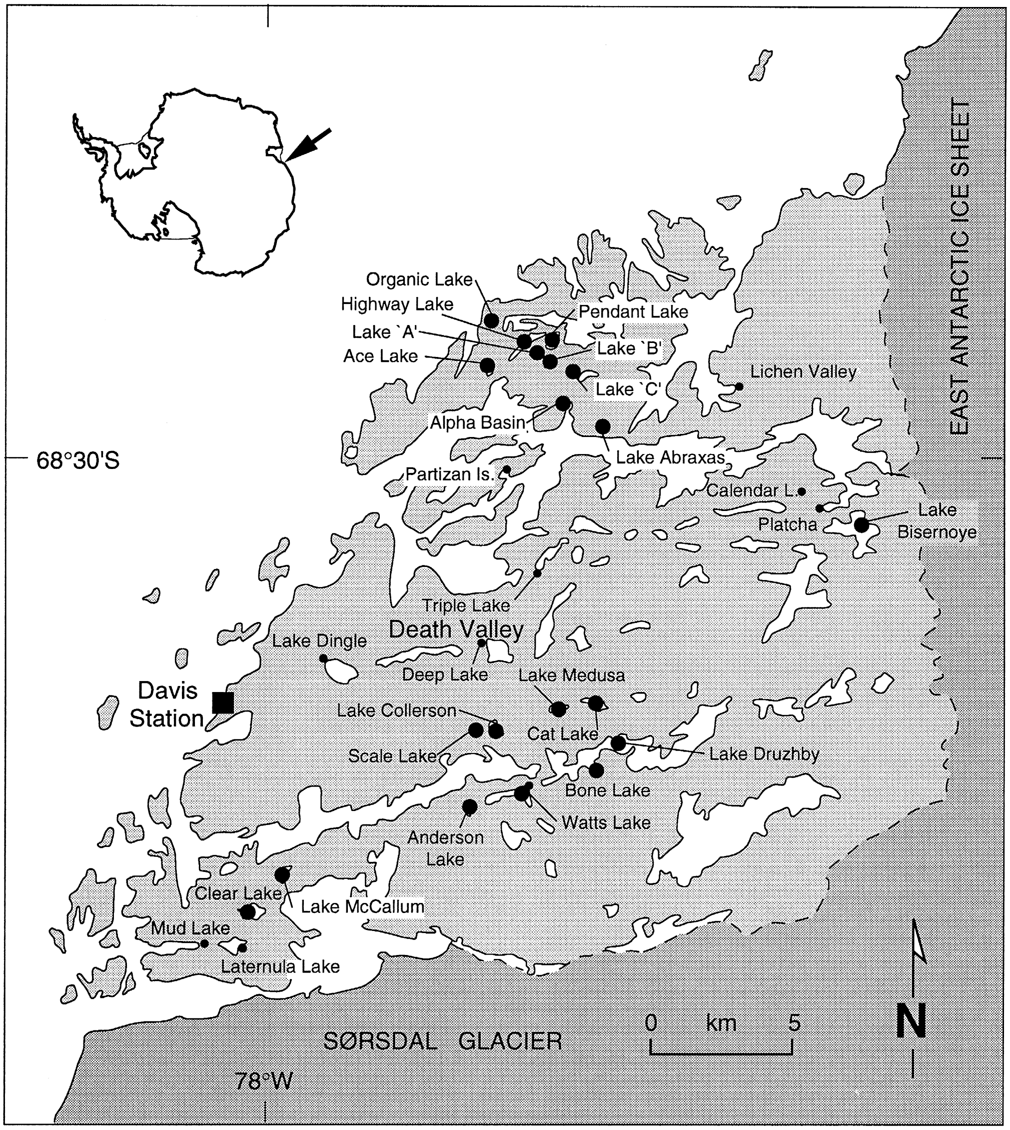

Fig. 1. Location map for Vestfold Hills, showing lakes cored for this study (*large dots*) and locations of published radiocarbon ages (*small dots*).

Antarctica is poorly defined compared to any other continent, for several reasons. Most importantly, only 5% of the coastline consists of rock [10], and it is only on these areas that former sea-levels can be recorded and preserved. In locations where the coastline does consist of rock, the unusual coastal environment enclosed in sea-ice for most of the year, and the rarity of living organisms compared to warmer regions, mean that the sea-level record is usually poorly preserved, imprecise and difficult to date. In contrast, the sea-level record presented in this paper, obtained by dating isolation events in lakes which were formerly connected to the sea, is of high precision and chronologically well constrained for the past 8000 yr.

2. Sea-level change from lake isolation events

During a sea-level highstand, marine basins close to shore accumulate marine sediment (Fig. 2). As sea-level falls, basins with submarine sills are progressively isolated, and, if they have freshwater input, are flushed and begin to accumulate freshwater lacustrine sediments. By recognising and dating the marine–lacustrine transitions in sediment cores from these basins, and measuring the elevation of the lakes' former outlet to the sea, a precise sea-level record can be obtained. If sea-level has oscillated relative to the land, crossing the sill of a lake more than once, each transgression and isolation will be preserved in the sediment record (Fig. 3). This method of determining past sea-levels has two major advantages over the use of beach ridges: by identifying the sill which represents the lake's last connec-

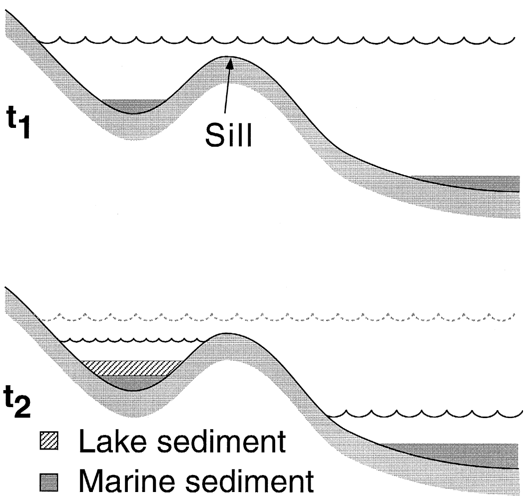

Fig. 2. Schematic representation of lake sedimentation in a changing sea-level environment. Sea-level changes may be recorded in lake sediments, if sea-level moves through the elevation of the basin's sill. In this simple example of sea-level fall, marine sediment is deposited in a nearshore basin at time t_1, when sea-level stands higher than the sill. At a later time t_2, sea-level has dropped below the sill and lake sediments are deposited in the basin on top of the older marine sediments.

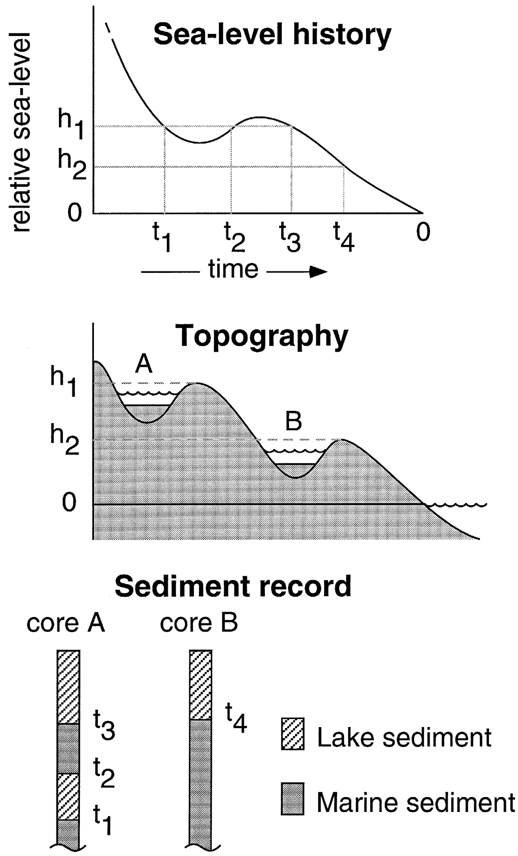

Fig. 3. The sediment record from lakes with different sill heights can be used to reconstruct complicated sea-level histories. In this example of oscillating sea-level, the elevations and ages of the sea-level highstand and lowstand are constrained by the dated sediment records from lakes A and B. Each marine–lacustrine transition in the sediment core corresponds to a point on the sea-level curve.

tion to the sea, the relationship between the dated transition and the sea-level is clear; and by dating the freshwater material at the transition, the need to apply a reservoir correction to the radiocarbon date is avoided (see Section 5.3).

This method has been used extensively in Fennoscandia to measure the sea-level change due to glacial rebound there [11–13], and also at some Antarctic sites [14–16].

3. The Vestfold Hills

The Vestfold Hills (Fig. 1) lie on the eastern edge of Prydz Bay on the Ingrid Christiansen Coast, at 68°35′S, 78°E. They are bounded to the east by the East Antarctic Ice Sheet and to the south by the Sørsdal Glacier, an outlet glacier of the ice sheet. The ice-free region, consisting of long peninsulas, fjords and low hills, covers an area of 410 km^2 [17]. Raised beaches, saline and freshwater lakes are found throughout the region.

Zhang and Peterson [18] obtained radiocarbon ages for in-situ marine shells from several terraces around 6 m a.s.l. in the Vestfold Hills, all of which fall near 6000 ^{14}C yr BP (see Table 2). They also note possible shoreline features up to 15 m a.s.l., which do not contain dateable material. These shells represent a lower limit to relative sea-level at the time at which they grew. Adamson and Pickard [23] claim a maximum emergence of 11 m at one site just to the south of Davis Station, though their highest dated sample comes from 5.5 m a.s.l. From elevations of the highest marine terrace at locations throughout the Hills and radiocarbon dates obtained from marine algae and shells within these deposits (Table 2), they attempted to reconstruct sea-level. Their contour maps of emergence and emergence rate for the area are based on bracketing constraints on age and sea-level, and are also subject to the vagaries of beach ridge formation and preservation. This may account for implausible results such as the accelerating rate of sea-level rise to the present day.

Several lake isolation events have been recognised in the Vestfold Hills (Table 3). Pickard et al. [24] recognised a marine–lacustrine transition in sediments exposed on the shore of Watts Lake, in the southern Vestfold Hills. From the range of ages obtained from marine organisms in these sediments, they dated the recession of seawater below the sill at

Table 2
Radiocarbon ages from marine organisms in growth position in emerged marine terraces in the Vestfold Hills

Location	Material	Elevation (m)	Uncorrected age (^{14}C yr BP)	Sample code	Ref.
Mud Lake	shells	3.0	3325 ± 103	ZDL 66	[18]
Mud Lake	shells	3.0	3500 ± 86	ZDL 69	[18]
Watts Lake	shells	3.0	6100 ± 108	ZDL 70	[18]
Watts Lake	algae	3.0	3600 ± 95	ZDL 71	[18]
Triple Lake	shells	6.0	6141 ± 90	ZDL 78	[18]
Dingle Lake	shells	6.0	5600 ± 77	ZDL 79	[18]
Deep Lake	shells	6.0	6632 ± 118	ZDL 80	[18]
Platcha	algae[a]	6.0	5677 ± 94	ZDL 81	[18]
Watts Lake	algae	3.7	4760 ± 190	SUA 1828	[19]
Watts Lake	sediment	2.4	6225 ± 85	Beta 4761	[19]
Watts Lake	shells	5.5	7590 ± 80	SUA 2026	[20]
Laternula Lake	shells	2.0	2410 ± 90	SUA 1411	[21]
Death Valley	shells	2.6	4710 ± 70	ANU 1011	[19]
Death Valley	shells	2.6	5340 ± 90	SUA 1237	[21]
Calendar Lake	shells	1.8	6850 ± 160	SUA 2030	[22]
Lichen Valley	shells	2.0	6910 ± 150	SUA 2027	[20]
Partizan Island	shells	3.0	7370 ± 95	Beta 4767	[19]

The locations mentioned in this table are indicated in Fig. 1.
[a] This sample is described as both algae and shells in Zhang and Peterson [18]. Provided the algae was marine, this does not affect the interpretation.

Table 3
Published former sea-levels derived from isolation of lakes in the Vestfold Hills

Lake	Sill height (m)	Isolation time (corr. ^{14}C age, yr BP)	Ref.
Organic Lake	3.5	2700	[16]
Watts Lake	4.3	3400	[24]
Highway Lake	7.7	4600	[16]
Nicholson Lake	8.5	4650	[15]

Uncertainties for the time of isolation were not generally provided by the original authors.

3400 corr. ^{14}C yr BP. Bronge [15] collected a sediment core from Nicholson Lake, a higher sub-basin of the former embayment now containing Watts, Nicholson and Anderson Lakes (Fig. 4), and dated the marine–lacustrine transition there at 4650 ± 200 corr. ^{14}C yr BP. Accurate measurements of the sill heights of these lakes, 4.3 and 8.5 m above mean sea-level for Watts and Nicholson Lakes, respectively, imply emergence rates of 3.4 mm/yr between the isolation times of the two lakes, and 1.3 mm/yr since.

Bird et al. [16] identified marine–lacustrine transitions in cores from two lakes in the northern Vestfold Hills: Highway and Organic Lakes (Fig. 1). The time at which relative sea-level fell below the sill connecting each lake to the sea was estimated by dating sediment samples from both the upper (freshwater) and lower (marine) parts of the core. The sedimentation rate obtained from these dates was then interpolated to the depth of the marine–lacustrine transition to obtain the time of transition. At least two dates were obtained from each section of core, and the ages obtained from extrapolations above and below the transition agree well, when the

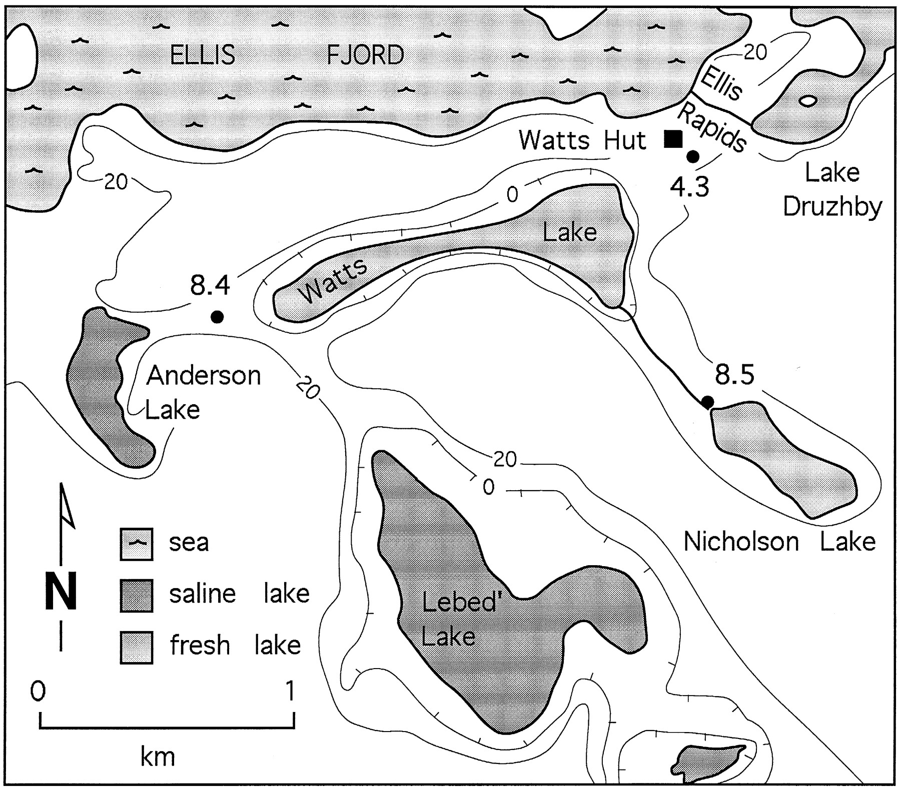

Fig. 4. Map of Watts–Nicholson–Anderson lake system. The sea formerly occupied an embayment which now contains the basins of Watts, Anderson, Nicholson and Lebed' lakes, as well as Oblong Lake to the south (not shown on map). The sill height of lakes from which sediment cores have been taken are indicated. Elevations are in metres, and contours above 20 m are not shown.

marine radiocarbon reservoir correction is applied to the marine samples. Highway Lake, with a sill height of 7.7 m, was isolated from the sea ~ 4600 corr. ^{14}C yr BP. Organic Lake, with a sill at 3.5 m, was isolated at 2700 corr. ^{14}C yr BP. These points on the relative sea-level curve imply emergence rates of 2.2 mm/yr between 4600 and 2700 yr ago, and 1.3 mm/yr since then. Although the rates differ slightly, this slowing of emergence rate is consistent with the result from Watts and Nicholson Lakes. A core from Ace Lake (sill 8.8 m) was also analysed by Bird et al. [16], but its relevance to sea-level change was not discussed, as the significance of the fresh–marine–fresh sediment sequence was not recognised. New analyses on this core are included in the present work.

4. Methods

In November and December 1991 several lakes in the Vestfold Hills were studied by a field party from the ANU Research School of Earth Sciences as part of the Australian National Antarctic Research Expedition (ANARE). Using a hammer-type piston corer, sediment cores were recovered from seventeen lakes (Fig. 1) with sill heights ranging from intertidal to ~ 40 m a.s.l. (Table 4). All lakes sampled develop a winter ice cover which persists until mid-summer and provided the platform from which to operate the corer (a number of hypersaline lakes in the Vestfold Hills do not freeze, and could not be sampled). When possible, cores were taken from the centre of the lake basin, in an attempt to avoid cores with breaks in sedimentation. Cores were sealed in the core barrel and frozen for transportation as soon as possible after recovery.

Sill heights were measured using a theodolite and electronic distance meter, using benchmarks installed in the Vestfold Hills by the Australian Division of National Mapping between 1979 and 1986. Two closed traverses between benchmarks indicate that surveyed heights are accurate to within 5 cm. Since sills were not usually on bedrock, the height could have changed slightly due to sediment movement since the sea was at that level. However, most lakes do not presently overflow their sills, and there is no evidence of significant sediment movement (stream deposits, deltas, etc.) in the region of the sills. Any changes in sill height are assumed to be less than a few tens of centimetres, and heights are quoted to the nearest 10 cm.

Table 4
Location and characteristics of lakes cored in the Vestfold Hills, November and December 1991

Lake	Location[a]	Sill height (m)	Water depth[b] (m)	Salinity[c]
Alpha Basin	875008	~ 0	8.5	saline
Pendant	870030	3.1	17	13.2–17.5 ‰
Organic[d]	848034	3.5	7.5	176–250 ‰
Watts	886873	4.3	33	slightly saline
Bisernoye	982970	4.9	15	fresh
Highway[d]	863026	7.7	15	8–10 ‰
Druzhby	889885	8.0	25	fresh
Anderson	849869	8.4	13	31.8–132.3 ‰
Ace *	847017	8.8	25	28–40 ‰
Bone	893880	~ 9	1.6	fresh
‘‘B’’	868022	12.4	6.2	fresh
Abraxas	889000	13.5	22.5	< 20 ‰
McCallum	842788	13.9	32.5	< 24 ‰
‘‘C’’	881015	14.5	5	fresh
Clear	776830	16.4	27	4.9–8.2 ‰
‘‘A’’	865024	19.2	4.3	fresh
Collerson	857895	26.9	10.5	6.5–7.8 ‰
Cat	891901	40 +	17.8	slightly saline
Medusa	877902	40 +	20.4	3.2–4.2 ‰
Scale	859892	40.2	12.5	saline

[a] Locations are given as grid references on the 1:50 000 map sheet ‘‘Vestfold Hills’’ [25].
[b] This is the water depth where the core was taken, not the maximum lake depth.
[c] Where numerical values are given, salinity was determined by conductivity measurements (unpublished measurements compiled at Davis Station). Ranges apply where salinity is stratified within the lake.
[d] From Bird et al. [16].

Radiocarbon ages for large samples were determined by the Australian National University Quaternary Dating Research Centre. Ages for small samples were obtained by accelerator mass spectrometry at the Department of Nuclear Physics, ANU. The marine reservoir correction in the Vestfold Hills has been estimated at 950–1310 yr [19], from radiocarbon assays of modern marine bivalves. Where ‘‘corrected’’ radiocarbon ages are cited in this paper, this range has been adopted. No radiocarbon ages have been ‘‘calibrated’’.

5. Results

5.1. Core stratigraphy

The stratigraphy of four key cores from lakes with sill heights below 9 m is described in Table 5. Three sediment types were observed in these cores, similar to those found in cores from other Antarctic oases such as the Larsemann Hills [26], King George Island [14] and the Windmill Islands [27]:

5.1.1. Reworked till

The lowermost unit in many cores is a dark-grey, plastic, clay-rich sediment containing a variable amount of coarser sandy sediment and occasional pebbles up to several centimetres in diameter. It is characterised by both low water and low organic carbon content, although near the top of the unit it may be interbedded with more organic-rich algal layers. The unit generally becomes more compact with depth, placing a limit on the depth to which it was usually possible to drive the corer. This sediment is considered to be reworked glacial till, washed into the lake basins from the drift deposits which would have covered the Vestfold Hills after the last retreat of ice cover.

5.1.2. Algal lake sediment

The unit found at the top of each core is characterised by high organic carbon (10–15%) and high water content, with a variable but generally small amount of clay- to sand-sized clastic inorganic material. In fresh to moderately saline lakes, the organic matter occurs as green and black laminated algal mats or masses of filamentous moss. These beds sometimes contain white flecks of biogenic carbonate, and may be interbedded with clay- to sand-sized clastic layers. In hypersaline lakes, the organic-rich units tend to be diffusely laminated or structureless. These units vary in colour from green to black and may contain abundant authigenic mirabilite or gypsum.

Table 5
Descriptions of selected cores taken from lakes in the Vestfold Hills, November and December 1991

Lake	Interval (cm)	Sediment type	Description
Watts	0–14	lacustrine	green/black laminated algal mat material, lamination becoming less distinct towards base
	14–269	marine	structureless watery dark green algal sediment with low clastic content; diffuse green/black bands occur from 140 to 212 cm, and sediments become more prominently banded below 254 cm
Druzhby	0–30	lacustrine	black/green laminated algal mat material, low clastic content
	30–233	marine	homogeneous, watery, green/black algal sediment, low organic content
Anderson	0–20	lacustrine	diffusely-banded watery clastic-poor green/black algal material
	20–35	lacustrine	as above with ~5 mm gypsum crystals
	35–43	transitional	finely laminated grey-green algal sediment
	43–103	marine	structureless watery black/green algal material, low clastic content, laminated below 101 cm
	103–111	lacustrine	organic-rich laminated sediment with abundant filamentous algae and some carbonate
	111–135	till	structureless dark grey clay, becoming gritty and pebbly towards base
Ace[a]	0–35	lacustrine	black and reddish black laminated algal material with occasional light <0.5 mm carbonate-rich bands
	35–130	marine	watery, diffusely banded green sediment
	130–185	lacustrine and till	black in the upper portion, laminated algal material similar to unit 1, with occasional carbonate-rich bands; changing gradually over ~15 cm to grey laminated algal material with progressively fewer algal laminations and more fine clastic material down the core; from 170 to 180 cm there is very little macroscopic algal material and the sediment is predominantly composed of grey silt-sized clastic material

[a] Ace Lake core description from Bird et al. [16].

5.1.3. Marine sediment

These units are generally homogeneous along their length, consisting of black, watery, diffusely banded organic-rich (1–5% organic carbon) sediment with a low clastic content. Fine laminations are sometimes visible. These sediments are similar in character to those found in marine inlets in the Vestfold Hills [16], and contain a marine diatom assemblage [28]. These sediments are thought to have been deposited during times of higher relative sea-level, when the lake basins were occupied by the ocean as bays or fjords connected to the open sea by shallow sills in the same manner as Ellis Fjord is today.

The subdivision of marine and lacustrine sediments based on sediment characteristics, as described above, is supported by detailed diatom stratigraphy obtained for the Anderson Lake core [28,29], and the Ace Lake core [30]. The diatom stratigraphy of Ace Lake [30] reveals a unit (170–185 cm) not described in the visual description [16]. The interpretation of the basal 5 cm of this unit is complex, since it contains open-marine, freshwater, and pioneer diatom species in similar proportions. Fulford-Smith and Sikes [30] propose that these sediments were deposited at a time when the Ace Lake basin was a tidally affected inlet, with both meltwater and tidal marine input. However, detailed paleosalinity reconstruction [31] and carbon isotope measurements (unpublished data) indicate fresh lacustrine conditions extending to the base of the core, and this interpretation is adopted in the present work.

5.2. Core interpretation

All cores show organic lacustrine sediment at the top, except Pendant Lake (top of core not recovered), Alpha Basin (still connected to the sea) and Lake Bisernoye (inorganic clastic sediment throughout core). Lakes can be subdivided according to the underlying sediment: One class (e.g., Watts, Druzhby) has a thick bed of marine sediment extending to the bottom of the recovered sequence. These lakes have sills below 8.0 m. A second class (Anderson and Ace Lakes) have marine sediments underlain by an older lacustrine sequence and till. Both these lakes have sills between 8 and 9 m. A third class of lakes, with sills above 13.5 m contain continuous sequences of lacustrine sediment underlain by till.

The presence of marine sediments in all cores from lakes with sills below ~9 m indicates that sea-level has been at least 9 m above its present level at some time in the period represented in the cores. Similarly, the absence of any marine sediment in cores from lakes with sills higher than 13.5 m indicates that sea-level has not stood this high in the period represented.

In the cores from Ace and Anderson Lakes, the lacustrine–marine–lacustrine sedimentary succession indicates that the basins were occupied by freshwater lakes before invasion by rising sea-level, and were isolated again when relative sea-level fell (see Fig. 3). The oscillation in relative sea-level results from the combination of postglacial ''eustatic'' sea-level rise (ocean volume increase), and the isostatic response (crustal rebound) to changing ice and water loads (Fig. 5).

The nature of the transition from marine to lacustrine sedimentation varies among the lakes, reflecting gradual isolation from the sea (tidal range is 1.75 m), and the subsequent influxes of meltwater and wind-blown salt into their catchments. Where a sharp boundary is absent, the transition is taken as the first occurrence of layered algal material.

5.3. Radiocarbon dates

Radiocarbon dates obtained from the cores from the Vestfold Hills lakes are presented in Table 6. Samples labelled ''AMS'' were measured by accelerator mass spectrometry. Samples were chosen to date the marine–lacustrine and lacustrine–marine

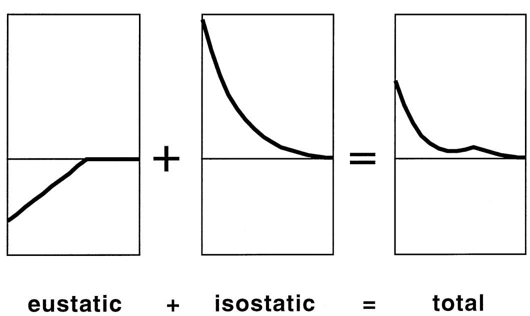

Fig. 5. Sea-level oscillations can be the result of interaction between several influences. Here, the decreasing rates of eustatic sea-level rise and isostatic rebound cause an oscillation in a generally falling sea-level history.

transitions, as well as the onset of organic sedimentation. The latter is not directly relevant to the relative sea-level record, but is of interest when considering the regional history of the ice sheet.

The simplest transition age to estimate is that of the lower, lacustrine–marine, transition, since the freshwater material below the transition is uncontaminated by marine carbon and hence does not require a reservoir correction. Two or more age determinations made from this section allow the sedimentation rate to be estimated, and the age of the transition calculated by extrapolation.

The age of the upper, marine–lacustrine transition can be estimated by extrapolating the age of a dated lacustrine sample downwards to the transition. Several properties of the core must be assumed: sedimentation within the upper section must have been at a constant rate between dated samples, and without significant breaks. Compaction must be uniform, and material must not have been lost from the top of the section during coring if the top of the core is assigned a zero age to determine the sedimentation rate. Cores were taken from the deepest part of lake basins, where possible, to maximise the chance of constant sedimentation, and the water depth was sounded before each core was taken, in order to ensure that the uppermost sediment was sampled.

Because a length of core must be sampled in order to provide enough carbon for dating, some extrapolation is required even if a sample was taken adjacent to the transition. The age obtained is assigned here to the mid-point of the dated interval. In this study, core-lengths required for dating varied from ~3–6 cm of organic-rich lacustrine sediment to 10–15 cm of marine sediment and ~20 cm of organic-poor till. There is a trade-off between errors when choosing the sample size, as decreasing the length of core dated reduces the errors due to extrapolation, but increases the uncertainty of the radiocarbon measurement.

Freshwater lakes that maintain a young and well-mixed carbon pool in equilibrium with atmospheric CO_2 do not require a reservoir correction. Radiocarbon ages of modern freshwater algae from several lakes which are immediately adjacent to the ice sheet in the Vestfold Hills (Table 7) indicate near-equilibrium conditions, and no reservoir correction has been applied to ages of freshwater sediment. However, the lacustrine organisms immediately above the marine–lacustrine transition may have grown from a carbon pool which was largely marine in origin. Ages from this sediment may therefore require a reservoir correction of up to 1300 yr [23], although this should decrease progressively above the transi-

Table 6
Conventional and AMS radiocarbon ages obtained from cores from lakes in the Vestfold Hills

Lake	ANU No.	Age (^{14}C yr BP)	Depth (cm)	Description[a]
Watts	AMS-334	3250 ± 340	13–14	L, above m–l transition
	8391	4540 ± 200	10–14	L, above m–l transition
	8146	4890 ± 300	254–269	M, base of core
Druzhby	8147	5240 ± 200	25–30	L, above m–l transition
	8148	7490 ± 230	213–233	M, base of core
Anderson	8446	6730 ± 200	38–43	at m–l transition
	8349	7110 ± 210	103–107	L, below l–m transition
	8145	8450 ± 210	107–111	L, lowest organic-rich
Ace	6414[b]	5310 ± 90	20–35	L, above m–l transition
	6419[b]	6110 ± 180	35–75	M, below l–m transition
	8263	6740 ± 230	135–140	L, below l–m transition
	8166	8380 ± 110	160–175	L, below l–m transition

[a] M = marine sediment; L = lacustrine sediment; T = ‘‘till’’; m–l = marine → lacustrine transition; l–m = lacustrine → marine transition.
[b] Dates from Bird et al. [16].

Table 7
Radiocarbon assays from modern algae in three lakes adjacent to the Antarctic ice sheet in the Vestfold Hills

Sample	^{14}C assay (% modern)	ANU number
Dec 1991 atmosphere	113 ± 0.5	–
Pauk Lake	112.8 ± 2.2	8156
Lake Bisernoye	113.4 ± 2.5	8164
Lake Druzhby	116.9 ± 0.9	8169

The results indicate that old CO_2 from the ice sheet has no effect on the ^{14}C content of the lake. The atmospheric radiocarbon assay is from Cape Grim, Tasmania [32].

tion as the marine carbon reservoir became exhausted and the lake achieved equilibrium with the atmosphere. In meromictic lakes (lakes with a basal layer which does not mix with the upper part) the influence of marine carbon is expected to be significant for a longer period of time after isolation than if the lake is fully mixed. This is presently the case for several lakes from which cores were taken — Abraxas, Ace, Anderson, Clear, McCallum and Pendant Lakes — and may also have applied at the time of lake isolation.

By applying the reservoir correction to the marine radiocarbon ages and extrapolating along the cores, maximum and minimum ages for the lacustrine–marine and marine–lacustrine transitions in lakes of the Vestfold Hills have been estimated, and these are presented in Table 8.

Table 8
Ages of marine–lacustrine transitions in lakes in the Vestfold Hills, including the reservoir correction and measurement errors

Lake	Sill height (m)	Transition[a]	Age range[b] (corr. ^{14}C yr BP)
Organic[c]	3.5	$m \rightarrow l$ (M)	3040–3890
		$m \rightarrow l$ (L)	2730–3060
Watts	4.3	$m \rightarrow l$ (L)	3430–3830
Highway[c]	7.7	$m \rightarrow l$ (M)	4320–5190
		$m \rightarrow l$ (L)	4280–4520
Druzhby	8.0	$m \rightarrow l$ (L)	5500–5940
Anderson	8.4	$l \rightarrow m$ (L)	6020–6860
		$m \rightarrow l$ (M)	5090–5920
Ace	8.8	$l \rightarrow m$ (L)	6350–6860
		$m \rightarrow l$ (M)	4140–4960
		$m \rightarrow l$ (L)	5000–6870

[a] M = estimated from ages of marine sediment; L = stimated from ages of lacustrine sediment; $l \rightarrow m$ = lacustrine to marine transition; $m \rightarrow l$ = marine to lacustrine transition.
[b] Age range includes counting error, uncertaintly in the marine reservoir correction, and the extrapolation of the age to the sediment transition.
[c] Dates from Bird et al. [16].

5.4. Relative sea-level change

The relative sea-level history of the Vestfold Hills can be obtained by plotting the ages of lacustrine–marine and marine–lacustrine transitions in lake cores against the elevation of the sill connecting each lake to the sea. The sea-level curve should pass through each age/height point, or within the error limits imposed by uncertainty in measurement of the sill height and in radiocarbon dating. These uncertainties are included in Fig. 6.

An additional source of uncertainty, which cannot be estimated easily, is the exact timing of the marine–lacustrine transition observed in the sediment in relation to the raising of the lake's sill above mean sea-level. Maximum peak-to-peak tidal range at the Vestfold Hills is presently ~1.75 m (Australian National Tidal Facility observations), so the sill connecting a basin to the sea could lie within the tidal range for more than 1000 yr. The effective transition from marine to lacustrine sedimentation in the lakes probably does not correspond to the same point in the tidal range at all sites, but depends on the freshwater input to the lake. For example, a lake with significant freshwater inflow may maintain sufficiently low salinity to make the transition from recognisably marine to lacustrine sedimentation occur before the basin is completely isolated from the sea; a basin with low freshwater inflow, on the other hand, will become less saline only after the highest tides cease to overflow the sill. The largest freshwater drainage in the Vestfold Hills currently enters Ellis Fjord via Lake Druzhby, and also flowed through Watts Lake at the time it was isolated from the sea [24]. These lakes may therefore have been isolated relatively early, and we can anticipate that

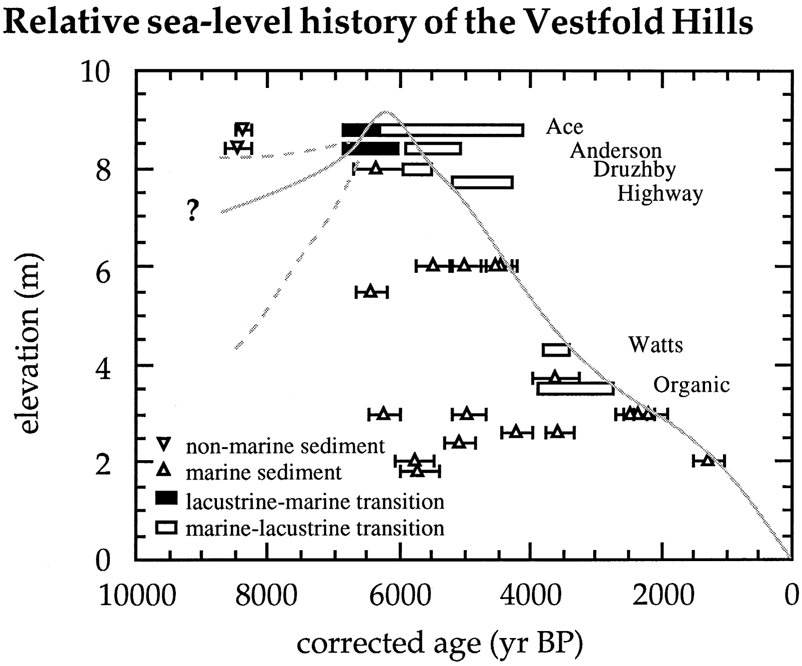

Fig. 6. The relative sea-level history of the Vestfold Hills, based on lake isolation observations. Marine sediment ages from Zhang and Peterson [18] and Adamson and Pickard [23].

the dated sediment transitions will appear older than the trend from other lakes.

Using the principles above, we have produced a relative sea-level history for the Vestfold Hills for the last 7000 yr based on both the dated lake sediment transitions and published ages of raised marine sediment (Fig. 6). In this record, the existence of a sea-level maximum during the Holocene is demonstrated. The marine–lacustrine transition ages from the higher lakes show a well-defined sea-level highstand at ~6200 corr. ^{14}C yr BP. The absolute constraints on the elevation of this highstand are only that it was higher than 8.8 m (Ace Lake) and lower than 13.5 m (Lake Abraxas), but the shape of the sea-level curve suggests that the maximum was probably 9–9.5 m a.s.l. Before ~7 ka, the relative sea-level curve is only constrained by limiting observations: basal ages from Anderson and Ace Lakes show that sea-level was below ~8.5 m for the period ~10 ka–7 ka. There is currently no evidence that sea-level at the Vestfold Hills ever stood higher than ~9.5 m a.s.l. in the time since deglaciation.

If the basal portion of the Ace Lake core is in fact marine or inter-tidal (see Section 5.1), the interpreted sea-level curve would fall initially, isolating Ace and Anderson Lakes, before the rise and fall shown in Fig. 6. This fall in relative sea-level at a time of rapid eustatic sea-level rise would indicate that glacial rebound rates at that time were high, indicating the removal of more ice than is implied by the sea-level interpretation adopted here.

In the last 4 kyr, the minimum transition ages for Watts and Organic Lakes indicate that some of the in-situ *Laternula elliptica* samples which are currently 2–3 m a.s.l. (Table 2) grew very close to sea-level. This is at odds with modern observations, which suggest that *Laternula* lives below the zone of ice abrasion, deeper than 3–5 m [33,34]. Apart from this, the sea-level record derived from lake isolations is consistent with all published constraints (Table 2).

6. Discussion

In the absence of vertical tectonic movements, sea-level change at the Antarctic margin over thousands of years is the sum of:

(1) a eustatic component, which is essentially a measure of global ice volume, and is a function of time only, and

(2) an isostatic component, responding to the movements of ice and water masses on the surface of the Earth. This component varies with time and position, depending on a site's proximity to the changing water and ice loads.

Unloading due to the retreat of a significantly thickened late Pleistocene ice sheet would result in a sea-level curve dominated by the local isostatic component. In contrast, if the ice thickness has remained constant, the sea-level curve would be dominated by a eustatic rise, followed by a small late Holocene fall due to the increased load on the sea-floor. Such a fall is observed at tectonically stable locations far from any former ice sheet, such as Queensland, Australia, where a highstand of ~1 m is observed 6000 yr ago [35,36] The sea-level fall in the Vestfold Hills, ~9 m in 6000 yr, is much greater than this ''background'' change, indicating that there has been a significant change in the thickness of the Antarctic ice sheet.

6.1. Comparison with numerical models

Since the sea-level changes due to changing ice and water loads can be described and calculated numerically [37,38], we can use the observed isostatic component of sea-level change to constrain the history of the ice sheet. However, sea-level observations from a single site cannot lead to a unique ice-sheet reconstruction, since the observed crustal rebound could be due to the removal of a large thickness of ice far away, or a smaller amount locally. Observations from a number of sites around Antarctica are necessary to resolve this issue, and this work will be presented in another paper. Nevertheless, using simplified models of the ice sheet, numerical predictions of the rebound do indicate the likely ranges of regional ice-sheet thinning and retreat.

The predicted rebound is influenced by two groups of input parameters: the rheology of the Earth, and the ice load history. The rheological models used here are of a radially-symmetric Earth, with an elastic lithosphere of thickness H_{lith} overlying a visco-elastic two-layered mantle characterised by upper- and lower-mantle viscosities η_{um} and η_{lm}, respectively. The upper–lower mantle boundary is at 670 km depth, and the core is considered to be fluid. Such rheological models have been found adequate to describe sea-level change in other parts of the world, and more complex models are not justified by the sea-level data available in the Antarctic region. This study uses a range of model parameters, with H_{lith} in the range 50–100 km, η_{um} 10^{20}–10^{21} Pa s, and η_{lm} 10^{21}–2×10^{22} Pa s, which encompass values found for the other regions studied [39–41]. Following the studies on which this work is based [38,39], the uncalibrated radiocarbon timescale is used.

To simulate the ice-sheet margin in the Vestfold Hills region, a circular ice-sheet model was used, whose radius (1100 km) and thickness (3700 m) were chosen to simulate the present ice-sheet profile over the region. Melting scenarios were considered in which ice removal takes place by central thinning and margin retreat, or by margin retreat alone. The distribution of ice removed is similar for the two models, with the greatest thinning of the ice sheet occurring near the coast. The shapes of the melting curve for this regional ice-sheet model and of the global eustatic sea-level curve were based on melting models ANT3 and ARC3 [1], respectively.

Calculations of isostatic rebound were performed for a range of values of ice-sheet retreat and thinning, and using the range of Earth rheology models described above. The sea-level predictions of these models were quantitatively compared with the observed sea-level history, to determine the ice-sheet history. Minimum variances between predicted and observed sea-levels were achieved for ice models with 30–40 km of margin retreat and 600–700 m thinning of the ice sheet in the vicinity if the Vestfold Hills. These values are generally insensitive to the rheological model used, although a high-viscosity upper mantle (10^{21} Pa s) is preferred. In the predicted sea-level curves from these ice models (Fig. 7) the maximum sea-level highstand occurs exactly at 6000 yr BP, ~200 yr later than in the observed sea-level curve. This is consequence of the global eustatic curve used in the prediction, which has an abrupt decrease in gradient at this time. Since the crest of the highstand corresponds to the time when the rate of eustatic sea-level rise is of the same magnitude as the rate of isostatic rebound, the use of

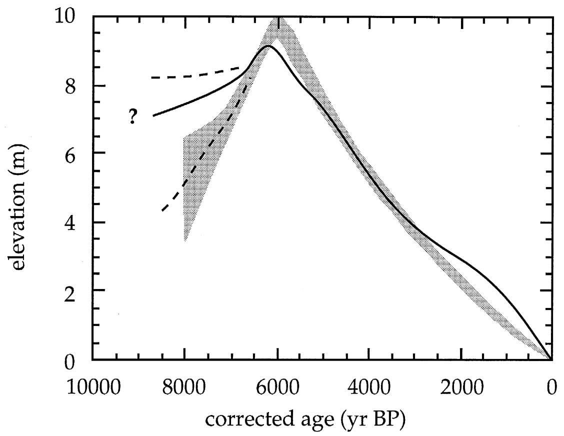

Fig. 7. The range of sea-level predictions (*shaded grey*) produced by the ice-sheet histories adopted in this paper. The predictions closely match the observed sea-level change from Fig. 6 (*dark line*), and suggest that sea-levels before 7000 yr BP were in the lower part of the area constrained by the observations.

a more realistic eustatic curve, with a gradual decrease in the rate of rise around 6000 yr BP would shift the time of the maximum sea-level earlier, in agreement with the observations.

6.2. Comparison with other estimates

There are few published estimates of the former ice cover of the Vestfold Hills region. On land, the highest exposed rock at 158 m a.s.l. is glacially striated, but the age of the last ice cover is unknown. Colhoun et al. [5] estimated that the former ice thickness was 400–480 m, but this was based on a poorly-constrained sea-level record, assuming that the highest raised beach was formed at the time of deglaciation. The new record presented in this paper shows that this was not the case. Regarding the former position of the ice-sheet margin, sediment cores offshore from the Vestfold Hills at ODP Site 740 [42] and the Four Ladies Bank [43] indicate that the Amery Ice Sheet has extended to the continental shelf edge, far beyond the 30–40 km of retreat indicated by the regional-scale ice-sheet modelling, but there are no time constraints on this. A ''discontinuous line of moraines'' on Broad Peninsula, ~ 15 km from the present ice margin, cited by Pickard [44] as a possible former ice margin position is also undated. The estimates for ice-sheet retreat and thinning presented in this paper, however, represent regional averages due to the lithosphere's damping effect on isostatic rebound, and do not necessarily have to coincide with the ice retreat history of the Vestfold Hills itself.

7. Conclusions

(1) A record of Holocene sea-level change in the Vestfold Hills is preserved in low-lying lakes, which have been invaded by, and isolated from, the sea. Sea-level was below ~ 8.5 m above a.s.l. for the period ~ 10 ka–7 ka, rose to a highstand of 9–9.5 m a.s.l. around 6.2 ka, and fell steadily from then until the present.

(2) A sea-level fall of ~ 1 m in the last 6000 yr is expected, due to the isostatic response of the Earth to the large eustatic sea-level rise since the LGM. The observed sea-level fall at the Vestfold Hills is larger than this water-load component. Since the region is believed to be tectonically stable, this implies that isostatic rebound has occurred due to thinning of the Antarctic Ice Sheet.

(3) Adopting a simple model for the East Antarctic ice sheet in the region of the Vestfold Hills, numerical modelling of the Earth's isostatic response suggests 30–40 km retreat of the ice-sheet margin and 600–700 m thinning since the last glacial maximum.

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