C. R. Bentley: How many satellite crossing lines are there in the large-scale (10 m contour line) map of surface elevations around the dome area?

Zwally: This preliminary map includes only about 12 lines. Therefore, some of the smaller features are probably artificial.

RECONSTRUCTION AND DISINTEGRATION OF ICE SHEETS FOR THE CLIMAP 18 000 AND 125 000 YEARS B.P. EXPERIMENTS: THEORY

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Abstract. Size, shape, and surface albedo of former ice sheets are needed in order to model atmospheric circulation for the CLIMAP 18 000 years B.P. experiment. Both the size and shape of an ice sheet depend on the hardness of ice and its coupling to bedrock. Ice hardness is controlled by ice temperature and fabric, which are not adequately described by any ice flow law. Ice–bed coupling is controlled by bed roughness and basal melt water, which are not adequately described by any ice sliding law. With these inadequacies in mind, we assumed equilibrium ice-sheet conditions 18 000 years ago and combined the standard steady-state flow and sliding laws of ice with the equation of mass balance to obtain separate basal shear-stress variations along ice-sheet flow lines for a frozen bed when the flow law dominates and for a melted bed when the sliding law dominates. Theoretical basal shear-stress variations were then derived for freezing and melting beds on the assumption that separate melted areas of the bed had water films of constant thickness which expanded and merged for a melting bed but contracted and separated for a freezing bed. Theoretical basal shear-stress variations were also derived for ice streams along marine ice-sheet margins and ice lobes along terrestrial ice-sheet margins on the assumption that the entire area of their bed was wet so that further melting increased the water-layer thickness, which would then be decreased by freezing. Melting was assumed to continue to the grounding line of an ice stream and the minimum-slope surface inflection line of an ice lobe, where freezing began and continued to the ice-lobe terminus. Ice–bed uncoupling is complete at an ice-stream grounding line and maximized at an ice-lobe minimum-slope inflection line, so ice velocity and consequent generation of frictional heat were assumed to reach maxima across these lines. Theoretical basal shear-stress variations were derived for the zone of converging flow at the heads of ice streams and ice lobes, and from domes to saddles along the ice divide for both frozen and melted beds.

Criteria based on the glacial geology and topography were developed to assess which areas underneath ice sheets 18 000 years ago were covered by freezing, frozen, melting, or melted beds, ice streams or lobes, and ice domes or saddles. Our ice sheets were then reconstructed using a finite-difference model that requires as input the ice thickness near the ice-sheet margin, the basal topography under ice-sheet surface flow lines, flow-line lengths, and basal shear-stress variations along flow lines. Initial ice thicknesses could be somewhat arbitrary because they only affected the flow-line surface profile close to the ice-sheet margin. Present bed

topography was used for the areas covered by ice sheets 18 000 years ago, this bed was then depressed isostatically by the reconstructed ice sheet, and a new ice sheet was reconstructed on the depressed bed.

Application of our model required snow accumulation-rates over the former ice sheets and evaluation of parameters in the standard flow and sliding laws of ice. All these were obtained from the present Greenland and Antarctic ice sheets. Snow accumulation-rates are not important variables in our ice-sheet reconstruction model. Flow- and sliding-law parameters were obtained by matching our reconstructed flow-line profiles with present Greenland and Antarctic profiles for regions where the basal topography is known and where our criteria for locating zones of frozen and melted beds agree with zones calculated from an Australian model which incorporates the equations of heat flow (Budd and others, 1970).

The last interglaciation peaked about 125 000 years B.P. when mean global sea-level was about six meters higher than present and mean global temperature was apparently a few degrees warmer than present. Among ice sheets existing during the present interglaciation, the marine West Antarctic ice sheet is most likely to disintegrate as a result of small increases in sea-level and air temperature. The 125 000 B.P. increase in sea-level is nearly identical to the increase expected from collapse of the present West Antarctic ice sheet, and the 125 000 B.P. increase in air temperature might have melted the confined ice shelves which now buttress this ice sheet. A Maine CLIMAP ice-sheet disintegration model was developed to couple with the Maine CLIMAP ice-sheet reconstruction model to treat disintegration of marine ice sheets by means of surging ice streams. This model was then applied to the West Antarctic ice sheet, as reconstructed for the CLIMAP 18 000 years B.P. experiment, and disintegration was allowed to proceed to completion for the 125 000 B.P. sea-level and air-temperature boundary conditions.

In the Maine CLIMAP ice-sheet reconstruction model (Hughes, in press), ice-stream grounding lines are across the tops of sills at the seaward end of fore-deepened channels on the floor of continental shelves formerly covered by marine ice sheets. Isostatic sinking of continental shelves underneath these ice sheets is assumed to be zero at ice-stream grounding lines, ice streams have a concave surface profile above the channels, and a zone of converging ice flow may exist at the landward end of these channels, particularly if they continue as fiords through coastal mountain ranges. Ice–bed uncoupling obeys a damped cosine function in the channel, with complete uncoupling at the sill.

In the Maine CLIMAP ice-sheet disintegration model (Stuiver and others, in press), an ice-stream surge law related to ice–bed uncoupling represents the driving force for ice-stream flow along the channel, and the hydrostatic potential difference between ice and water columns represents the driving force for ice-stream flow across the sill. Grounding-line retreat during the surge is caused by decreasing the difference between the heights of the ice and water columns at the sill. This decrease can be triggered by a negative mass balance in the ice-stream drainage basin, isostatic depression of the sill, a rise in sea-level, or a rise in air temperature. In our disintegration model, mass balance changes mainly by changing areas of ice-stream drainage basins rather than changing snow accumulation-rates over them, isostatic depression of the sill is not allowed, sea-level rises as all ice sheets disintegrate before 125 000 B.P. but as only the West Antarctic ice sheet disintegrates during that interglaciation, and air temperature rises only enough to ablate the ice-shelf fringe of West Antarctica during disintegration. Isostatic rebound lags ice-sheet disintegration by prescribed amounts. Fast and slow disintegration models are derived. In the fast model, calving bays closely follow the grounding lines retreating along evacuated ice-stream channels. In the slow model, the ice-shelf fringe expands southward as the grounding line retreats. Both models pinpoint Pine Island Bay in the Amundsen Sea as the site where the present-day West Antarctic ice sheet is most vulnerable to collapse, provided that Thwaites and Pine Island Glaciers have no high bedrock sills.

REFERENCES

Budd, W. F., *and others*. 1970. The extent of basal melting in Antarctica, by W. [F.] Budd, D. Jenssen, and U. Radok. *Polarforschung*, Bd. 6, Jahrg. 39, Nr. 1, 1969, p. 293–306.

Hughes, T. J. In press. Numerical reconstruction of paleo ice sheets. (*In* Denton, G. H., *and* Hughes, T. J., *ed. The last great ice sheets*. New York, Wiley–Interscience.)

Stuiver, M., *and others*. In press. The history of the marine ice sheet in West Antarctica during the last glaciation: a working hypothesis, by M. Stuiver, G. H. Denton, and T. [J.] Hughes. (*In* Denton, G. H., *and* Hughes, T. J., *ed. The last great ice sheets*. New York, Wiley–Interscience.)

RECONSTRUCTION AND DISINTEGRATION OF ICE SHEETS FOR THE CLIMAP 18 000 AND 125 000 YEARS B.P. EXPERIMENTS: RESULTS

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Abstract. Late-Wisconsin ice sheets were reconstructed for the CLIMAP 18 000 years B.P. experiment. This experiment modeled the ice-age steady-state climate using boundary conditions that differed from present ones mainly in Earth-surface albedos, sea-surface areas, and land-surface topography. These required determinations of the area, volume, and elevation of Late Wisconsin ice sheets. An initial-value finite-difference numerical model for ice-sheet reconstruction was developed from a recursive formula which gave ice thickness for known variations of bed topography and theoretical variations of basal shear stress. Ice thicknesses were calculated in 50 km to 100 km steps along flow lines from margins to domes of late-Wisconsin ice sheets. We assumed that terrestrial margins were along the furthermost moraines, marine margins were along the present 500 m bathymetric contour, domes were centers of maximum post-glacial isostatic rebound, and flow lines were along glacial lineations (eskers, striations, drumlins, etc.) connecting margins to domes. At various locations ice-sheet margins were verified by dated moraines for terrestrial margins and Egga-type moraines for marine margins. Ice-sheet elevations and thicknesses were contoured from profiles reconstructed for 40 Antarctic flow lines and 137 Northern Hemisphere flow lines for a maximum ice-sheet extent, and 86 Northern Hemisphere flow lines for a minimum ice-sheet extent.

Maximum and minimum Northern Hemisphere ice-sheet reconstructions were necessary because glacial geological studies in the Arctic are inconclusive (Hughes and others, in press). One body of work favors ice sheets which extended to the margins of the Arctic continental shelf, but another body has these ice sheets terminating near present Arctic shorelines. Ice sheets were reconstructed assuming isostatic equilibrium and rock–ice density ratios of 3 and 4. For the maximum reconstruction, a density ratio of 3 requires removing 172 m of ocean water, Laurentide ice up to 3 230 m high with 2 930 m mean thickness, Scandinavian ice