Constraints on the Former Antarctic Ice Sheet from Sea-Level Observations and Geodynamic Modelling

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Abstract - Sediment cores from low-lying lakes in the Vestfold Hills, East Antarctica, contain marine sediments, indicating that the lakes were formerly connected to the sea and have subsequently been isolated as sea level fell relative to the land. Radiocarbon dating of transitions between marine and lacustrine sedimentation in these cores, combined with accurate levelling of the lakes' last connection to the sea, indicates that relative sea level in that region rose from about 7.5 m at 8000 years ago to a height of 9 m above present sea level around 6000 years ago, and has fallen steadily since. These results and sea-level observations compiled for other Antarctic sites have been compared with the predictions of numerical glacio-hydro-isostatic calculations for various simplified models of melting at the ice sheet margin. The results indicate that at the Last Glacial Maximum the East Antarctic ice sheet margin at the various sites extended from 25 to 110 km beyond its present position and that 500 - 1100 m of ice thinning occurred at sites now on the coast. If these values are representative of the entire eastern Antarctic margin and no ice volume changes occur within the interior of the ice sheets, then the total East Antarctic contribution to eustatic sea level since the Last Glacial Maximum is about 3 - 5.5 m.

Keywords: sea-level change, Antarctic ice sheet, isostasy, Vestfold Hills

INTRODUCTION

An approach to estimating former ice sheet dimensions that is complementary to geomorphological studies is to model the effects of changes in the ice sheets on sea level. In the absence of vertical tectonic movements, sea-level change over thousands of years can be attributed to the combined effect of the movements of ice and water masses on the surface of the earth and the concomitant gravitational and isostatic responses. These sea-level changes can be described and calculated using the sea-level equation, as formulated in Farrell & Clark (1976) and Nakada & Lambeck (1987):

\[ \Delta Z(\phi, \lambda, t) = \Delta Z_i(t) + \Delta Z_s(\phi, \lambda, t) + \Delta Z_{is}(\phi, \lambda, t) \] (1)

where \( \Delta Z_i \) is the sea-level change relative to its present value, at time \( t \), latitude \( \phi \), and longitude \( \lambda \). The first term on the right hand side of the equation is the eustatic sea level, which is uniform over the whole earth and is only a function of time. Over Quaternary time, the eustatic sea level is essentially a measure of the amount of water stored on land in ice sheets. The remaining two terms are the vertical isostatic responses to the changing loads of ice and water on the surface of the earth. These latter terms depend on the geographic distribution of the loads, and on the rheology of the earth. They include the effects of the gravitational attraction between the ice and water and the deformation of the Earth.

The aim of studies in glacio-hydro-isostasy is to use observations of sea-level change (the left side of equation 1) to constrain the parameters which control the terms on the right-hand side. Previous workers have produced adequate models for the ice sheets of the northern hemisphere for the last 18 000 years and for the rheology of the earth, but few constraints have been placed on the history of the Antarctic ice sheet. This is because there has been little observational evidence for relative sea-level change in the neighbourhood of the Antarctic ice sheet and sea-level change at distant sites is not sensitive to the changes in this ice volume. The goal of the present work is to obtain new estimates for the size and shape of the Antarctic ice margin since the last glacial maximum (LGM), using new sea-level observations from the Antarctic coast.

MEASURING SEA-LEVEL CHANGE

The sea-level record around Antarctica is poorly defined compared to any other continent, for several reasons. Most importantly, only 5% of the coastline consists of rock (Drewry et al., 1982), 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 difficult to interpret and date.

BEACH RIDGES

Ancient beach deposits standing higher than their present-day counterparts are the most common evidence of past sea-level observed in Antarctica. However, because they can be formed by a variety of processes, their relationship to sea level is not precise. Beach ridges are commonly dated using fragments of marine shells...
incorporated in the beach material, which provides a maximum age for the formation of the beach. Better dating control is provided when shells can be found in growth position, such as the burrowing bivalve *Laternula elliptica*, although such deposits may only be found some distance from the associated beach ridge. Due to the seasonal formation of fast ice, *Laternula* usually lives in at least 3 m water depth (Colhoun & Adamson, 1992), so the link between the age of the surrounding sediments and a beach feature some distance away is not always well defined. However, in regions of falling sea level, such as the Antarctic coast during the Late Holocene, shells in growth position provide useful minimum sea-level constraints.

**ISOLATED LAKES**

Another record of changing sea level is found in sediments deposited in lakes near the coast and appropriate methods of analysis have been developed and used extensively in Fennoscandia (e.g. Anundsen, 1985; Svendsen & Mangerud, 1987; Hafsten, 1983), and also at some Antarctic sites (Mausbacher et al., 1989; Bird et al., 1991). During a sea-level highstand, basins close offshore accumulate marine sediment. When sea-level falls, those with submarine sills are cut off and begin to accumulate lacustrine sediments. A lake's sediment may reflect freshwater, saline, or hypersaline conditions, depending on the hydrology of its catchment, but in most cases the lacustrine sediment can be distinguished from marine sediments by its appearance, chemical and stable isotope composition, clastic content and diatom flora (e.g. Bird et al., 1991; Gillieson, 1991). 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 relative sea level has oscillated, crossing the sill of a lake several times, each transgression and isolation will be preserved in the sediment record. 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 connection to the sea, the relationship between the dated transition and the sea level is clear and by dating the fresh-water material at the transition, the need to apply a reservoir correction to the radiocarbon date may be avoided, at least for small, seasonally-ventilated lakes.

**ANTARCTIC SEA-LEVEL RECORDS**

**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. The ice-free region, consisting of long peninsulas, fjords and low hills, covers an area of approximately 20x20 km (Pickard, 1986). Raised beaches and saline lakes are found at low elevations throughout the region,

![Fig. 1 - Location map of the Vestfold Hills, showing locations of lakes cored.](image-url)
indicating a fall in relative sea level during the Holocene. Published estimates of sea-level change at the Vestfold Hills based on radiocarbon dates from emerged marine shells (Zhang & Peterson, 1984; Adamson & Pickard, 1986) showed that the sea stood above its present level for at least the last 8000 years, but provide no indication of an upper limit to the sea-level curve.

In conjunction with the 1991/92 Australian National Antarctic Research Expeditions (ANARE) field program in the Vestfold Hills, sediment cores were recovered from seventeen lakes (Fig. 1) with sill heights ranging from intertidal to ~40 m a.s.l. (Tab. 1). Sill heights were measured by theodolite and electronic distance meter (EDM), 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, heights 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 probably a few tens of centimetres at most and heights are therefore quoted to the nearest 10 cm.

Three main types of sediment are found in the cores from Vestfold Hills lakes:
1 - 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. 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.

2 - Algal lake sediment: The unit found at the top of each core is characterised by green and black laminated algal mats or masses of filamentous moss. This type of sediment is currently accumulating in most of the lakes cored.

3 - Marine sediment: These units are generally homogeneous along their length, consisting of black, watery, diffusely banded organic-rich sediment with a low clastic content. They are identical in character to those found in marine inlets in the Vestfold Hills (Bird et al., 1991), and contain diagnostic marine diatoms (Lewis, 1994). These sediments are interpreted as having been deposited during times of higher relative sea level when some lake basins were occupied by the ocean as bays or fjords connected to the open sea in the same manner as Ellis Fjord is today.

In cores from lakes with sill heights over 9 m, freshwater sediments directly overlie reworked glacial till. Marine sediments were found in all cores from lakes with sills below 9 m a.s.l., placing a limit on the maximum height of postglacial sea level. The marine-lacustrine transitions were identified in these cores, and dated using radiocarbon determinations from sediment on both sides of the transition (Tab. 1). A reservoir correction of 1000-1300 years was used for the marine sediment, based on the radiocarbon "age" of modern bivalves from the Vestfold Hills (Adamson & Pickard, 1986). In two cores, from Lakes Anderson and Ace, fresh-water sediment was found below marine sediment, recording marine incursion of lakes which existed prior to the mid-Holocene highstand. In those lakes with sill heights below 8 m, the full marine sequence was not penetrated by the 3 m core barrel due to rapid sedimentation rates in the marine environment.

These results tightly constrain the relative sea-level history of the Vestfold Hills over the last ~7000 years (Fig. 2). The marine-lacustrine transition ages from the higher lakes show a well-defined sea-level highstand at ~6200 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 history of the Vestfold Hills overlapped that of the northern Ross Sea region, and sea level was similar to that of the present. Thereafter the relative sea-level curve of the Vestfold Hills shows a distinctive progression that is not shared with the region of the sills. Any changes in sill height are probably a few tens of centimetres at most and heights are therefore quoted to the nearest 10 cm.

### Tab. 1 - Ages of marine-lacustrine transitions in lakes in the Vestfold Hills for those lakes containing marine sediments. Radiocarbon ages have been corrected for the reservoir effect.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Sill height (m)</th>
<th>Transition*</th>
<th>Lower bound (yr)</th>
<th>Upper bound (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic*</td>
<td>3.5</td>
<td>m→l (M)</td>
<td>3040</td>
<td>3890</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m→l (L)</td>
<td>2730</td>
<td>3060</td>
</tr>
<tr>
<td>Watts</td>
<td>4.3</td>
<td>m→l (L)</td>
<td>3430</td>
<td>3830</td>
</tr>
<tr>
<td>Highway*</td>
<td>7.7</td>
<td>m→l (M)</td>
<td>4320</td>
<td>5190</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m→l (L)</td>
<td>4280</td>
<td>4520</td>
</tr>
<tr>
<td>Druzhby</td>
<td>8.0</td>
<td>m→l (L)</td>
<td>5500</td>
<td>5940</td>
</tr>
<tr>
<td>Anderson</td>
<td>8.4</td>
<td>l→m (L)</td>
<td>6020</td>
<td>6860</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m→l (M)</td>
<td>5900</td>
<td>920</td>
</tr>
<tr>
<td>Ace</td>
<td>8.8</td>
<td>l→m (L)</td>
<td>6350</td>
<td>6860</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m→l (M)</td>
<td>4140</td>
<td>4960</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m→l (L)</td>
<td>5000</td>
<td>6870</td>
</tr>
</tbody>
</table>

*M = estimated from ages of marine sediment; L = estimated from ages of lacustrine sediment; l→m = lacustrine to marine transition; m→l = marine to lacustrine transition. *Dates from Bird et al. (1991).
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. We see no evidence that sea level ever stood higher than ~9.5 m a.s.l. in the time since deglaciation of the region.

OTHER SITES

Published Holocene sea-level observations have been compiled for five other sites on the margin of the East Antarctic ice sheet (Tab. 2). These are summarised below, and the inferred relative sea-level curves plotted in figure 3.

Emerged marine sediments in McMurdo Sound (77° 30' S, 163° 30' E) provide a lower bound for the sea-level curve for a period of ~1500 years in the mid-Holocene (Stuiver et al., 1981). An algal deposit within a marine delta implies a relative sea level of more than 4 m at some time since 6010±70 14C-yr BP (QL-71). The highest dated shell is from 8.1 m a.s.l. (QL-163), with an age of 5400±60 14C-yr BP (reservoir-corrected age 4480±90 yr BP). This height also represents a lower limit to sea level at that time, although it may have been much higher, depending on the depth at which the shellfish grew. This lower bound is very close to the estimate from a dated elephant seal at Marble Point (Nichols, 1968), and these points constrain the upper limit of the sea-level envelope shown in figure 3. The lower bound of the envelope is obtained by assuming that both the shell sample and the highest bed containing algae were deposited very close to sea level.

At Terra Nova Bay (74° 50' S, 163° 30' E), in northern Victoria Land, Baroni & Orombelli (1991) determined more than 40 radiocarbon ages from marine shells and penguin remains collected from raised beaches, to obtain lower and upper bounds on the relative sea-level curve. As in the Vestfold Hills and McMurdo Sound, the elevation of dated in situ pelecypod shells, including *Laternula elliptica* and *Adamussium colbecki*, provide a lower limit of sea level at that time. Shells collected from the surface of the beaches are thought to be transported, most likely by katabatic winds that transported shell fragments upslope from the surface of the adjacent Hells Gate ice shelf (Baroni, 1990). These reworked samples supply a minimum age for the beach on which they are found. Penguin remains and guano were also sampled and dated, providing an upper limit to the sea-level curve.

In the Windmill Islands (66° 17' S, 110° 32' E) the marine limit is preserved more than 30 m above present sea level in many places, but few age constraints have been obtained. Cameron (1964) obtained an age of 6040±250 14C-yr BP (M-1052) from a beach 23 m a.s.l., and Goodwin (1993) dated a short sediment core from the shore of Hall Pond A, which is bounded by a bedrock depression and lies at an elevation of 28 m (lake surface) in a location where the marine limit is 31.5±1.5 m. As the sill joining this lake to the sea lies at ~29 m (Goodwin, 1993), this basin may contain sediments from a marine incursion. The basal 5 cm of the core, consisting of black gravelly mud, returned a radiocarbon age of 8160±300 14C-yr BP (ANU-6401). The former sea level implied by this sample depends on whether it is marine or fresh-water sediment, and both possibilities are indicated on the curve in figure 3.

In the Bunger Hills (66° 10' S, 101° E), four ages from in situ marine shells (three from Colhoun & Adamson, 1992, and one from Bolshiyanyov et al., 1991) can be used to constrain the relative sea-level curve. The sample elevations are a lower bound for sea level at that time, although the shells in question usually grow in more than 3 m of water, which implies a lower limit this far above the sample position. A useful upper limit to the relative sea-level curve has not been obtained, as there are no reported radiocarbon ages on terrestrial material at relevant elevations.

Studying raised beaches at Skarvsnes and other sites in Lützow-Holm Bay (69° 30' S, 39° 35' E), Yoshida & Moriwaki (1979) dated enough samples of emerged marine

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**Tab. 2 - Ice surface lowering and margin retreat estimated at sites around East Antarctica. The range of values for each site reflect the different combinations of ice- and earth-model parameters adopted.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Lowering (m)</th>
<th>Retreat (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vestfold Hills (Davis Station)</td>
<td>600 - 700</td>
<td>30 - 40</td>
</tr>
<tr>
<td>65° 35' S, 77° 58' E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skarvsnes, Lützow-Holm Bay</td>
<td>850 - 950</td>
<td>60 - 80</td>
</tr>
<tr>
<td>69° 30' S, 39° 35' E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunger Hills</td>
<td>520 - 630</td>
<td>25 - 33</td>
</tr>
<tr>
<td>66° 10' S, 101° E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terra Nova Bay</td>
<td>1400 - 1750</td>
<td>160 - 320</td>
</tr>
<tr>
<td>74° 50' S, 163° 30' E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Explorers Cove, McMurdo Sound</td>
<td>650 - 740</td>
<td>35 - 50</td>
</tr>
<tr>
<td>77° 30' S, 163° 30' E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windmill Islands (Casey Station)</td>
<td>960 - 1135</td>
<td>80 - 110</td>
</tr>
<tr>
<td>66° 17' S, 110° 32' E</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Fig. 3 - Summary of sea-level observations for Antarctic sites. Upper and lower limits are illustrated where appropriate.**
shells and worm tubes in growth position to produce a useful lower bound to the sea-level curve, showing a sea-level highstand of at least 16 m between 6000-7000 radiocarbon years ago, falling monotonically to the present. The presence of material older than 7000 years, but none higher than the 16 m highstand, suggests that this was in fact the maximum emergence, with lower sea levels beforehand, though this is not conclusive. An upper bound to the sea-level curve can be derived from marine-lacustrine transitions in two lakes from the Skarvsnes area. Initial results (Hayashi, 1994) indicate that Lakes Suribati and Hunazoko, both with sill heights slightly over 10 m a.s.l., were isolated from the sea before 4000 and 1000 corr. ^14C-yr BP respectively.

**GLACIO-HYDRO-ISOSTATIC MODELLING**

The formation of a large ice sheet has several effects on global sea level. First, a large amount of water is removed from the oceans, causing a global sea-level fall. Second, isostatic compensation to the altered ice (and water) loads causes a relative sea-level rise within and immediately beyond the limits of the ice load where crustal subsidence occurs, and a relative fall in the region of the “peripheral bulge” well beyond the area of ice loading. Third, the redistribution of mass from the oceans onto the land causes the geoid, which defines sea level, to rise near the ice sheet and fall elsewhere while the internal mass redistribution further modifies the geoid through time. When an ice sheet melts, the sea-level changes described above are reversed as melt-water returns to the ocean basins. Farrell & Clarke (1976) developed theoretical techniques to calculate these effects over the whole Earth, and subsequent refinements and improvements in computing power brought these studies to the point where the ice- and earth-model parameters, discussed below, can be constrained by comparison of calculated sea-level changes with those observed in the field (eg Chappell et al., 1983; Nakada & Lambeck, 1989; Tushingham & Peltier, 1992; Lambeck, 1995).

Two groups of input parameters influence the model’s sea-level predictions: the Earth rheology, and the ice load history. In this work, we use previously-obtained models for the rheology and northern hemisphere ice sheets, combined with new models for the Antarctic ice sheet, to produce sea-level predictions which can be compared with the observations described above.

**RHEOLOGICAL MODEL**

The rheological models used here are of a three-layered 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 $\eta_{up}$ and $\eta_{lm}$ respectively. The upper-lower mantle boundary is at 670 km depth, and the core is considered to be fluid. More complex rheological models are not justified by the sea-level data available in the Antarctic region. Published studies, using similar methods and observations, do not presently concur on the best values for the rheological parameters. For example, Nakada & Lambeck (1989) suggest an effective $H_{lith}$ of around 60-100 km, $\eta_{up}$ of 1-2 x $10^{20}$ Pa.s and $\eta_{lm}$ of about $10^{22}$ Pa.s. (see also Lambeck, 1993). In contrast, Tushingham & Peltier (1992) suggest values of 120 km, $10^{21}$ Pa.s, and 2 x $10^{21}$ Pa.s. for the same parameters. Since the sea-level observations from Antarctica are insufficient to place further constraints on the earth rheology, this study uses a range of model parameters, with $H_{lith}$ in the range 50-100 km, $\eta_{up} \approx 10^{20}$, $10^{21}$ Pa.s, and $\eta_{lm} \approx 2 x 10^{21}$ Pa.s.

**ICE SHEET MODELS**

The six sites from East Antarctica for which we have Holocene records are insufficient to justify a model for the entire ice sheet. Instead, regional models are used which simulate the ice sheet margin in the vicinity of all of the observation sites. These regional ice sheet models (Fig. 4) are circular, which simplifies the calculation of sea-level change considerably, and have a parabolic profile, following glaciological models that assume plastic flow of the ice (Paterson, 1969). A large number of different melting scenarios were investigated using this type of model, but all evolve to the same final state, whose radius (1100 km) and thickness (3700 m) were chosen to simulate the present ice sheet profiles at the observation sites as closely as possible.

The distribution of the additional ice in the former ice sheet was modelled in two ways. The first involves a constant aspect ratio of the model ice sheet during melting. As melting takes place, both the height and the radius of the ice sheet decrease. The second involves retreat of the ice sheet margin while the height remains constant. The distribution of ice removed is similar for the two models, with the greatest thinning of the ice sheet occurring at the coast.

![Fig. 4 - The regional ice sheet model for the Bunger Hills. These models are circular and approximately half the width of the actual Antarctic ice sheet. Sites of sea-level observations used in this paper are marked (MM=McMurdo Sound; TN=Terra Nova Bay; WI=Windmill Islands; BH=Bunger Hills; VH=Westfold Hills, SK=Skarvsnes).](image-url)
The timing of melting was modelled in three ways. The first, based on evidence that several of the observation sites were not covered by ice 10 000 years ago, has melting complete by that time. In the second, melting is proportional to that of the northern hemisphere ice sheets and is completed 6 000 years ago. In the third model, melting is 90% complete 6 000 years ago, and the remaining 10% takes place between then and the present. This model was included because sea-level observations from both Australia and Great Britain indicate that up to 3 m of eustatic sea-level rise has occurred during the late Holocene (Lambeck & Nakada, 1990; Lambeck, 1993).

CALCULATION OF SEA-LEVEL CHANGE

The sea-level history at a coastal site due to all combinations of the ice- and earth-models described above were calculated using the method of Johnston (1993). These predicted sea-level changes only simulate the effects of local changes in the Antarctic ice sheet in the vicinity of each observation site, and cannot be directly compared with the observed sea-level changes. The total sea-level change is the sum of these local effects, those due to ice in more distant parts of Antarctica (>1000 km away), and the contribution from the northern hemisphere ice sheets. In this work, it has been assumed that the isostatic effects of ice sheet changes in other parts of Antarctica are negligible. The eustatic component of sea-level change was taken to be the same as that of Nakada & Lambeck (1988), with a total eustatic rise of 126 m since the LGM. The isostatic effects of the northern hemisphere ice sheets and the entire water load component are also calculated according to the model of Nakada & Lambeck (1988).

RESULTS

To assess the validity of the regional ice sheet models, the predicted sea-level histories were quantitatively compared with the observed histories at each site. This yields estimates of the optimum ice sheet retreat and thinning which best reproduce the observed sea-level history, for each combination of ice-melting style and rheological model. The estimates of former ice sheet thickness and extent determined in this way are shown in Tab. 2. Because there are no firm constraints on either the rheological model or the ice melting style, these values are presented as ranges, covering all the possibilities discussed above.

DISCUSSION

The estimates of ice sheet thinning and retreat summarised in Table 2 can be compared with previous estimates from the same locations. At all sites, the estimated thinning is greater than that proposed by Colhoun et al. (1992), based on simple local isostatic arguments. The difference is due in part to the application of the more appropriate regional model for isostasy, and to the different interpretation of the various sea-level records.
Bay, the elevation of the Terra Nova Drift indicates that the region was covered by 500 m of ice at the LGM (Orombelli et al., 1990), which is about one-third the regional estimate of 1400-1750 m. Although these results are not contradictory, no useful constraints can be determined from the new estimate. At McMurdo Sound, the LGM ice thickness varied from ~700 m to zero, as it flowed in from the Ross Ice Sheet and terminated in the Dry Valleys (Stuiver et al., 1981). It is therefore impossible to interpret the estuaries from the regional models in any realistic form.

The presence of Law Dome adjacent to the Windmill islands makes the applicability of the regional ice models to this region also questionable, but the radius of the dome is ~100 km, so the perturbation on the regional models, which have a radius of 10 deg (~1100 km), should not be too great. Budd & Morgan (1977) used ice core measurements from Law Dome to propose that the ice at the LGM extended ~60 km beyond its present position, and was ~1200 m thick at the present coastline. This is in excellent agreement with the estimates derived from the regional-scale ice models, which suggest ice 960 - 1135 m thick at the Windmill Islands, and an ice margin retreat of 35 - 50 km.

For the parabolic regional model with 50 km of ice margin retreat and assuming a constant ice height in the interior of the ice sheet, the change in ice volume is about 140 km³ per kilometre of coastline. Thus the total ice-volume change for the East Antarctic margin is about 1.2x10⁹ km³ and the contribution to eustatic sea level is about 3.5 m. Estimates based on the individual results for the four sites given in table 2 range from 3 to 5.5 m for this latter contribution.

CONCLUSIONS

A new sea-level record has been determined for the Vestfold Hills, East Antarctica, by dating the lacustrine-marine and marine-lacustrine transitions in sediment cores from lakes which were formerly connected to the sea. Using cores from lakes with sill heights up to 40 m above present sea level (a.s.l.), a well-constrained record has been obtained for the period back to ~8 ka. At 8 ka, sea level was about 7.5 m higher than present. Sea level rose until ~6.2 ka, when it reached a highstand 9.5 m a.s.l, after which it fell steadily until the present. The maximum at ~6.2 ka is clearly seen in two sediment cores, where a lacustrine-marine-lacustrine sedimentation succession records the transgression of the lakes by rising sea level and their subsequent isolation as sea-level fell.

Sea level at other sites on the East Antarctic margin also appears to have fallen throughout the last 6000 years, without any evidence of oscillations during this time. Apart from the Vestfold Hills record, no evidence is seen for a local sea-level maximum, a period of sea-level rise preceding the mid-late Holocene fall. This does not necessarily mean that such a maximum did not occur, but reflects the greater accuracy and completeness of the new lake-isolation record compared to the dating of raised shoreline features, which is the most common source of information on former Antarctic sea levels.

To study the influence of ice-sheet changes on sea level at East Antarctic sites, a range of plausible simplified models of the ice sheet margin has been constructed. These models do not attempt to simulate the behaviour of the entire Antarctic ice sheet, but only a region on the margin, on the order of 1000 km. Using realistic models of the earth’s response to changing surface loads, the regional ice models described above were used to predict sea-level histories at coastal sites. A large range of scenarios has been investigated, allowing for variation in the maximum extent of the ice and its melting history, and the rheological parameters of the earth.

The optimum ice sheet histories indicate that at the LGM the East Antarctic ice sheet margin advanced 25-100 km beyond its present position, resulting in ice thicknesses of 500-1000 m at sites now on the coast. At the Windmill Islands, these results are in excellent agreement with the reconstruction based on ice core data from the adjacent Law Dome (Budd & Morgan 1977). The estimates for McMurdo Sound and Terra Nova Bay are larger than those of reconstructions based on the glacial geology, perhaps reflecting the influence of the expanded Ross Ice Sheet. No good constraints have previously been obtained from the other observation sites.

REFERENCES


