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GLACIAL DYNAMICS (glaciology)

Ian Whillans[1]

I. Introduction

This report reviews recent results from studies of ice dynamics that relate to the objectives of the WAIS initiative. It emphasizes what we have discovered, which is very considerable. It also emphasizes what we do not understand in order to stimulate further discussion.

The best evidence shows that the ice sheet in West Antarctica is the most rapidly changing ice sheet on earth today. Its rate of change is much faster than most glaciologists had expected and it is changing in a manner much more complex than foreseen.

Follow-on questions are 'why is the ice sheet changing and why so rapidly ?'. The changes have two broad causes:

(1) a delayed but ongoing response to the termination of the last glaciation about 10 000 years ago

(2) automatic, internally-caused flow adjustments.

It is not fully known why the response to the last global termination is so delayed, nor is the operation of internal instabilities understood, and certainly we are not yet in a position to predict the future course of the evolution of the ice sheet. Deeper study of special features of the West Antarctic Ice Sheet is needed. Many of these studies require multidisciplinary approaches.

II. Styles of Ice Flow

After the discovery of the mass imbalances, the most stunning discovery from the studies of the ice streams is that there are several styles of ice flow. Very likely these two discoveries are related, in that the mass imbalances result from switches between styles of flow. The flow styles are listed below in order of slowest to fastest speed. Examples are labelled in Figure 1.

[1] Byrd Polar Research Center and Department of Geological Sciences, 125 South Oval Mall, Columbus OH 43210

'Smooth' Ice Flow

Where deformation rate at depth is slow, the most important deformation style is vertical compression and horizontal spreading. With time and net snow accumulation, the glacier adjusts to form a smooth upper surface.

Smooth ice is found near ice divides and on ice shelves. Most of the interstream ridges in West Antarctica are smooth.

'Mottled' Ice Flow.

Where deep ice speed is faster and there are basal irregularities, the ice surface is alternately steeper and flatter, forming steps or undulations. If the bed variations are random, so are the disturbances to the surface, and a mottled pattern is evident in satellite imagery. Often the mottles appear to be aligned in a direction perpendicular to solar illumination. One should not be misled by this solar bias.

Mottled surfaces dominate for much of the grounded inland ice. Parts of the interstream ridges are also mottled (for example, ridge A/B). This could be due to locally large bed variations or more likely to locally (and anomalously) faster ice flow.

'Streaming' Ice Flow.

As ice streams form, the mottles give way to linear stripes variously called streamlines, flowlines, sutures, septa, plumes, and flow traces. In their extreme development, they are reminiscent of medial moraines on a valley glacier, although, of course, they contain no rock debris and occur in a zone of net snow accumulation.

The leading contenders for the genesis of flow traces are (1) that they are a plume of buried crevasses, and the traces stand high because of lower mean density, and (2) that they are made of softer ice which is squeezed upward by lateral compression, the ice is soft because of different crystal size or orientation.

The courses of ice streams are influenced by bed topography and their surface is lower than that of the inland ice to either side. Their lateral boundaries are strong shear zones.

The ice streams can be extremely fast (> 800 m/a) and are restrained mainly by basal friction. The basal friction is small because of effective basal lubrication. The leading contenders for the lubricant are:

(1) continuous water film,
(2) discontinuous water film punctuated with 'sticky spots',
(3) water and debris slurry with sticky spots, and
(4) a continuous very viscous debris-with-water paste.

The development of an understanding of this lubrication should constitute a major effort within the WAIS initiative.

There are also interesting problems associated with the boundaries to the ice streams, none of which appear to be stable. The lateral boundaries are easily mapped by recognizing the shear margins. The upper and lower boundaries are not so distinct. Switches in flow style from inland ice, smooth or mottled, to streaming sometimes occurs in jumps, and chunks of inland ice are incorporated into the ice stream and carried down-flow as rafts. The process is not understood. Furthermore, there seem to be examples of margin migration due to narrowing of ice streams.

These hyperactive ice streams are potential means for the rapid evacuation of the inland-ice reservoir. Indeed, it is entirely possible that such an evacuation is underway now.

Ice Shelf Flow.

The floating portion of the ice sheet is called ice shelf and is controlled by drag past grounded ice or rock. Early theory advocated great importance to backstress (dynamic forces from the ice shelf on grounded ice) but where measured this has been relatively small. However, being part of the train of flow from ice divide to the calving front, any change in the ice shelf must propagate up-flow. The propagation time for East Antarctica is calculated to be thousands of years (Figure 2), but is probably in the range of hundreds of years for the lower-elevation portions of West Antarctica.

Major interest in the ice shelves stems from their thinness, coastal position, and relation with ocean currents:

- their thinness makes them more quickly reactive to climatic change because the ice shelf's total strength is rapidly affected by changes in ice temperature or surface mass balances.

- their coastal position and high snowfall means that quite small changes in atmospheric circulation and the delivery of snow can make large early impacts on the ice sheet in this region.

- a major component in the mass balance is basal melting and freezing. This is largely governed by ocean dynamics. A major objective of the Filchner-Ronne-Ice-Shelf-Programme (FRISP) is concerned with this. A very strong coupling between ocean and ice-shelf dynamics has been documented, and major generation of Antarctic Bottom Water is proved.

The ice shelf also contains flow traces. These are distorted because of raft incorporation, and also perhaps, fluctuations in ice stream discharge. The result is that the position of the flow traces at the calving front changes with time. This may be very important to the control of calving rate, and it may be noted that the recent breakout from the Filchner ice shelf followed such sutures. There are also enormous crevasses on the Ross Ice Shelf, well back from the barrier. The stability of the barrier has not been studied. Weakness due to flow traces and crevasses may be important.

III. Input

Probably the most important single controlling process for ice sheets is the net accumulation rate. It's broad pattern today in East Antarctica is relatively simple; nearly all of it falls near the coast. In West Antarctica it is more complex (Figure 3), it is larger near the seaward coast but is about 150 mm of ice per year around the West Antarctic ice streams. Within the region of the ice streams it is about 100 mm/year. The cause of this hole is not known. The depth of the hole is about the same, in relative terms, as the negative mass balance of ice stream B.

The value and distribution of net accumulation, for both today and in the past, is crucial to the ice sheet. It is the primary reason for the existence of the ice sheet, yet we have a very poor understanding of it.

The accumulation rate has been analysed by several disciplines. Glaciologists have taken the approach of mapping the present-day distribution and attempting to infer the causal processes from this map. This approach has been able to account for only the coarsest scale of variation. Meteorologists have analysed radiosonde data and satellite imagery, and have had some success in East Antarctica (D. Bromwich), but there has been little modern work for West Antarctica. Past changes have been inferred from ice core work, in particular for the very dry interior at Vostok, but the inferences, if valid there, can be extended only very conjecturally to sites at lower and snowier elevations. Glaciologists are generally not equipped to address this problem, and we urge sister scientists to take up this question.

IV. Relative Sea Level

This is the other most crucial control on ice sheets, especially for East Antarctica and much of Greenland, and most especially for the marine ice sheet of West Antarctica. The response to changes in sea level is quite rapid (Figure 2). Only just recently have good eustatic sea level curves become available for the past 20 000 years. These can be used to calculate relative sea level changes for various portions of Antarctica. With the emerging understanding of ice-shelf and ice-stream mechanics, and with the possibility to measure off-shore gravity and crustal rebound rates, there would seem to be good prospects for meaningfully modelling this effect, provided there are reliable data on past ice thickness against which to check the results.

V. Surface Temperature

This is important to the ice sheet because (1) it affects the stiffness of ice, (2) it is a factor determining whether the glacier can slip at its bed, and the rate of basal melt or freeze, and (3) it determines the possibility of penetrating melt water. Some authors also argue that the surface accumulation rate is simply linked with temperature, but that is debatable, especially for low-elevation or coastal sites.

Surface temperature is less important to the objectives of the WAIS initiative than some of the other factors. It is more important at longer time scales. Changes in surface temperature take a long time to penetrate the ice sheet (Figure 4). Most of the inland ice and the ice streams are wet-based and would remain so even with quite large changes in surface temperature. Only exceedingly dramatic and rather improbable climatic changes could start significant meltwater penetration in Antarctica.

VI. Mass Balance Under Ice Shelves

This affects the mechanics of the ice sheet by (1) altering its mass, thickness and extent, and (2) changing the stiffness of the ice shelf.

VII. Mass Balance Under Grounded Ice

Under ordinary circumstances, this is relatively unimportant as a cause of glacial variation. Normal geothermal plus ice-frictional heat melts some 10 to 20 mm of ice per year. This is small compared with surface mass balance, but is adequate and important in providing water-lubrication to sliding.

Landsat imagery shows a large feature of positive relief with a half-moon shape, in the center of ice stream E (Figure 5) that looks like a large sub-glacially formed volcano that is little eroded. Such an eruption can have dramatic effects on the ice sheet. Maybe the volcano is new and is affecting the ice sheet now.

VIII. Changes During the Past 20 000 Years

This history is important to understanding the present behavior of the ice sheet. The evidence comes from several lines:

(a) results from the Byrd Station core hole and radio-echo layers up-flow from Byrd Station indicate that the ice sheet is now near its maximum size and was thinner during the Wisconsinan-equivalent. A problem is that the scatter in the total gas measurements on the core is severe.

(b) relict flow features in the existing ice sheet are interpreted to show changes in flow on shorter time scales.

(c) modern mass balance show rapid changes

(d) the interpretation of the glacial-geologic record and of the presence of concentrations of meteorites on blue ice leads to the following conclusions:

- at 20 000 years BP, the interior regions of East Antarctica were similar, or perhaps (in accord with the interpretation of the Vostok ice core) a little thinner than today.

- at 20 000 years BP, much or most of the present region of the Ross Ice Shelf was grounded.

- at 20 000 years BP, the region around McMurdo Sound contained nearly stagnant ice. There were trapped lakes and the ablation rate was only on the order of 0.001 m/a [2].

[2] Calculated from Denton and others, 1989, , *Quaternary Research*, **31**, p. 157, fig. 5. At 167°E, the surface slope is 100 m / 15 km, and ice thickness is greater than 600 m. Thus the driving stress is > 36 kPa. Using a stiffness parameter of 500 kPa $a^{1/n}$, which corresponds to cold ice, and n = 3, and assuming lamellar flow, the mean ice velocity is $[2/(n+2)](tau/B)^n H$, in the common notation. This works out to be 0.1 m/a, a very small number, plus any basal slip. Selecting a different stiffness could increase this perhaps ten times. The down-glacial flowline is 70 km long with little lateral divergence, and so for balance, and an ice flux of 0.1 m/a, the ablation rate must be about 1 mm/a, or somewhat more if there was basal sliding or the ice were

- a major retreat of ice occurred from the McMurdo Sound region, ending about 6 000 years BP

(e) results from the marine record are not as clear. Some kind of till was deposited over most of the continental shelf of the Ross Sea, and there are also deposits in deeper water.

IX. Ice Flow Mechanics

Here is a brief summary of the field:

- Internal deformation can be modelled relatively well. It is important to the flow of inland ice, where frozen to the bed, as for example, in Greenland, and of ice shelves. There are discrepancies between theory and observation, but these are minor compared to the problems in understanding basal slip.

- Basal motion is very poorly understood. The ice streams demonstrate an interesting paradox. Often basal slip is supposed to increase as basal drag increases. The ice streams demonstrate the reverse, fast slip under small stress. There must be much subglacial water or mud, or the bed must be smooth. The debate on this has been enlivened by the discovery of a soft bed under ice stream B, that may itself be deforming.

- Dimensions of ice streams. There is no known control on the width or upglacial extents of the ice streams.

- Interplay between erosion and deposition and ice-sheet evolution. Especially at the grounding line, it is possible for the ice sheet to deposit its own bed, or erode it easily.

- Calving. This has been largely ignored. No good theory exists.

X. Subglacial Geology

The style of ice flow changes where the basal relief changes. Very probably the boundary is between a hard bed, with relief determined by geologic structure, and a soft bed of tilted marine clays, with relief formed partly by glacial processes.

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softer. The calculations could be made more carefully, but, by any account, the ablation rate in this region was very small.

XI. Ice Flow Modelling

The results of this can be only as good as the understanding of the physics governing ice flow, as noted above. An all-inclusive model is not yet appropriate, but models to test and evaluate certain aspects have been and are very helpful.

XII. The WAIS Initiative

The Siple Coast Project has discovered that the ice sheet is changing rapidly now, and that it has features that seem to make it prone to rapid and massive change. The implications have first-order global significance.

An attack on this problem requires much more than just glaciologists. For example, some of the not-fully glaciological questions that need solution are:

- What are the controls on surface mass balance ? ... role of sea ice, katabatic flow, etc..

- What has been the time-variation in surface mass balance, especially at low-elevations?

- What has been the history of change of the glaciers, especially during the past 20 000 years, and for prior intervals of glacial fluctuation ? Representative sites need to be studied, as well as arid sites such as the dry valleys.

- What are the values, and what controls the rate of melt / freeze at the base of the ice shelf?

- Is there a possibility of active subglacial volcanism in West Antarctica?

There are, no doubt, many other questions, and some of those above will need revision, but maybe this list can stimulate discussion of the problems and research strategy for The WAIS initiative.

The glaciologic discoveries in West Antarctica have been very considerable. They have lead to a quantum leap in the science of glaciology, in which the relative dominance of theory and observation have been reversed. We have emerged from a time of numerous untested theories, to a time with new data that contradict many older theories and a shortage of good theory on the crucial processes.

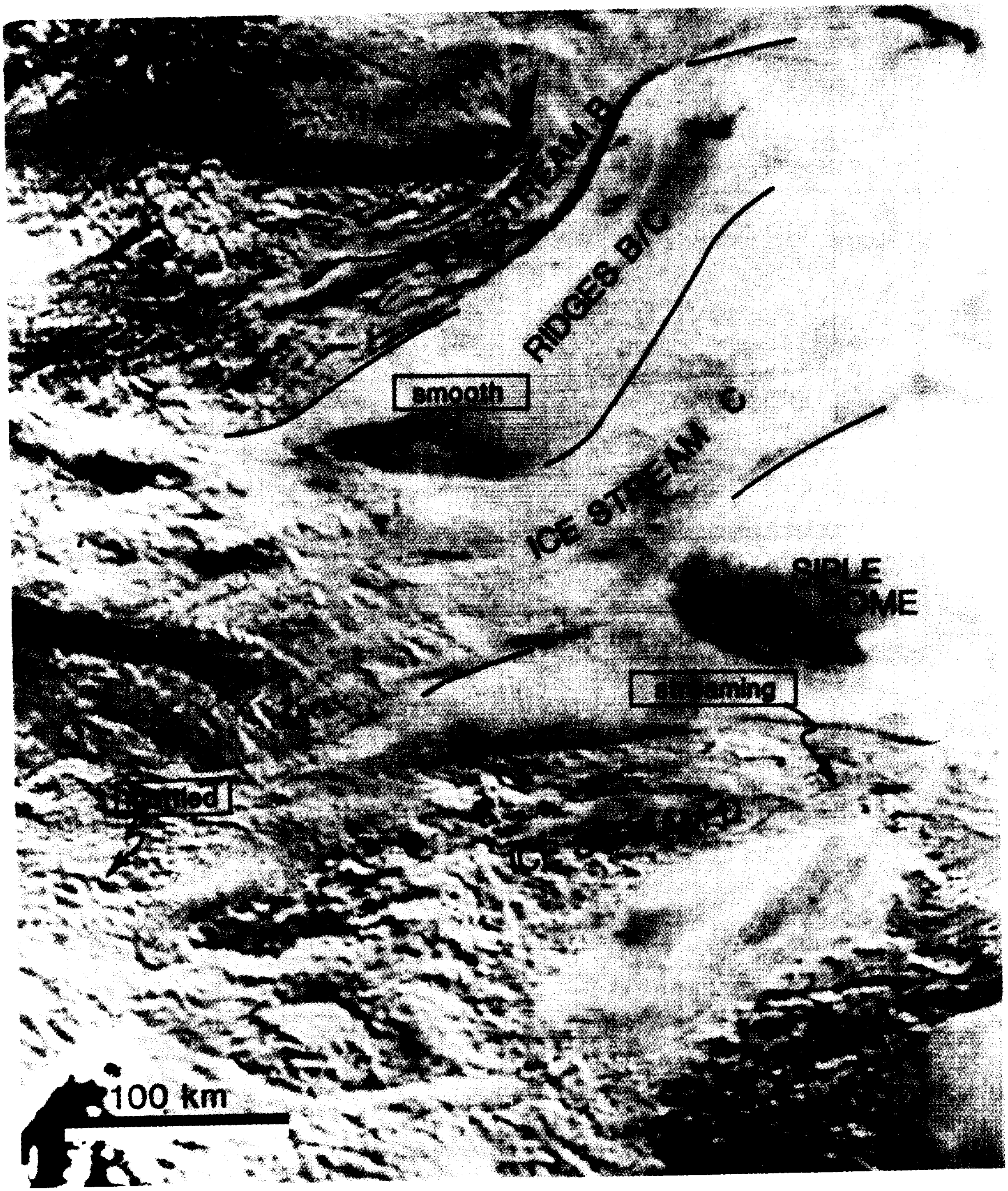

Figure 1. Satellite image of ice streams B, C, D, and E and vicinity. Flow is left to right. The Ross Ice Shelf is off-scene to the right. South is toward the top, and solar illumination is from the right. Image obtained by AVHRR (R.A. Bindschadler and P.L. Vornberger, EOS, 71(23), 1990 cover.

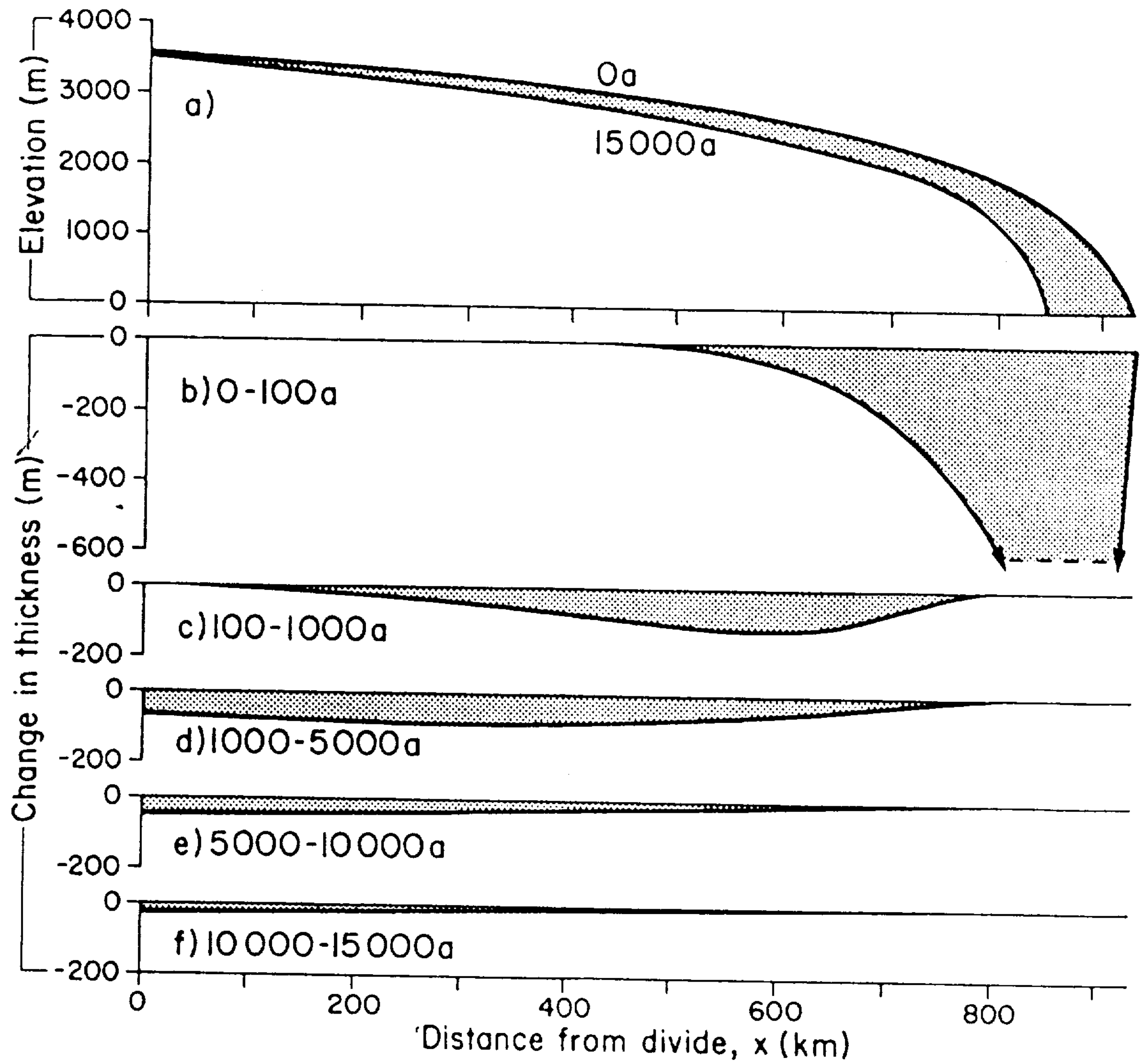

Figure 2. Progression of adjustment to a change in sea level for the East Antarctic Ice Sheet. In this calculation, the adjustment is controlled by internal ice deformation. It is mainly complete after 5000 years. Most glaciologists expect a much faster response for the ice sheet in West Antarctica. Figure from Alley and Whillans, JGR.

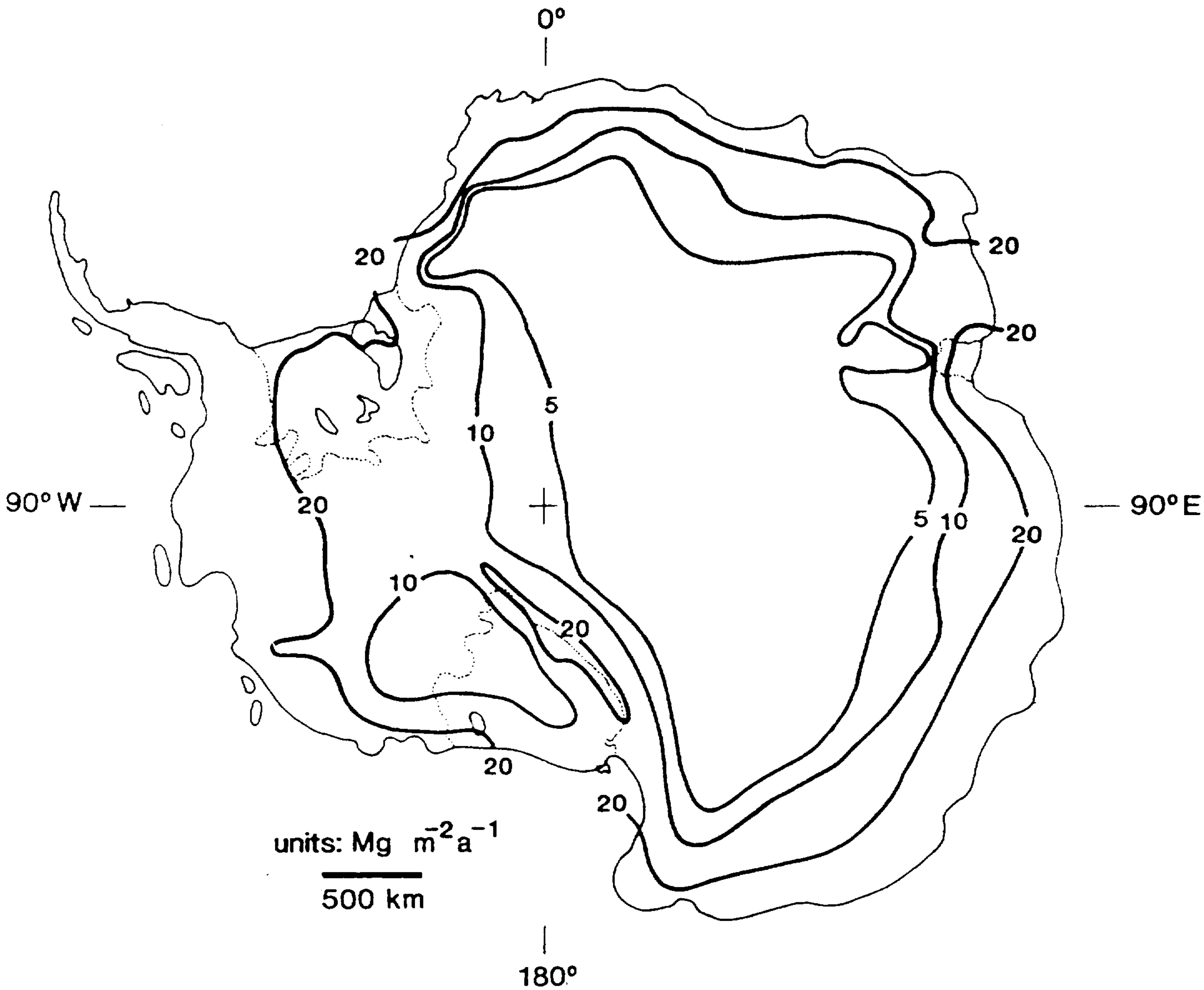

Figure 3. Net surface accumulation, from M. Giovinetto and C.R. Bentley. 1985. *Antarctic Journal of the U.S.*

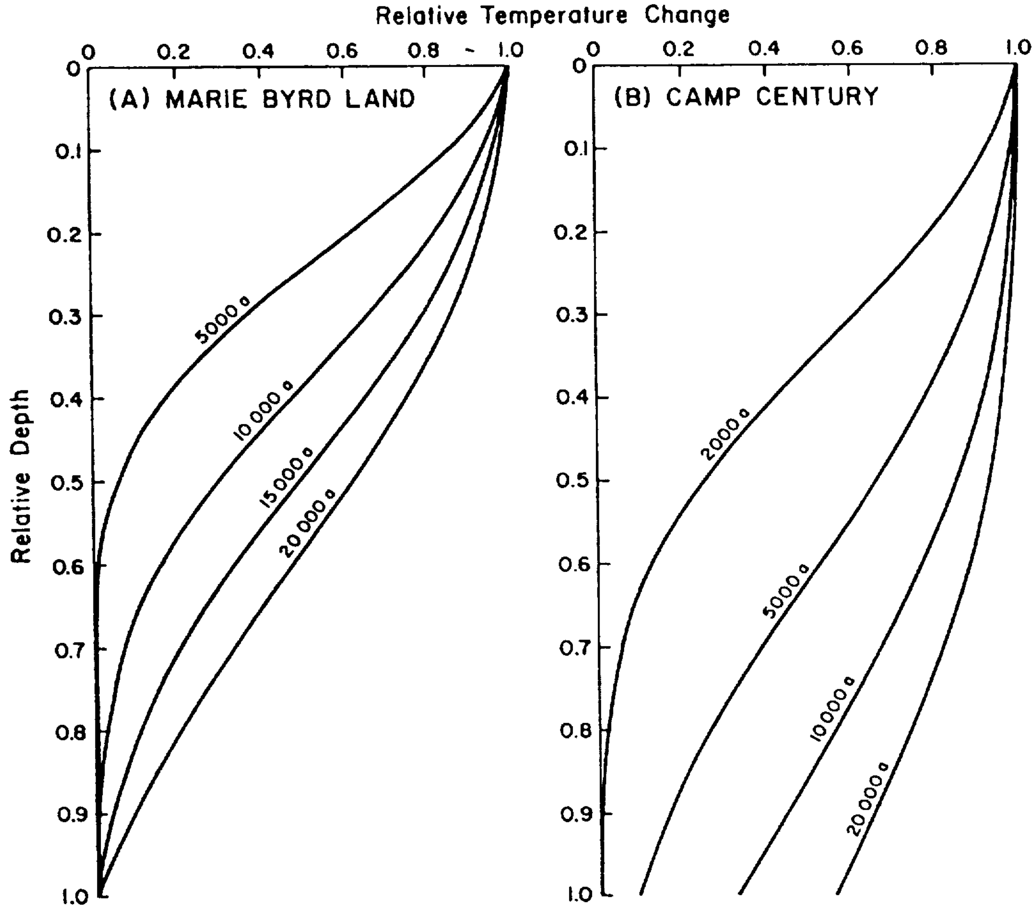

Figure 4. Propagation of surface temperature change into thick ice sheets. For Byrd Station, the temperature change at the half-depth reaches only 1/3 of the surface change after 10 000 years. The response in thin ice is much faster. Figure from Whillans, JGR, 1981.

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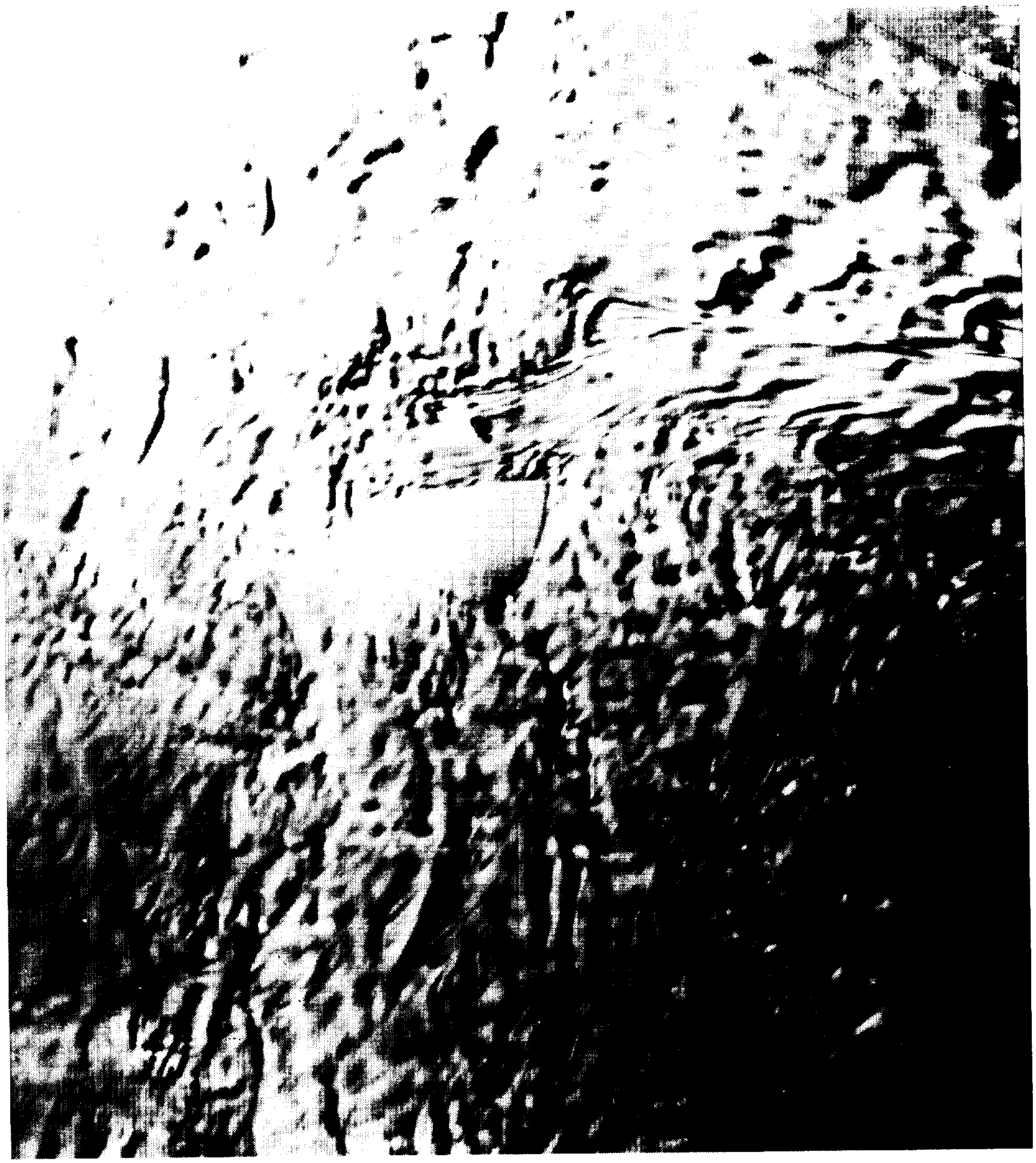

Figure 5. Landsat TM image of the onset of ice stream E. The flat half-moon feature is due to something with positive relief in the bed. It is speculatively interpreted as a table-top mountain formed by a subglacial eruption. It is about 20 km across (top-bottom). South is toward the top, and solar illumination is from the upper left. Image 014/117, personal communication from R.A. Bindschadler.