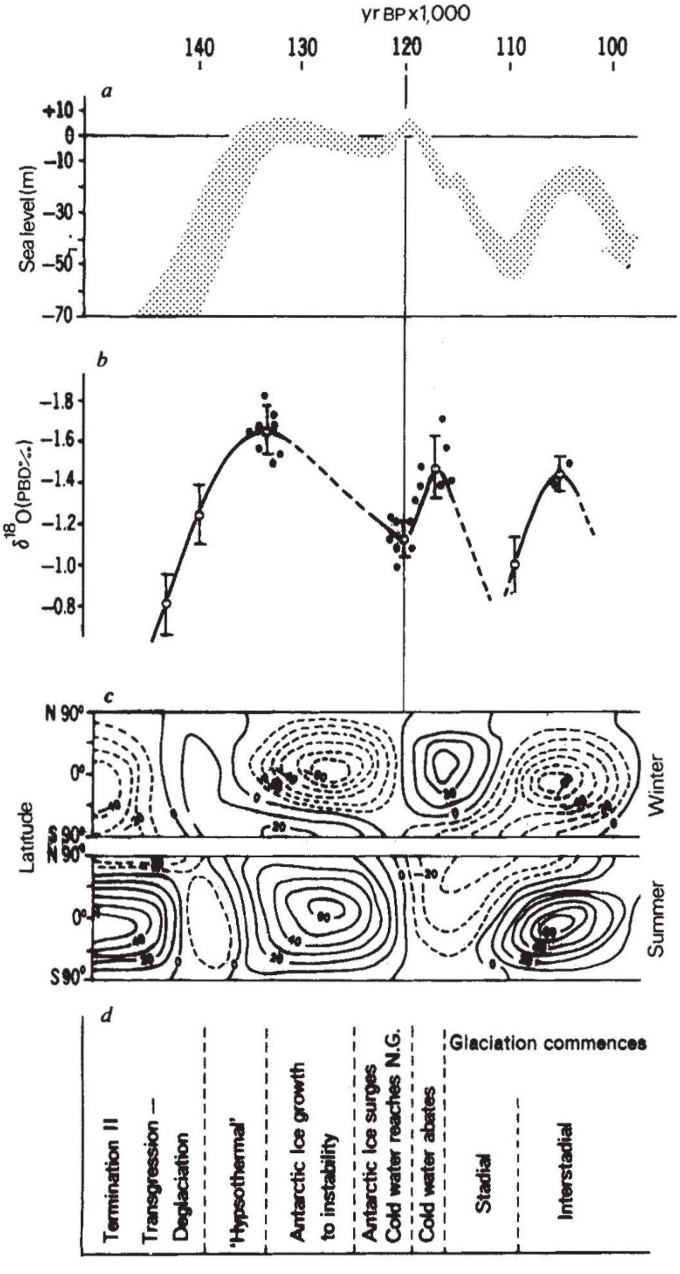

Fig. 2 Sea levels, δ^{18}O, and insolation changes, 150–100 kyr BP. *a*, Sea levels[10,11]; *b*, δ^{18}O from *Tridacna gigas*, New Guinea reefs. ●, Specimen values; ○ are group means for each stratigraphic unit, bars are group 1σ values. *c*, Deviations of solar radiation from present values in Langleys per day[30]. *d*, Interpretation.

about 3,000 yr after the VIIb peak, that is, when the VIIb patch reefs formed (point Y in Fig. 1), as temperatures similar to present are indicated (Table 1). (Although this result is from samples which grew within, as against outside, a lagoon, we believe lagoon ponding was not involved as the geometries are similar to modern, fully flushed lagoons at Huon Peninsula.) Hence, irrespective of the mechanism which produced the 2 °C cooling during the VIIb sea-level rise, it seems that its manifestation waned in the tropics while the northern glaciation was initiated. We do not know whether the surging ice mass was more likely to have been East Antarctica (Wilson hypothesis[3,4]) or West Antarctica (Mercer hypothesis[5,6]).

Note also that the Milankovitch factor predicts strong warm-summer–cool-winter contrast during the 125–130 kyr interval, a condition normally taken as inimical to northern continental ice growth. Such a radiation pattern may favour enhanced summer snowfall in Antarctica, leading to icesheet building towards instability. This might explain the minor sea-level decline from the VIIa peak before the VIIb rise. Figure 2*d* summarises the sequence of events, and we conclude that an Antarctic ice surge seems likely to have initiated the last glaciation.

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Isostatic equilibrium grounding line between the West Antarctic inland ice sheet and the Ross Ice Shelf

Larry L. Greischar & Charles R. Bentley

Geophysical and Polar Research Center, University of Wisconsin-Madison, Madison, Wisconsin 53706

The Ross Ice Shelf is widely believed to be a Holocene feature, that is, during the late Pleistocene the inland (grounded) ice sheet extended out nearly to the continental shelf break in the Ross Sea, and retreated to its present position between 5,000 and 10,000 yr BP. If so, and if the grounded ice sheet remained in that position for at least 10,000 yr, then a sea floor uplift of the order of 100 m is still to be expected in the grid western part of the Ross Ice Shelf. Even for a smaller and more ephemeral extension of the grounded ice, the uplift would still be several tens of metres. Recently reported measurements indicate that there are extensive areas near the present grounding line where the water layer beneath the ice shelf is thin enough so that uplift would lead to a grounding line advance of at least 100 km. As the sea floor depth generally increases towards the grid east, however, the maximum extent would not be past the middle of the present Ross Ice Shelf.

Seismic soundings of submarine topography and radar soundings of ice thicknesses were made at sites on a 55 km grid covering the Ross Ice Shelf, Antarctica, during the Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS)[1–5]. The submarine topography, characterised by a general deepening to

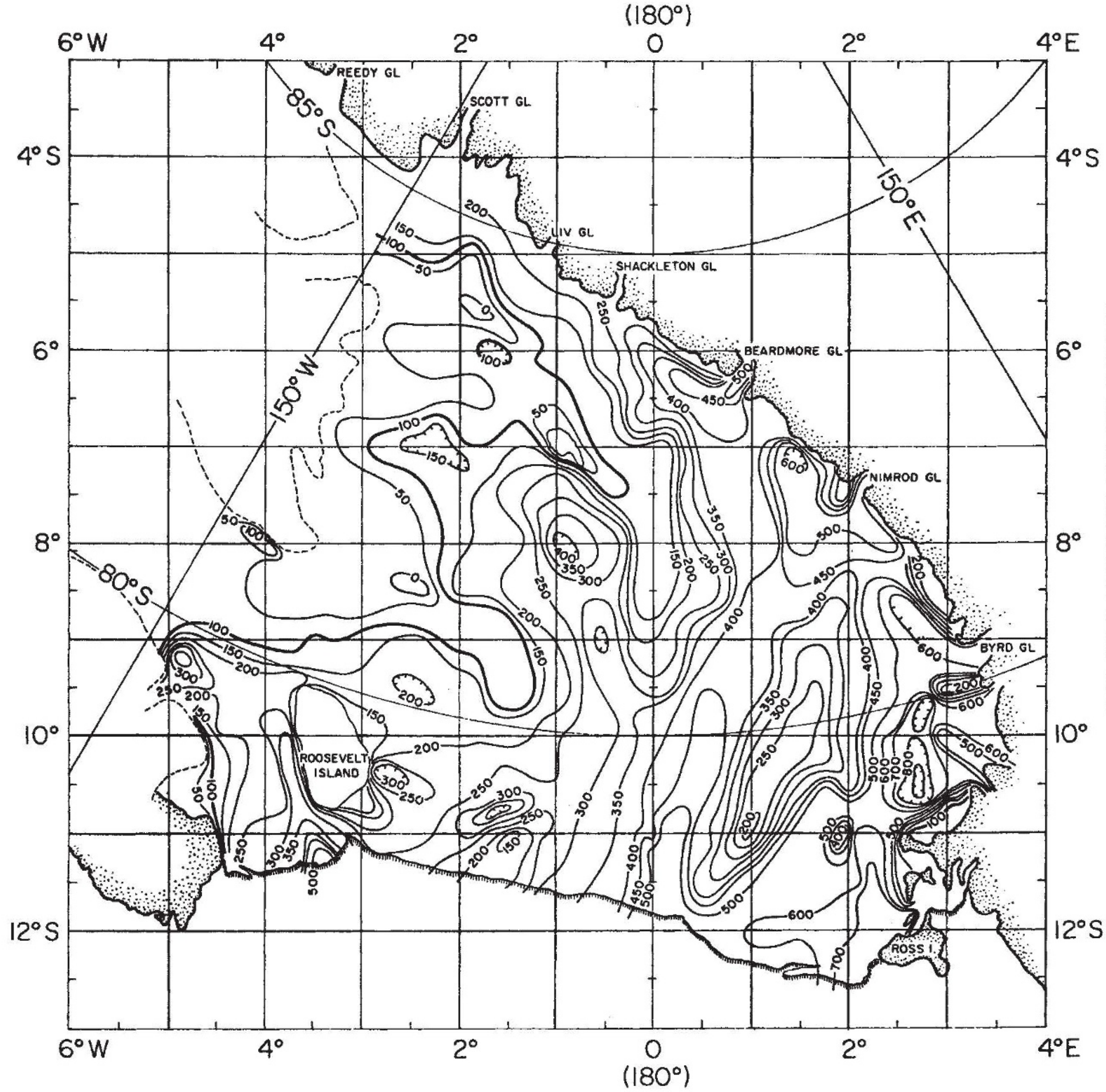

Fig. 1 Water depth beneath the Ross Ice Shelf. Standard grid coordinates are shown; grid north is towards Greenwich, and grid meridians are parallel to 180° W longitude. The present grounding line between the Ross Ice Shelf and West Antarctica is shown by the dashed line which is discontinuous in areas where ice streams enter the ice shelf. The contour interval is 50 m for depths from 0 to 500 m, and 100 m for greater depths.

the grid eastwards on which is superimposed a curving ridge–trough system, is reflected in a contour map of the 'water depth' (defined as the thickness of the water layer beneath the ice shelf) (Fig. 1). The position of the primary grounding line between the Ross Ice Shelf and West Antarctica was determined from airborne radar sounding measurements of ice surface elevations and strength and polarisation of bottom reflections[6]; the latter indicate whether water or rock is present directly below the ice. Seismic, radar and altimeter measurements made on the surface[1–3] were used for control. The surface topography shows the grounding line to be deeply indented beneath the West Antarctic ice streams, although scattering of the radar signals by heavy crevassing prevents accurate determination of its position. The ice shelf is also grounded at Roosevelt Island (grid position 10.0° S, 3° W), Crary Ice Rise (7.0° S, 1.0° W), near the Steershead Crevasses (8.5° S, 2.5° W), and possibly at RIGGS station F7 (5.5° S, 1.8° W) (see Fig. 3). Beneath much of the grid western part of the ice shelf, the water depth is < 100 m, and in some places it is only a few tens of metres.

Stuiver *et al.*[7] have reconstructed the Antarctic Ice Sheet at the 18,000 yr BP glacial maximum. Their reconstruction indicates that West Antarctic ice was then ~2,500 m thick near the present grounding line, and that the margin coincided with a line of sills parallel to the edge of the Ross Sea continental shelf. Two-by-two-degree mean isostatic gravity values at RIGGS stations on the Ross Ice Shelf[8], which are as much as 15 mGal negative compared with a fourth-order satellite gravity field[9], strongly suggest that glacio–isostatic depression of the grid western part of the present Ross Ice Shelf area still remains. Recent evidence from Ross Sea cores also suggests that grounded ice reached the continental shelf margin during the late Pleistocene[10]. Thomas and Bentley[11] calculated that if such a Ross Ice Sheet existed 18,000 yr ago, then it probably retreated rapidly to its present position between 13,000 and 7,000 yr BP. Geological data in the McMurdo Sound and dry valley areas yield minimum ages of ice retreat ranging from 3,000 to 10,000 yr BP (ref. 12) and have further been interpreted as showing that the grounding of the ice sheet occurred more than 47,000 yr ago[13].

Although some recent analyses of marine and glacial geological evidence indicate that only minor expansions of the grounded ice occurred during the Quaternary[14–16], we believe that the preponderance of evidence favours the existence of an extended grounded ice sheet of some form. The following analysis is based on the initial working hypothesis that a grounded 'Ross Ice Sheet' existed long enough to become isostatically compensated (~10,000 yr), and that it was removed rapidly between 5,000 and 10,000 yr BP. In that case, isostatic uplift of the loaded area should still be occurring. The grounding line between the West Antarctic Ice Sheet and the Ross Ice Shelf will advance as the sea floor rises. We have estimated the uplift remaining in the grid western portion of the Ross Ice Shelf, assuming a former ice thickness of 2,500 m (ref. 7). Following Bennett[17], we take unloading to have been instantaneous, and assume a simple exponential model of uplift:

$$Z = Z_0 \exp[-(t - t_0)/t_r] \qquad (1)$$

where Z is the amount of uplift remaining, Z_0 is the original isostatic depression due to the ice load, t_0 is the time of load removal and t_r is the time constant of isostatic rebound. Z_0 can be estimated from the former ice thickness, T, and the estimated average depth of the present sea floor, $\bar{D}$, by

$$Z_0 = \frac{\rho_i}{\rho_m} T - \frac{\rho_w}{\rho_m}(\bar{D} - Z) \qquad (2)$$

where ρ_i, ρ_w and ρ_m are densities of ice, sea water and mantle rock, respectively. Substitution of equation (2) into equation (1) yields an expression for the remaining uplift:

$$Z_p = \frac{\left[\frac{\rho_i}{\rho_m} T - \frac{\rho_w}{\rho_m}\bar{D}\right] \exp[-(t_p - t_0)/t_r]}{1 - \frac{\rho_w}{\rho_m}\exp[-(t_p - t_0)/t_r]} \qquad (3)$$

wherein Z_p and t_p are the present remaining uplift and the present time.

The average water depth at RIGGS stations, $\bar{D}$, is ~650 m. The relaxation time constant, t_r, was estimated for an area the size of the Ross Ice Shelf from values measured in the Northern Hemisphere and predicted by model studies (Fig. 2, adapted from Cathles[18]). The linear dimension of the Ross Ice Shelf is of the order of 1,000 km, so t_r was chosen to be ~4,400 yr, the value used by Cathles for central Fennoscandia. Note that t_r is relatively independent of both the linear dimension of the ice load and the crustal rigidity for ice loads of this size. Densities used in equation (3) were $\rho_i = 0.91$ Mg m^{-3}, $\rho_w = 1.03$ Mg m^{-3}, and $\rho_m = 3.33$ Mg m^{-3}.

The results of the calculation (Table 1) show a remaining uplift ranging from 50 to 170 m. This estimate agrees well with that from the mean isostatic gravity anomalies which suggest as much as 150 m residual depression near the grounding line[8]. Because of the linearity of equation (1), these figures can easily be modified to fit other assumptions. Thus, for example, if the initial depression were only half as large as has been assumed, the uplift remaining would still be at least 50 m if the time since removal is less than 7,000 yr. That initial depression, in turn, could correspond to a fully compensated grounded ice sheet whose margin extended only about as far as a line extending from Edward VII Peninsula to Byrd Glacier, to a fully extended ice sheet which was in position for only ~3,000 yr, or to a 'low profile' extended ice sheet that might be compatible with the shape of internal reflecting horizons found in the West Antarctic interior[27]. Thus 50 m is a reasonable approximation to an uplift to be expected even assuming a smaller or more ephemeral ice sheet.

Table 1 Uplift remaining since ice removal

Time since ice removal (yr)	Remaining uplift (m)
5,000	170
6,000	135
7,000	105
8,000	80
9,000	65
10,000	50

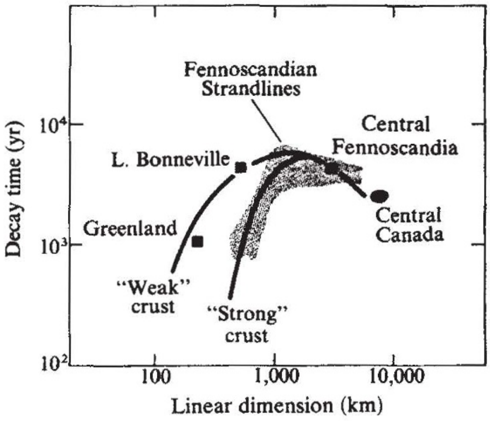

Fig. 2 Decay time constant for isostatic uplift versus the linear dimension of areas formerly covered by ice sheets (Canada, Greenland, Fennoscandia) or water (Lake Bonneville). Adapted from Cathles[18].

We have, therefore, estimated a maximum and minimum predicted advance of the grounding line based on a remaining uplift of 50–170 m and the assumption that the ice shelf thickness remains constant at the grounding line (Fig. 3). The maximum predicted grounding line extends grid northeastwards across the ice shelf from the seaward end of Roosevelt Island, and is deeply indented by extensions of the present ice streams. The minimum predicted grounding line advance would result from an advance of the central part of the present grounding line, with additional minor advances occurring near Edward VII Peninsula, Roosevelt Island and Crary Ice Rise.

The present rate of uplift is, from equation (1):

$$\left.\frac{dZ}{dt}\right|_{t=t_p} = -\frac{Z_p}{t_r} \qquad (4)$$

for $Z_p = 110$ m, the uplift rate is 25 mm yr^{-1}. Division by the water depth gradient, which varies from 10^{-4} to 10^{-3} near the present grounding line, yields a rate of advance of the grounding line of 25–250 m yr^{-1}. At this rate, several thousand years would be required for the grounding line to advance to its predicted maximum position. As uplift occurs, however, points seaward of the primary grounding line will be pinned on high points of the sea bed, forming new ice rises. Compressive strains upstream from these pinning points will greatly accelerate the rate of grounding line advance. We believe this is now occurring upstream of Crary Ice Rise (grid 7.0° S, 1.0° W)[19], and also near the Steershead Crevasses (grid 8.5° S, 2.5° W).

The possibility that sedimentation may have been an important factor during isostatic adjustment can be dismissed on the basis of ocean floor cores taken at station J9 (grid 7.5° S, 1.5° W). Little or no Pleistocene or Recent sediment is present at that location[20], whereas a sedimentation rate of the order of 55 mm yr^{-1} would be required to produce a present state of isostatic equilibrium[17]. Furthermore, even if the basal layers of the ice shelf contain as much as 10% morainal material, the latter sedimentation rate would imply a bottom melt rate of ~0.5 m yr^{-1}, whereas temperature and resistivity measurements indicate a near-zero melt-freeze rate at J9 (ref. 21). Also, preliminary observations on ice cores from the lowest layers, obtained at J9 in December 1978, suggest an average bottom freezing rate of ~0.03 m yr^{-1} (J. W. Clough and I. A. Zotikov, personal communication).

Peltier[22] has pointed out that the longest wavelength components of the depression may 'feel' the Earth's core, and decay non-exponentially. On any realistic Earth model, however, that applies only to wavelengths of many thousands of

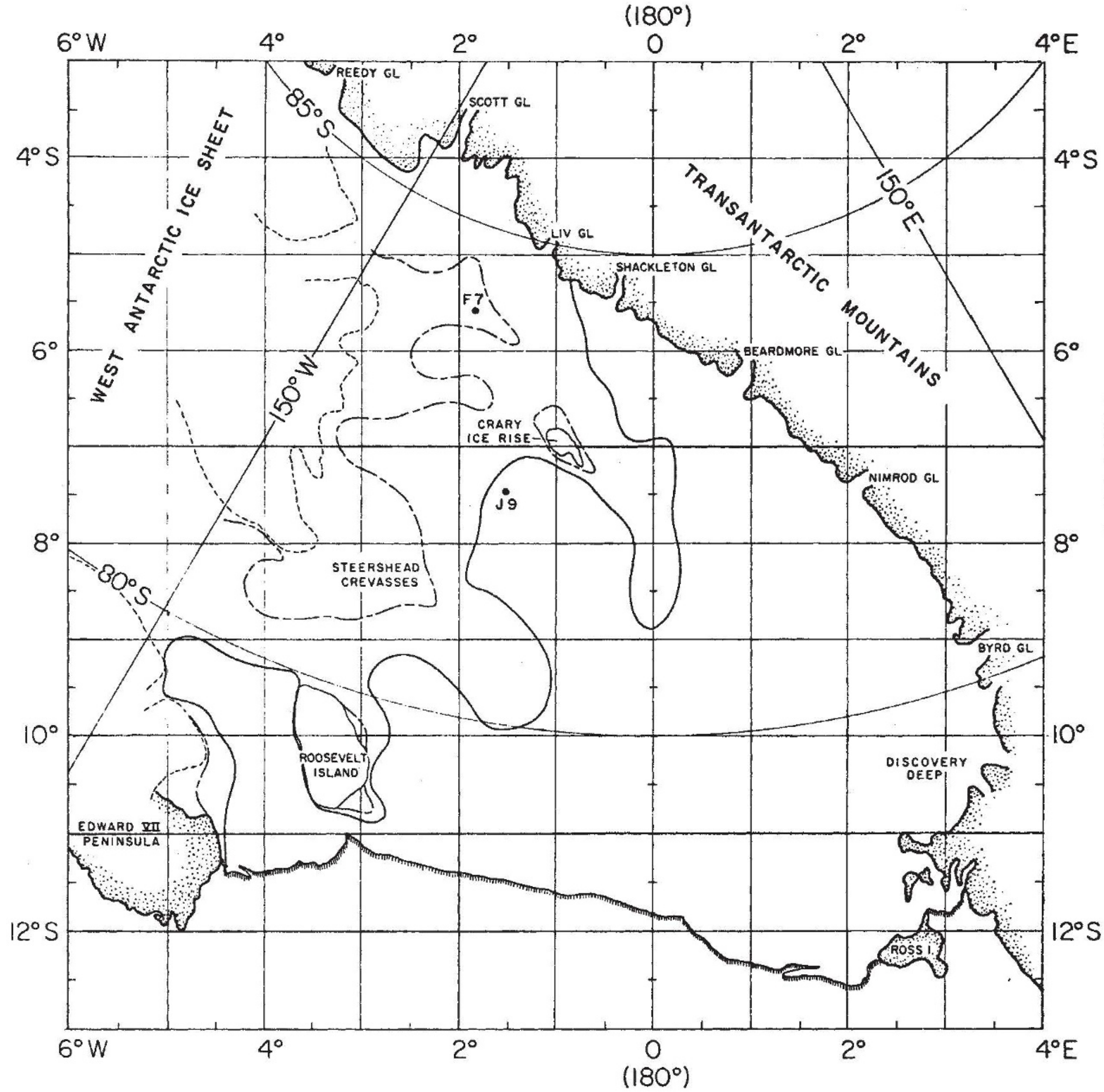

Fig. 3 Minimum (dashed line) and maximum (solid line) predicted seaward advance of grounding line, based on 50–170 m of additional isostatic uplift.

kilometres—much larger than the Ross Ice Shelf. Using Peltier's[22] Green functions in the Farrell–Clark[23] model and the Stuiver *et al.*[7] Antarctic reconstruction, Lingle and Clark[24] have computed a relative sea-level curve for 2,000 yr BP to the present near the centre of the Ross Ice Shelf. As their curve indicates a rate of emergence ($\sim$11 mm yr^{-1}) that is nearly constant rather than exponentially decreasing with time, it is impossible to use their method at the current stage of development to estimate the remaining uplift. Furthermore, as exponential decay describes well the uplift data from central Canada[25,26], it seems to be a reasonable assumption for uplift of the sea floor beneath the Ross Ice Shelf.

The model presented here does not, of course, consider the possibility of non-equilibrium of the West Antarctic ice sheet. Growth or shrinkage of that ice sheet due to climatic or inherent dynamic causes could produce grounding line movement which is large compared with that from isostatic uplift. However, if the West Antarctic inland ice sheet is approximately in steady state, an advance into the Ross Ice Shelf is still to be expected. The corresponding lowering of world sea level would be of the order of 0.5 m.

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