Reports

West Antarctic Ice Sheet: Present-Day Thinning and Holocene Retreat of the Margins

Abstract. *Retreat of the margins of the West Antarctic ice sheet associated with rising sea level during the last 15,000 years is the main cause for the thinning of the ice sheet by approximately 300 meters. The West Antarctic ice sheet during the late Wisconsin was at least 30 percent wider than it is today, and Holocene retreat of its margins has added about 6 meters to the world sea level.*

Ice-sheet profiles trend toward a "steady-state" shape such that snow accumulation is balanced by ice discharge. The summit height of the ice sheet is then determined by the snow accumulation rate A, the basal ice temperature θ, and the ice-sheet radius R. Theory (*1*) suggests that a 10 percent decrease in summit elevation can be achieved by halving A, or increasing θ by 5°C, or decreasing R by 20 percent. If warming of the basal ice is sufficient to cause the transition from frozen-bed to melted-bed conditions, then the thinning may be significantly greater (*2*). Field studies indicate that the West Antarctic ice sheet (Fig. 1a) currently is thinning (*3*) and that its summit elevation decreased by 10 to 20 percent during the Holocene (*4, 5*). Because an ice sheet has such a large mass and thermal capacity, the change from one equilibrium profile to another takes a long time; a surface warming of 5°C over the West Antarctic ice sheet 10,000 years ago would have resulted in only a 1°C warming of the basal ice (*6*). Although this small increase in temperature is sufficient to soften the ice appreciably, it would result in little total thinning of the ice sheet. Instead, I suggest that the main cause for Holocene thinning of the West Antarctic ice sheet was a retreat of the ice-sheet margins (so that R decreased) in response to rising sea levels. I shall attempt here to derive a relationship between ice-sheet thickness and R that takes account of Holocene warming and present-day thinning, and I shall use available measurements to give an indication of past ice-sheet behavior.

An idealized ice sheet is shown in Fig. 1b. The bed is assumed to be horizontal, and I shall neglect the effects of isostatic depression. When the ice sheet has achieved steady state, ice discharge exactly balances snow accumulation. If Q is the ice-discharge flux across a vertical section of unit width at a distance x from the center of the ice sheet and A is the total ice-accumulation flux upstream of the section, steady state is represented by $Q = A$. If $Q > A$, the ice sheet thins; if $Q < A$, the ice sheet thickens. Let us assume that A does not change with time (*7*) but that Q does; initially, it takes the value Q_0 such that $Q_0 = A$, and after some time interval t it changes to Q_t. The driving force for movement is proportional to the product of ice thickness H and surface slope α, and the expression for Q can be generalized (*1*):

$$Q \propto H^a (\alpha H)^b \exp[-(c/\theta)] \qquad (1)$$

where θ is the temperature (in degrees Kelvin) of ice that is approximately 10 to 15 percent of the ice thickness above bedrock (*8*). For a frozen-bed ice sheet, movement is caused by internal deformation and $a = 2, b = 3$, and $c \sim 10^4$°K. These values of a and b have support from fieldwork (*8*), and the value of c corresponds to an activation energy for the creep of ice of ~ 80 kJ/mole. If movement is caused entirely by bottom sliding, $a = 1$, $b = 2$, and $c = 0$. This value for b should be regarded as a first approximation; it is taken from glacier-sliding theory (*9*), which still awaits experimental confirmation. The state of equilibrium at any time can be expressed by $E = (Q_0 - Q_t)/Q_0$. The ice sheet is in steady state when $E = 0$; a negative E implies a thinning ice sheet, and a positive E indicates thickening. For the West Antarctic ice sheet, which is thinning and warming

$$E = 1 - (H_1/H_0)^a (\alpha_1 H_1/\alpha_0 H_0)^b \times \exp[c(\theta_1 - \theta_0)/\theta_0\theta_1] \qquad (2)$$

where the subscript 1 refers to the present day, and the subscript 0 refers to the late Wisconsin when the ice sheet is assumed to have been in steady state. The present-day values of the parameters in Eq. 2 can be measured, and Whillans (*6*) has shown how values of θ_0 can be estimated. We have no indication of late Wisconsin values of α_0, but the expression for equilibrium ice-sheet profiles (*1*) gives an estimate of how the surface slope at a fixed distance from the summit of a steady-state ice sheet changes as H and R vary. For a point close to the summit, α is approximately proportional to $H[R^{-(1+1/b)}]$. The summit region of the West Antarctic ice sheet appears to have retained a quasi-equilibrium profile for about 30,000 years (*10*), so I shall assume that the above proportionality can be applied at Byrd Station (80°01′S, 119°31′W) where a borehole was drilled to bedrock, and which is well within the summit region. Equation 2 then becomes

$$E = 1 - (H_1/H_0)^{a+2b}(R_0/R_1)^{1+b} \times \exp[c(\theta_1 - \theta_0)/\theta_0\theta_1] \qquad (3)$$

The values of H_1 and R_1 can be measured, and a good estimate can be made of the effects of Holocene warming (the exponential term) and of E. This leaves H_0 and R_0 unknown, and, if independent evidence gives an estimate of one of these parameters, then the other can be calculated. Currently, there is a controversy over the maximum areal dimensions of the late Wisconsin West Antarctic ice sheet. Analysis of the microfossil content of seabed cores indicates that grounded ice filled the Ross Sea as far north as the continental slope at least once during the last 500,000 years, but differentiation of individual advances may never be possible (*11*). Geological data from the west side of the Ross Ice Shelf have been intepreted to imply that, within the last 20,000 years, either the ice sheet almost filled the Ross Embay-

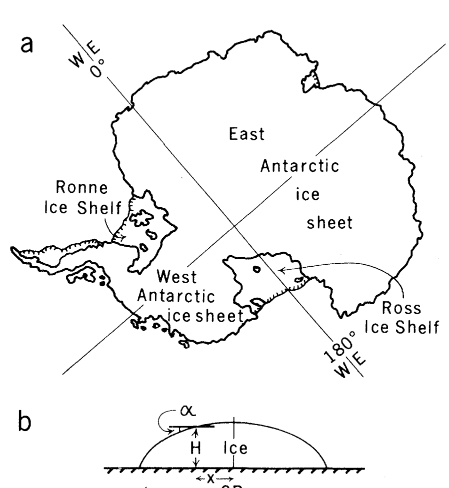

Fig. 1. (a) Map of Antarctica. Most of the drainage from the West Antarctic ice sheet flows into the Ross and Ronne ice shelves. (b) An idealized ice sheet.

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ment (*12*), implying $R_0/R_1 \sim 2$ ("ice-sheet" model), or there were large but localized grounded areas within an extended Ross Ice Shelf (*13*) and $R_0/R_1 \sim 1.4$ ("ice-shelf" model). Consequently, we must regard R_0 as unknown. Analysis of oxygen isotope ratios (*4*) and of the total gas content (*5*) of ice from the borehole at Byrd Station indicates that the ice sheet has thinned during the Holocene by several hundred meters, and Robin (*14*) has suggested a total thinning $(H_0 - H_1)$ of 300 m.

At the site of the borehole $H_1 = 2200$ m, $\theta_1 \sim 260°\mathrm{K}$ (*15*), $\theta_1 - \theta_0 \sim 1°\mathrm{K}$ (*6*), $E \sim -0.2$ if movement is caused by internal deformation of the ice, or $E \sim -0.5$ if movement is due entirely to basal sliding (*3*). Equation 3 can then be rephrased to give the relationship between total thinning $(H_0 - H_1)$ and R_0/R_1 that is shown in Fig. 2a. A thin layer of water at the bottom of the borehole suggests that some sliding is taking place, but there is also internal deformation within the ice column (*16*), and so the two curves in Fig. 2a provide upper and lower limits for R_0/R_1. For a value of $H_0 - H_1$ of ~ 300 m, Fig. 2a indicates that $R_0/R_1 \sim 1.3$, which would imply that the late Wisconsin West Antarctic ice sheet was larger, but not dramatically larger, than it is today (*17*).

Before accepting the results of this calculation as support for the ice-shelf interpretation of the geological data, we must consider limitations imposed by the model. First, the estimate of Holocene thinning is only an approximation. However, thinning is unlikely to have exceeded 500 m, implying that $R_0/R_1 < 1.5$. Second, the assumed dependence of surface slope on H and R is strictly applicable only for the transition from one steady-state profile to another. The ice sheet appears to be close to steady state now (*3*), but, if it was advancing across the Ross Embayment and had not achieved steady state during the late Wisconsin, the calculated values of R_0/R_1 would be too small. Finally, the equations used here apply to ice-sheet profiles like that shown in Fig. 1b. The West Antarctic ice sheet is better represented by the profile shown in Fig. 2b, with a peripheral region where the surface slope decreases to seaward. The behavior of this peripheral region is not described by the analysis that I have presented here. This means that R_0 and R_1 are smaller than the actual ice-sheet radii, as shown in Fig. 2b. If the width of the peripheral region is always an approximately constant proportion of the total width, then my analysis should provide a reasonable estimate of the late Wisconsin dimensions of the West Antarctic ice sheet. However, grounding of the Ross Ice Shelf may have occurred, with only minor increase in thickness, to form a large, comparatively thin extension to the ice sheet (Fig. 2b). This would have contained several fast-moving ice streams draining the central portions of the ice sheet. Similar ice streams with low surface slope (and therefore a low driving force) exist today, but with lengths of approximately 200 km compared to the 500 km or more necessary to traverse the Ross Embayment. However, the lack of existing examples does not deny the possibility that such large ice streams may have existed, and our understanding of glacier sliding is too poor to permit us to make a theoretical assessment of their viability.

The only important difference between the ice-shelf explanation and the ice-sheet model described above is the basal condition of the ice streams: in the ice-shelf model the ice streams are afloat, and in the ice-sheet model the ice streams are grounded. Both models require low friction between the ice streams and their beds over distances of several hundred kilometers. Floating ice streams always satisfy this condition; existing grounded ice streams seldom do. The amount of ice contained within the ice sheet is about the same for both models. If we assume $R_0/R_1 \sim 1.3$ for the entire West Antarctic ice sheet and that ice in the Ronne Embayment behaved in the same way as ice in the Ross Embayment, then retreat of the ice sheet during the Holocene would have increased the global sea depth by approximately 5 m for the ice-shelf model and 7 m for the ice-sheet model. These estimates are considerably less than the 16-m rise in sea depth (*18*) appropriate to a reconstruction of the late Wisconsin ice sheet (*19*) that is consistent with the basal friction of present-day ice streams.

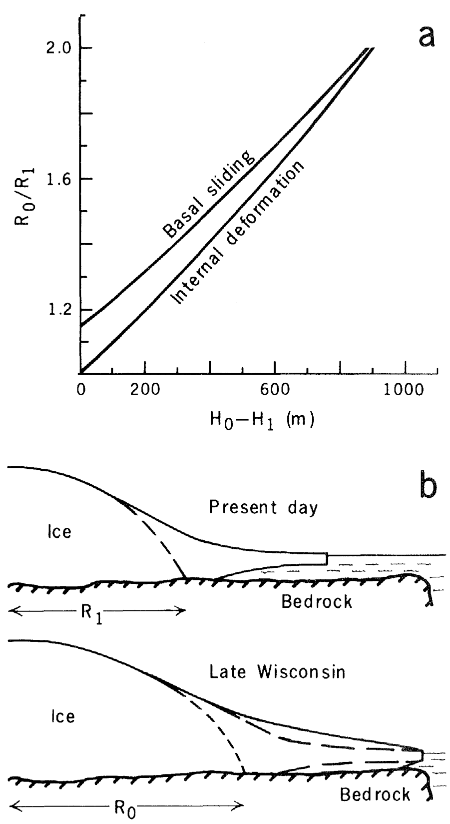

Fig. 2. (a) A plot of the ratio of late Wisconsin and present-day radii (R_0/R_1) against the total Holocene thinning $(H_0 - H_1)$ of the West Antarctic ice sheet. Ice movement is assumed to be by basal sliding or by internal deformation within the ice. Available data suggest that $(H_0 - H_1) \sim 300$ m so that $R_0/R_1 \sim 1.3$. (b) A generalized section through the present-day West Antarctic ice sheet and Ross Ice Shelf, and two hypothetical late Wisconsin profiles that are consistent with calculated values of R_0/R_1. The radii R_0 and R_1 refer to idealized ice-sheet profiles extrapolated from the summit region of the ice sheet. The two late Wisconsin profiles of the seaward half of the ice sheet correspond to grounding of the Ross Ice Shelf (solid line) and expansion of the Ross Ice Shelf (broken line).

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