Polar Geosci, 11, 249–259, 1998

HOLOCENE LAKE SEDIMENTS AND SEA-LEVEL CHANGE AT MT. RIISER-LARSEN

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Abstract: At sites where glacio-isostatic rebound has occurred, the record of sea-level change can be used to infer the former ice thickness and its melting history At Mt Riiser-Larsen, former sea-levels higher than present are indicated by the presence of raised beach deposits and ancient sediments deposited in brackish water Sediment cores from three ice-marginal lakes contained only fresh-water sediment, and a basal radiocarbon age shows that there has been no marine incursion in the last ~10000 years, limiting sea-level during that time to lower than 18 4 m above present A well-defined marine limit is present 15 m a s l , which will be dated using radiocarbon ages on stranded seals and abandoned penguin rookeries We anticipate an age of ~6 ka, because of the interaction between eustatic and isostatic components of sea-level change

key words sea-level, lake sediment, raised beach, Holocene

1. Introduction

Late Quaternary sea-level change is a combination of three contributions:
1) global eustatic sea-level change caused by the growth or melting of ice sheets,
2) the isostatic adjustment of the land surface in response to regional changes in ice and water distribution, and
3) local vertical tectonic movements.

East Antarctica has a tectonically stable rifted continental margin, so sea-level records from here are useful for studying the interaction between eustatic and isostatic sea-level contributions. A specific aim of these studies is to use the isostatic component of sea-level change to constrain the regional ice sheet history. Sea-level has fallen throughout the late Holocene at all coastal sites in East Antarctica, with highstands ranging from 9 m to more than 30 m a.s.l. (ZWARTZ *et al.,* 1997). The geomorphological field party of the 38th Japanese Antarctic Research Expedition (JARE-38) investigated several potential records of sea-level change at Mt. Riiser-Larsen: lake sediments, raised beaches, abandoned penguin rookeries, and mummified seals. These

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observations are presented here and their constraints on sea-level change discussed.

Mt Riiser-Larsen forms the largest ice-free region in Enderby Land, East Antarctica. It consists of a ridge running 13 km east-west along the northern side of Adams Fjord, in Amundsen Bay, at 50°40′E and 66°45′S (Fig 1) The south side of the ridge falls steeply to the fjord, while on the north side three large ice-marginal lakes are contained between the ice sheet and the mountain, separated by spurs extending north from the main ridge. Bedrock crops out over most of the steep terrain, but the western half of the region includes some large areas of glacial till. These till units have been identified as deposits of both the continental ice sheet to the north, and of alpine glaciers on Mt. Riiser-Larsen itself (Yoshida and Moriwaki, 1983; Aniya, 1989, Hayashi, 1990), and indicate several stages in the glacial history of the region: early formation of alpine landforms, expansion and retreat of the continental ice sheet; and subsequent growth and decay of local alpine glaciers. The ages of these events, however, are a matter of speculation Various attempts are being made to date the glacial history directly, using organic and inorganic deposits (Miura *et al.*, 1997a, b, Takada *et al.*, 1997; Zwartz and Stone, 1997) Establishing the record of sea-level change at Mt Riiser-Larsen is an attempt to date the glacial history indirectly, by inferring the amount and timing of ice melting required to cause the observed isostatic rebound

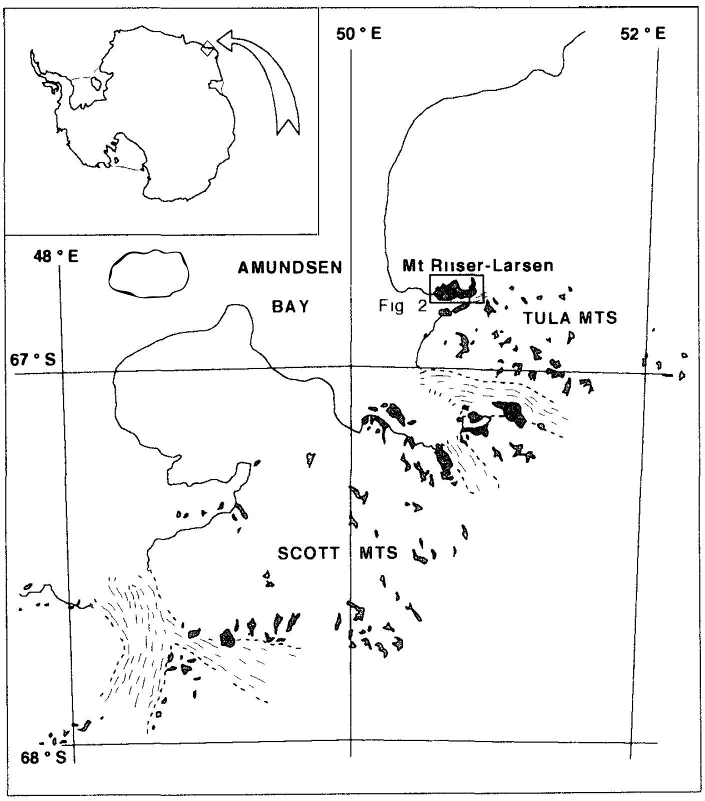

Fig 1 Location map of Mt Riiser-Larsen, in Enderby Land, East Antarctica

2. Lake Sediments

2.1. Sea-level change from lake sediment cores

In regions where sea-level has fallen, sediments in low-lying lakes may preserve a precise record of sea-level change. During a sea-level highstand, marine basins close to shore accumulate marine sediment. As sea-level falls, basins with submarine sills are progressively isolated, and, if they have fresh water input, are flushed and begin to accumulate fresh water 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.

This method has several advantages compared to the dating of raised beach deposits. First, the sediment transitions can be dated more precisely than marine deposits, because fresh-water sediments can be analysed, avoiding the need to apply a reservoir correction with its associated uncertainty (ZWARTZ *et al.,* 1998). Second, the precision of the sea-level measurement from each sediment transition depends mainly on the accuracy with which one can measure the elevation of the lake's outlet sill. This is approximately 0.1–0.5 m, which is less than the uncertainty in relating the elevation of raised beach deposits to sea-level at the time they formed. Third, because the sediment transition unambiguously indicates either a lake isolation (marine to fresh) or an inundation (fresh to marine), the record includes information on whether sea-level was falling or rising, respectively.

This method has been used extensively in Fennoscandia to measure the sea-level change due to glacial rebound there (*e.g.* HAFSTEN, 1983; ANUNDSEN, 1985; SVENDSEN and MANGERUD, 1987), and also at some Antarctic sites (BRONGE, 1989; MAUSBACHER *et al.,* 1989; BIRD *et al.,* 1991; ZWARTZ *et al.,* 1998).

2.2. Lakes at Mt. Riiser-Larsen

At Mt. Riiser-Larsen, there are five ice-marginal lakes and a number of smaller ponds in rock basins or depressions in the surface of the till. The western three ice-marginal lakes were studied: Richardson Lake, ~4 km long and 18.4 m above sea-level; and Lakes Y and X at 4.5 and 2.6 m a.s.l. respectively. All lake basins extend below sea-level, but are filled entirely with fresh water. Lake X, which is less than 1 km from the sea, has a diurnal tide, presumably pumped by the adjacent glacier. Richardson Lake overflows its basin through a gorge at its western end, into Lake Y. This lake has a rock sill to the south at 23 m a.s.l., but is presently drained under the ice to the west. Depending on the position of the ice, therefore, Richardson Lake would be inundated by a sea-level rise of between 18.4 and 23 m, and Lake Y by a rise of between 4.5 and 23 m. Lake X is separated from the sea by a moraine ridge approximately 17 m a.s.l., and would be inundated by a sea-level rise higher than this. However, since all three lakes extend below sea-level, the position of the ice edge may also control marine incursion.

The remaining two ice-marginal lakes are covered by permanent ice and snow, and are not of interest for sea-level studies, as they lie at approximately 210 m and 300 m a.s.l. (N.B. most elevations are taken from a topographic map produced at NIPR from aerial photographs in 1996. Elevations on this map are approximately 75% of those on the 1989 version of the same map. the summit of Mt Riiser-Larsen has been revised from 1153 m to 868 m) All the ice-marginal lakes are permanently covered with ice approx 3 m thick. The stability of the ice cover is demonstrated by the remains of a Russian aircraft wrecked on Richardson lake in 1968, still at the ice surface near the eastern end of the lake. Surface melting and wind action keep the lake surfaces level and free of snow in summer. The southwestern basin of Richardson Lake is not in contact with the ice sheet, and became ice-free during February 1997.

2.3. Lake sediment cores

Several sediment cores were collected from lakes at Mt Riiser-Larsen, using a portable impact corer at four locations: the main basin of Richardson Lake; the southwest basin of Richardson Lake, Lake Y, and Lake X (Fig 2) The stratigraphy of cores from these sites is presented in Table 1

The cores from Richardson Lake contained only organic fresh-water sediment The black algal mud in the core from the main basin of Richardson Lake (Richardson-1) indicates the reducing environment present on the lake bottom. The ice cover on the lake, which prevents mixing and oxidation of the water, was present continuously for the duration of time represented by this core The annual open water in the southwest basin is reflected in the more oxidised sediment there (Richardson-4). The black unoxidised sediment in the lower part of the core may represent a period of colder climate, when the basin did not become ice-free in summer. The present abundance of light and oxygen, compared to the main basin, probably also results in a higher biogenic sedimentation rate. The basal sediment from the core yielded an uncorrected conventional radiocarbon age of 9870±120 yr BP (ANU-10713) It is likely, based on analyses from other Antarctic lakes (ZWARTZ *et al.,* 1998), that no reservoir correction will be necessary This result indicates that relative sea-level at Mt. Riiser-Larsen has been lower than 18.4 m for the last ~10 ka.

Sediment cores from the two lower lakes contained a thin layer of fresh-water algal

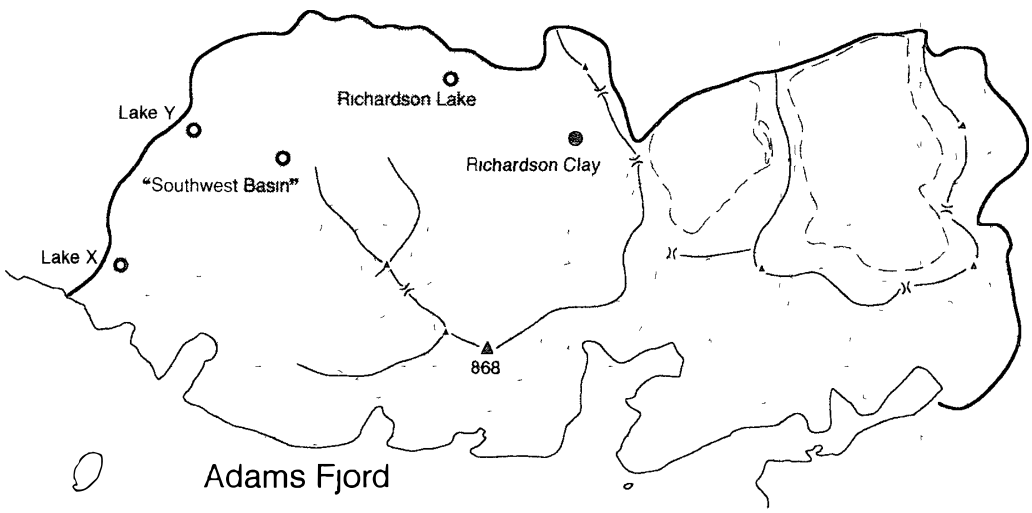

Fig 2 Map of Mt Riiser-Larsen, showing the locations of lake sediment cores collected by JARE-38 and the outcrop of the Richardson Clay Topographic contours are at 100 m intervals, and the grid square is 1 km

Table 1 Description of representative lake sediment cores from Mt. Riiser-Larsen Depths are in cm

Richardson-1 (water depth = 45 m)	
0–140	Black flaky algal mud Turns dark green on oxidation Becomes denser and contains less water towards the base Some sand/grit at base.
Richardson-4 (water depth = 57 m)	
0–125	Flaky/crumbly layered dark green algal clay No visible macroscopic material Slight darkening of colour downwards
	-break between core barrels-
125–256	Similar to top section, with lower water content Below 135 cm, interior of core is black, but texture is the same Uncorrected radiocarbon age at base of core 9870 ± 120 yr BP (ANU-10713)
Y-2 (water depth = 25 m)	
0–1	Green/brown loose flaky algal sediment
1–2	Black layer, loose flaky texture as above
2–4	Pale grey layer, same texture as above
4–22	Same as 0–1 cm Rusty coloured layer at 8–10 cm Crumbly texture, some clay
	-sharp contact-
22–47	Crumbly grey layered clay Layers less cohesive, more clay-rich than in overlying unit Becoming more cohesive and denser downwards No visible macroscopic material
47–51	Black and olive-green weakly-layered mud Flaking surfaces oxidise brown
51–56	Massive olive mud and fine sand
	-gradational contact-
56–64	Diffusely banded black and olive green mud and very fine sand
	-gradational contact-
64–72	Massive greenish-black very fine sandy mud
72–86	Black sandy and gritty mud, becoming coarser downwards Blue quartz grain > 5 mm ϕ at 75 cm Pebble 20 mm ϕ at 82 cm
X-1 (water depth = 26 m)	
0–12	Firm gelatinous pale brown very fine algal sediment Well bedded Prominent orange layer at 7 cm 30 mm ϕ pebble at 3 cm
	-sharp contact-
12–20	Pale grey gritty silt, grading to medium-grained, poorly-sorted sand at base
	-gradational contact-
20–29	Muddy sand and grit Angular to sub-rounded clasts, mostly lithic fragments
	-sharp contact, top of repeated section-
29–36	Same as 0–12, with less bedding detail preserved
36–42	Same as 12–17 cm
	-sharp contact, top of repeated section-
42–47	Same as 29–36 cm

sediment overlying inorganic reworked glacial till. Penetration of the corer was limited by this coarse sandy gravel material. No marine sediment was found. Since these lakes lie below the marine limit observed from raised beach deposits (see Section 3.1 below), this result indicates that the higher sea-levels are older than these sediments.

However, radiocarbon ages have not yet been obtained. If the adjacent glacier has advanced and retreated during the Holocene, depositing the till layer at the base of the cores, it is possible that marine sediment underlies the till layer

2.4. *The Richardson Clay*

At the east end of Richardson Lake, the thick till deposits are incised by an ephemeral stream which drains a higher ice-marginal lake into Richardson Lake In the wall of the channel, a varved lake deposit is exposed, the Richardson Clay (HAYASHI, 1990) The clay contains moss and diatom remains similar to those found in brackish and marine deposits elsewhere in Antarctica (AKIYAMA *et al.*, 1990) The presence of pyrite crystals also indicates a brackish environment, and the presence of sea birds such as penguins is indicated by vivianite, an iron phosphate This evidence indicates that the lake was either connected to the sea, or close enough to receive airborne salt and the runoff from coastal penguin rookeries This is not the case for Richardson Lake at present, so a higher sea-level is implied. HAYASHI (1990) reported that the deposit lies at an elevation of approx. 50 m a s.l , but using the revised topographic map an elevation of ~40 5 m a s.l was measured

Recent radiocarbon and thermoluminescence ages from the Richardson Clay (TAKADA *et al.*, 1998) indicate that it was deposited more than 40000 years ago MAEMOKU *et al.* (1997) reported sea-level higher than present during the period 46–32 ka BP in Lutzow-Holm Bay, 500 km from Mt. Riiser-Larsen, and the Richardson Clay could possibly correlate with this, but it more likely dates from the Last Interglacial period, or earlier

3. Other Sea-level Indicators

3 1 *Raised beaches*

Raised beach sequences were observed in three bays on Adams Fjord at the western end of Mt. Riiser-Larsen (Fig 3). The remainder of the coastline consists of rocky cliffs, where indicators of sea-level change are not preserved. Profiles of the beaches were measured using a staff and level (Fig. 4), and at all sites the marine limit is found at ~15 m a s l

Tide Gauge Bay is the most sheltered location on the coast at Mt. Riiser-Larsen, and the raised beaches here are the best-developed. Below the marine limit, the surface consists of a gently-sloping pavement of rounded and sorted cobbles, with only minor development of frost-sorting features, except where water is present from the melting of snowpatches In contrast, the ground above the marine limit is steeper and consists of angular unsorted material

In Middle Bay, the beach is steeper and coarser, and the presence of a large permanent snowbank means that only a narrow transect of raised beach is exposed As at Tide Gauge Bay, the marine limit is marked by a decrease in sorting and roundness of the surface material, and an increase in frost action

The raised beach sequence in Rookery Bay also consists of rounded and sorted pebbles and cobbles, with several shore-parallel terraces and swales. However, it has been reworked in places by a small stream, penguin rookeries, and long-lived snowbanks

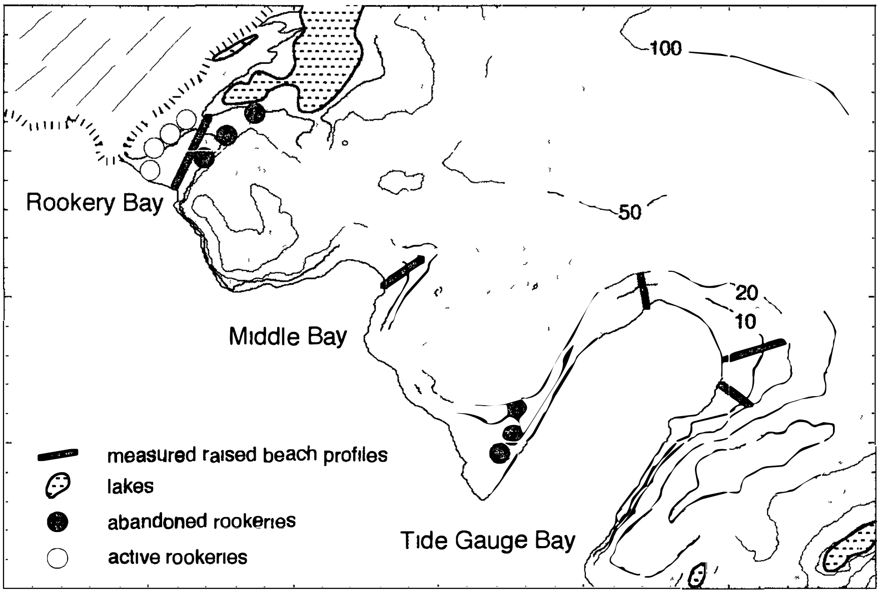

Fig 3 Detail of the coast at the west end of Mt Riiser-Larsen, showing the locations of raised beach profiles and rookeries mentioned in the text The grid square is 1 km Names of geographic features are informal

The marine limit is poorly defined, because the highest beach deposits overlap with marginal moraines from the adjacent glacier, and possibly with beach and outflow deposits of former ice-marginal lakes and ponds.

The beach material at all sites ranged from sand and gravel to large cobbles and boulders. The marine shell, *Laternula elliptica,* which is frequently used to date Antarctic raised beaches, is a burrowing organism which lives in fine sediment, and none were found at any of the sites. However, sediment samples were collected for luminescence dating.

3.2. Penguin rookeries

Abandoned Adélie penguin rookeries below the marine limit were found at 2 locations, in Rookery Bay and on the southwestern side of Tide Gauge Bay (Fig. 3). The rookery sites are evident as mounds of ~20 mm diameter pebbles used by the penguins for building their nests. The mounds are up to 10 m long and 2 m high, and the remains of individual nests are no longer discernable. The surface material is clean gravel, winnowed by wind and snowmelt, but from a shallow depth the rookeries contain remains of guano and eggshell fragments. These were sampled for radiocarbon analysis, which will provide a minimum age for the fall of sea-level below that point.

3.3. Mummified seals

Three mummified seals were found below the marine limit in Tide Gauge Bay. Since the sites must have been above sea-level when the seals arrived, the age of the seal provides a constraint on the sea-level curve. Samples of skin from seals at 6.4 m and 12.8 m a.s.l. yeilded radiocarbon ages of 1140±60 (ANU-10954) and 1080±70 yr BP (ANU-10956), respectively. Corrected for the marine reservoir effect, these ages are

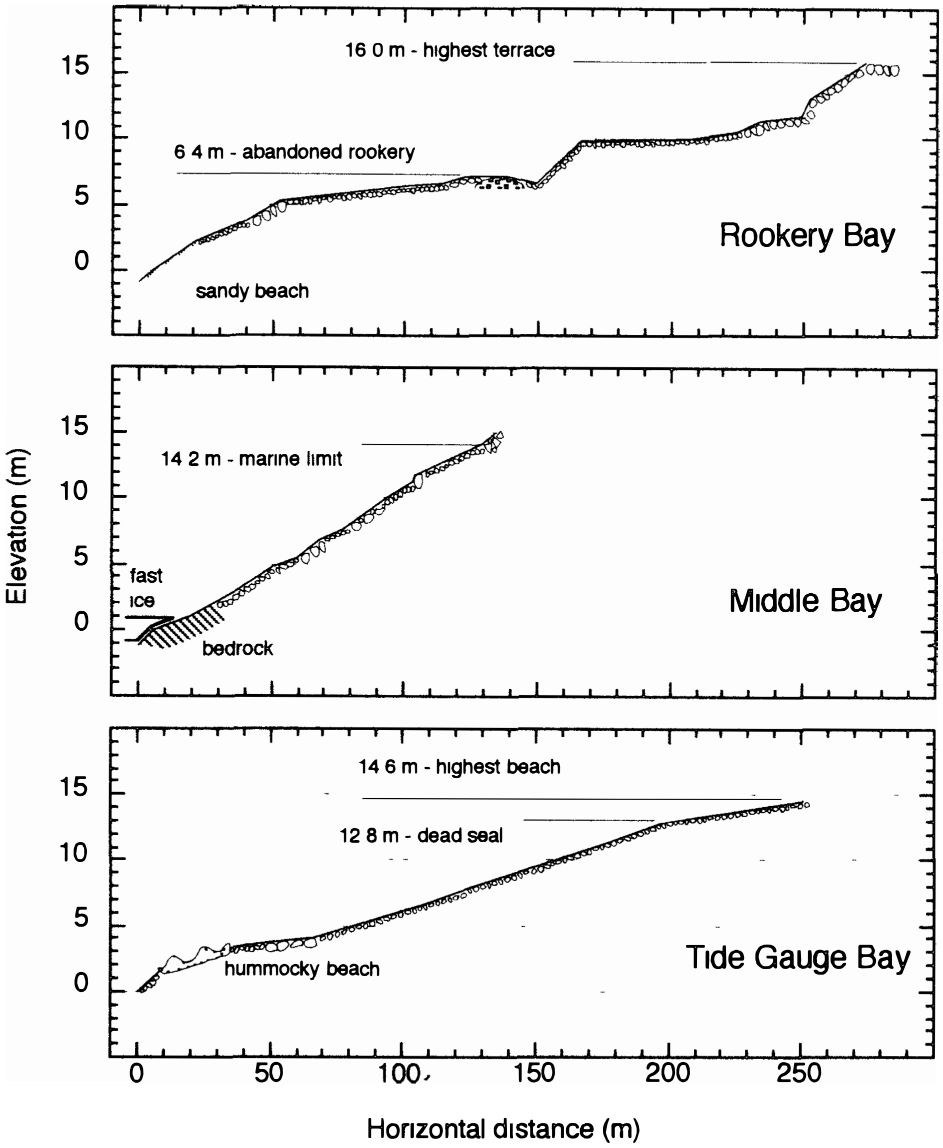

Fıg 4 Surveyed profiles of raısed beaches at Rookery Bay, Mıddle Bay, and Tıde Gauge Bay Elevatıons are ın metres above hıgh tıde The profile from Tıde Gauge Bay ıs the mıddle locatıon ındıcated on Fıg 3

roughly modern, so do not usefully constraın the sea-level curve.

4. Discussion and Conclusions

As at other coastal East Antarctıc sıtes, the presence of raısed beaches at Mt Rııser-Larsen shows that sea-level was formerly hıgher. At present, the only precıse sea-level constraınt obtaıned from thıs work ıs from the radıocarbon date from the core Rıchardson-4, whıch ındıcates that relatıve sea-level at Mt. Rııser-Larsen has been lower than 18 4 m, or possıbly 23 m, for the last ~10 ka (Fig. 5). Radıocarbon ages of mummıfied seals on beaches below the marıne lımıt are too young to gıve useful constraınts of the sea-level curve Further lımıtıng constraınts wıll come from the age

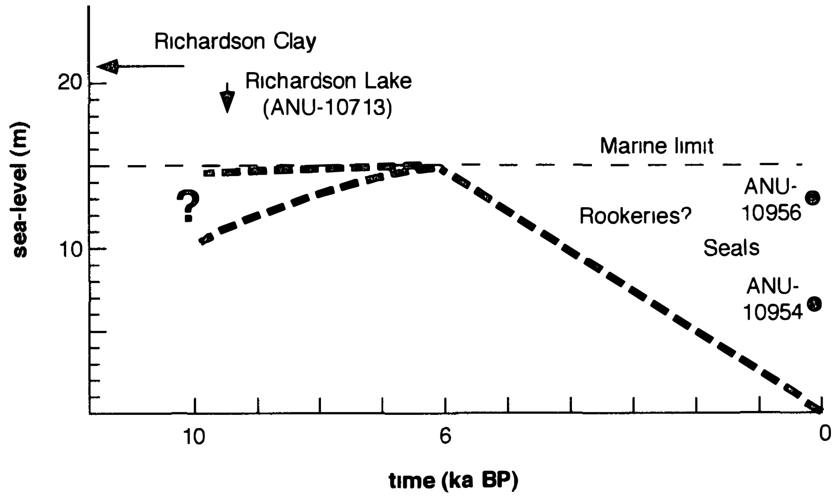

Fig 5. Sea-level history at Mt Riiser-Larsen.

of organic material from the base of cores Y-2 and X-1, and from the abandoned rookeries.

The presence of a well-defined marine limit at 15 m suggests two possibilities. Either sea-level was falling continuously from higher than this, and the marine limit represents the time at which the coast became ice-free and able to form beaches, as occurred in the McMurdo Sound region (STUIVER *et al.*, 1981), or sea-level rose to a maximum of 15 m above present and then fell again, as at the Vestfold Hills (ZWARTZ *et al.*, 1998). The crest of the sea-level highstand corresponds to the time when the rate of eustatic sea-level rise is the same as the rate of isostatic rebound. Since the rate of eustatic rise decreased rapidly around 6000 years ago, the sea-level maximum commonly occurs around this time, both in coastal Antarctic locations and at sites far from former ice sheets. We therefore predict that the marine limit at Mt. Riiser-Larsen will be dated to around 6000 yr BP.

Because the sea-level curve from Mt. Riiser-Larsen has not been fully refined, we have not yet performed any isostatic calculations to estimate the former ice thickness. However, the situation is similar to that at Skarvsnes, in Lutzow-Holm Bay (69° 30′S, 39° 35′E), where a Holocene sea-level highstand of 16 m is observed (YOSHIDA and MORIWAKI, 1979). The amount of ice which must be removed to cause the observed isostatic rebound depends on several poorly-known factors, including the rheological properties of the earth and the timing of ice removal. Allowing these to vary within reasonable bounds, ZWARTZ *et al.* (1997) obtained a best fit to the Skarvsnes sea-level data with ice thinning of 850–950 m and margin retreat of 60–80 km. Alternatively, using rheological parameters derived from Australian sea-level data, larger values of 1014 m of thinning and 91 km of retreat were obtained. Field observations from JARE-38 suggest the presence of a glacial trimline, indicating the level of the former ice sheet surface, at an elevation of about 500 m a.s.l. (ZWARTZ and STONE, 1997). Above this level, glacial erratic boulders were not seen, and the bedrock has no glacial polish or striations and is commonly deeply weathered. Rock samples have been collected to date this "trimline" using cosmogenic isotopes. If it is found to represent the last glacial maximum, then this will provide a useful comparison with the results from isostatic modelling. However, the ice thickness estimates 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 at Mt. Riiser-Larsen itself

Acknowledgments

We thank the geological party of JARE-38 for helping make the field work successful and enjoyable, and two reviewers for helpful comments on the manuscript

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(Received March 4, 1998, Revised manuscript accepted July 17, 1998)