Numerical reconstruction of a soft-bedded Laurentide Ice Sheet during the last glacial maximum

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ABSTRACT

We used a numerical ice-sheet model to reconstruct the North American Laurentide Ice Sheet during the last glacial maximum. Our model simulates ice-sheet conditions that can be specified experimentally as either a rigid substrate (hard bed) or a wet, deformable till (soft bed); basal sliding is excluded. We use geologic records of former basal ice-sheet processes to prescribe the distribution of hard and soft beds. Our reconstruction of the Laurentide Ice Sheet is significantly lower in ice-surface height and contains less ice volume than the CLIMAP (maximum) reconstruction. In contrast, our reconstruction agrees well with the ICE-4G reconstruction, both in height and volume. Because the ICE-4G reconstruction is based on the inversion of relative sea-level data, whereas our reconstruction is based on glacial geology and ice mechanics, this agreement suggests that soft beds provide a glaciological mechanism to explain the shape and volume of the Laurentide Ice Sheet that is most consistent with observations of relative sea-level change and other geodynamic considerations.

INTRODUCTION

Atmospheric general circulation models (GCMs) suggest that the Laurentide Ice Sheet, the largest of the former Northern Hemisphere ice sheets, had a far-reaching effect on global climate through its influence as a topographic obstacle to atmospheric circulation (Manabe and Broccoli, 1985; Kutzbach and Guetter, 1986). As the dimensions of the ice sheet changed, so did their corresponding influence on climate elsewhere on the Earth (Imbrie et al., 1992). Acknowledgment of this influence makes it important to refine the reconstruction of Laurentide Ice Sheet surface height and thickness at various points through a glacial cycle, as well as to understand the general principles that determine ice-sheet thickness.

A recent study of crustal rebound and relative sea-level observations has led to the ICE-4G reconstruction of the Laurentide Ice Sheet at the last glacial maximum (~18 000 ^{14}C yr B.P., ~21 000 calendar yr) (Peltier, 1994). ICE-4G differs markedly from the long-standing benchmark of Laurentide Ice Sheet reconstructions made by CLIMAP (CLIMAP Project Members, 1981) in that the ICE-4G reconstruction has a surface elevation that is on the order of 1000 m lower than that of the CLIMAP reconstruction in central parts of the Laurentide Ice Sheet. This result implies that the Laurentide Ice Sheet made less of a drawdown of eustatic sea level at the last glacial maximum than previously thought. ICE-4G is the product of geodynamic and relative sea-level data analysis. The CLIMAP reconstruction is the product of ice-mechanics considerations. The ice-mechanics factors that explain the lower elevation of ICE-4G thus remain a subject of debate. Here we present a reconstruction of the Laurentide Ice Sheet based on mechanical effects associated with deformable subglacial sediments. We demonstrate that the reduced size of ICE-4G can be explained by the widespread influence of deformable sediments flooring Hudson Bay, Hudson Strait, the Great Lakes, and the western Canadian Prairie regions.

NUMERICAL ICE-SHEET MODEL

Ice sheets and glaciers move by some combination of three processes: internal deformation, basal sliding, and subglacial sediment deformation. Several previous modeling efforts have evaluated the first two effects on ice-sheet size and behavior (Hughes, 1981; Payne, 1995; Greve and MacAyeal, 1996). Our purpose here is to evaluate the first and third effects using a finite-difference model that simulates ice-sheet conditions along flowlines of the Laurentide Ice Sheet, flowlines that traverse terrain that can be specified experimentally as either a rigid substrate (hard bed) or a wet, deformable till (soft bed) (Jenson et al., 1995, 1996). Processes represented in our two-dimensional flowline model include climatic forcing, vertical advection and conduction of heat through the ice, temperature effects on ice stiffness, ice deformation and basal shear stress, flow of sediment in response to basal shear stress, viscous heat production in the till, geothermal heat flow, basal melting, and isostatic adjustment. Over regions specified to have a hard bed, we restrict (for simplification) the ice flow to be that determined by internal ice deformation only. Ice deformation is modeled by applying an ice-deformation equation widely used in ice-sheet modeling (Huybrechts, 1992). For soft-bedded regions, ice flow is determined by the combined effects of internal ice deformation and sediment deformation (Jenson et al., 1995, 1996). Sediment deformation is initiated wherever the shear stress applied by the overlying ice exceeds the sediment strength. This strength and other rheological properties are derived from a general constitutive law that can treat a wide range of possible sediment behavior (Iverson, 1985).

Our model disregards basal sliding at the ice-sediment and ice-bedrock interfaces as a means to isolate the influence of subglacial sediment deformation on ice-sheet elevation. Ice-surface elevations calculated by our model are thus an upper bound on those that would occur with basal sliding and bed deformation combined. Because our interest is in evaluating subglacial sediment deformation as an explanation for the reduced ICE-4G topography, we can accept such an upper bound. Previous studies of the Laurentide Ice Sheet with sliding but no bed deformation (Hughes, 1981; Greve and MacAyeal, 1996) found that sliding alone is not sufficient to explain low surface elevations over Hudson Bay.

Mass flux values calculated from the stress-strain laws for the ice and sediment are inserted into the mass continuity equation to specify the variation of ice thickness over time. From the ice thickness, the model determines surface elevation, shear stress, and velocity profiles for ice and sediment. Divergence due to transverse spreading along a given flowline was not treated by our model. This simplification will generally yield somewhat greater ice thicknesses for parts of the Laurentide Ice Sheet that display radially directed flow from spreading centers. In some locations, such as near the terminus of the Laurentide Ice Sheet in Hudson Strait, flowlines may converge, and our model will thus slightly underestimate the local ice thickness.

We have conducted initial testing of a sample of till from Illinois to obtain the geotechnical parameters in the stress-strain flow law (Vela, 1994; Jenson et al., 1995). Results of this testing suggest that, for this one sample, the power law exponent in the flow law is ~1.25, suggesting that the sediment is only slightly nonlinear. We evaluated a range of effective sediment viscosities in the model (Jenson et al., 1996) and found that a value of 5.2×10^8 Pa·s resulted in longitudinal ice-surface gradients that were in close agreement with those reconstructed by glacial geology from margins of the Laurentide Ice Sheet that rested on soft beds (Mathews, 1974; Clark, 1992). This value is lower than the value of sediment viscosity determined experimentally on the till sample from Illinois (Vela, 1994; Jenson et al., 1995) and is near the lower end of values derived from studies of actively deforming subglacial sediment (Paterson, 1994).

To specify the ice-sheet surface temperature, we lowered modern mean annual temperature along the path of a given flowline by a uniform amount suggested from an ice-age GCM experiment (National Center for Atmospheric Research Community Climate Model 1) (John Kutzbach and Pat Behling, 1994, personal commun.). Specifically, we took the difference between modern temperature and the GCM temperature value at a location immediately distal to the ice margin along a given modeled flowline and uniformly lowered modern mean annual temperature along each given flowline by this amount. There are some geologic data near the former ice margin (Johnson, 1990) that suggest a temperature depression comparable to that derived from the GCM results for those regions. We then further depressed surface temperature along each flowline to account for ice-sheet elevation and an assumed dry adiabatic lapse rate in the atmosphere. Net accumulation was specified using a similar approach based on modern mean annual precipitation with an applied elevation desert effect. Maximum accumulation is prescribed to occur 10% of the distance downstream from the ice divide (Oerlemans, 1991). We imposed a linear negative gradient on net accumulation beginning from the point of maximum accumulation and adjusting the gradient in ablation rate, so as to place the steady-state ice margin at its historical terminus determined by end moraines.

Geologic records suggest that soft beds underlaid large areas of the Laurentide Ice Sheet (Hicock and Dreimanis, 1992; Clark and Walder, 1994), like those currently found beneath West Antarctic ice streams (Blankenship et al., 1986) and several valley glaciers (Blake et al., 1992; Humphrey et al., 1993; Iverson et al., 1995). We specified the distribution of soft beds in our model according to the nature of the present surficial geology and underlying bedrock. Fine-grained till that, when water-saturated, would readily deform beneath an ice sheet nearly completely mantles areas of sedimentary bedrock in central and western Canada and the Great Lakes region today, so exposed bedrock is largely absent. In contrast, discontinuous coarse-grained till with a large fraction of exposed bedrock is typical of areas of crystalline bedrock of the Canadian shield and Appalachian regions. On the basis of these observations, we specified a hard bed over crystalline bedrock and a soft bed over areas of sedimentary bedrock (Fig. 1), in a manner similar to two previous reconstructions (Boulton et al., 1985; Fisher et al., 1985).

LAURENTIDE ICE SHEET RECONSTRUCTION

We reconstructed the Laurentide Ice Sheet using the above-described flowline model by computing ice thickness, flow, and other properties along 56 predetermined flowlines that cover the general pattern of ice-sheet flow suggested by a paleogeographic map of the Laurentide Ice Sheet constructed from glacial geology (Dyke and Prest, 1987). This map constrains the location of ice margins, ice divides, and the paths of modeled flowlines as determined by a comprehensive interpretation of glacial geologic data. The map does not, however, constrain ice thickness (aside from determining the direction of decreasing surface elevation), and this is why our model adds independent information to the otherwise observationally constrained pattern of ice flow.

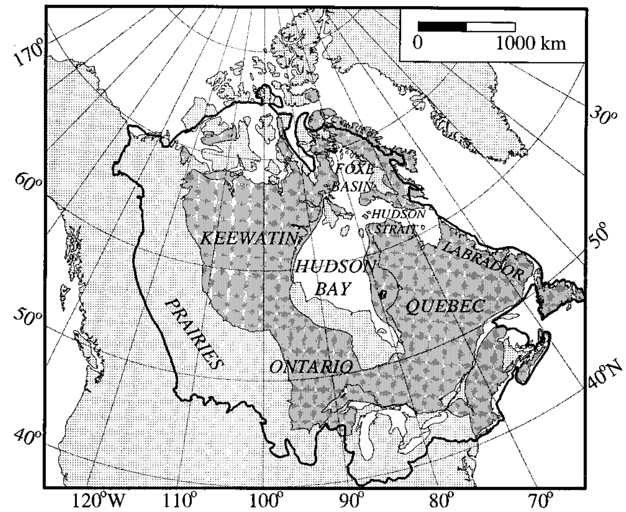

Figure 1. Extent of Laurentide Ice Sheet (heavy black line) on North America during last glacial maximum about 18 000 ^{14}C yr B.P. (from Dyke and Prest, 1987). Areas of soft beds used in model are shown by light shading within ice-sheet boundary as well as unshaded areas within ice-sheet boundary that are currently under water (e.g., Hudson Bay). Areas of hard beds used in model are shown by darker shading. Also shown are geographic names referred to in text.

The main feature of the paleogeographic map used to define the flowlines is a prominent ice divide that extends east-west from central Labrador across southern Hudson Bay and then bends north over Keewatin (Dyke and Prest, 1987). When we used the value of effective viscosity (5.2×10^8 Pa·s) for the soft-bed area underlying Hudson Bay and Hudson Strait, however, the model-predicted position of this ice divide was displaced far south of its mapped position. The resulting ice sheet is characterized by a U-shaped divide surrounding very low elevation ice (800–1200 m above sea level [asl]) over Hudson Bay and extending through Hudson Strait.

To reproduce the ice-divide position indicated on the paleogeographic map, we increased the effective viscosity of the soft bed in the Hudson Bay and Hudson Strait areas to 3.3×10^{10} Pa·s. Although this value is well within the range suggested by other studies (Paterson, 1994), it is significantly higher than the 5.2×10^8 Pa·s value used in the soft-bedded regions of the western and southern margins to fit ice-surface longitudinal profiles reconstructed there (Mathews, 1974; Clark, 1992). This viscosity contrast, which is constrained by the ice-divide position and the ice-surface profile data, suggests that hydrological conditions and other bed parameters were dissimilar between the core of the ice sheet (Hudson Bay and Strait) and its western and southern periphery at the time the ice divide was active.

In our reconstruction of the Laurentide Ice Sheet (Fig. 2), three domes reaching elevations up to 3600 m asl are superimposed on the main ice divide, and a fourth dome occurs over Foxe basin. The locations of the domes over Keewatin, Quebec, and Foxe basin are constrained by the flowlines derived from the paleogeographic map. The highest elevation reached by our reconstruction, however, is associated with a dome southwest of Hudson Bay that is not on the paleogeographic map. In our reconstruction, this dome reflects the high elevation reached by one flowline that traverses an extensive area of crystalline bedrock west of Lake Superior. We are not aware of any glacial geologic data that record the presence or absence of the Lake Superior dome.

In general, the ice-sheet surface topography is best described as a broad plateau with elevations of 2000–2500 m asl centered over the area of crystalline bedrock (Fig. 1) and surrounded on its southern, western, and northwestern sides (corresponding to areas of low-viscosity till) by a low brim of ice ranging in elevation from 500 to 1500 m asl (Fig. 2). The corresponding ice volume for this reconstruction is 19.7×10^6 km^3, which is equivalent to 49 m of global sea level.

Figure 2. Reconstructed surface topography of Laurentide Ice Sheet (500 m contour interval, Albers equal-area projection) at last glacial maximum about 18 000 ^{14}C yr B.P. Ice margin is from Dyke and Prest (1987).

COMPARISON WITH OTHER RECONSTRUCTIONS

We compare our reconstruction of the Laurentide Ice Sheet with the CLIMAP and ICE-4G reconstructions (Fig. 3). The CLIMAP (maximum) reconstruction (CLIMAP Project Members, 1981) (Fig. 3A), which has been used in previous GCM experiments of the last glacial maximum (Manabe and Broccoli, 1985; Kutzbach and Guetter, 1986), is significantly larger both in volume and in elevation than our reconstruction (Fig. 2). The ice dynamics employed in the CLIMAP reconstruction (Hughes, 1981) lack treatment of the very low basal stress regime associated with soft deforming sediment below significant portions of the ice sheet, although the CLIMAP reconstruction does include specification of basal sliding. The CLIMAP reconstruction thus displays a single, large ice dome centered over Hudson Bay, where surface elevations exceed 3800 m asl (Fig. 3A).

In the central and western areas of the ice sheet, our reconstruction is 500 to 1000 m lower than the CLIMAP reconstruction; the two are similar in elevation over southeastern Quebec and Labrador (Fig. 3B). The large elevation difference west of Lake Superior reflects the additional ice dome in that area featured in our reconstruction. The CLIMAP (maximum) reconstruction contains 34.2×10^6 km^3 of ice (85 m of global sea level), or 75% more ice than contained in our reconstruction.

Perhaps the most significant reconstruction with which to com-

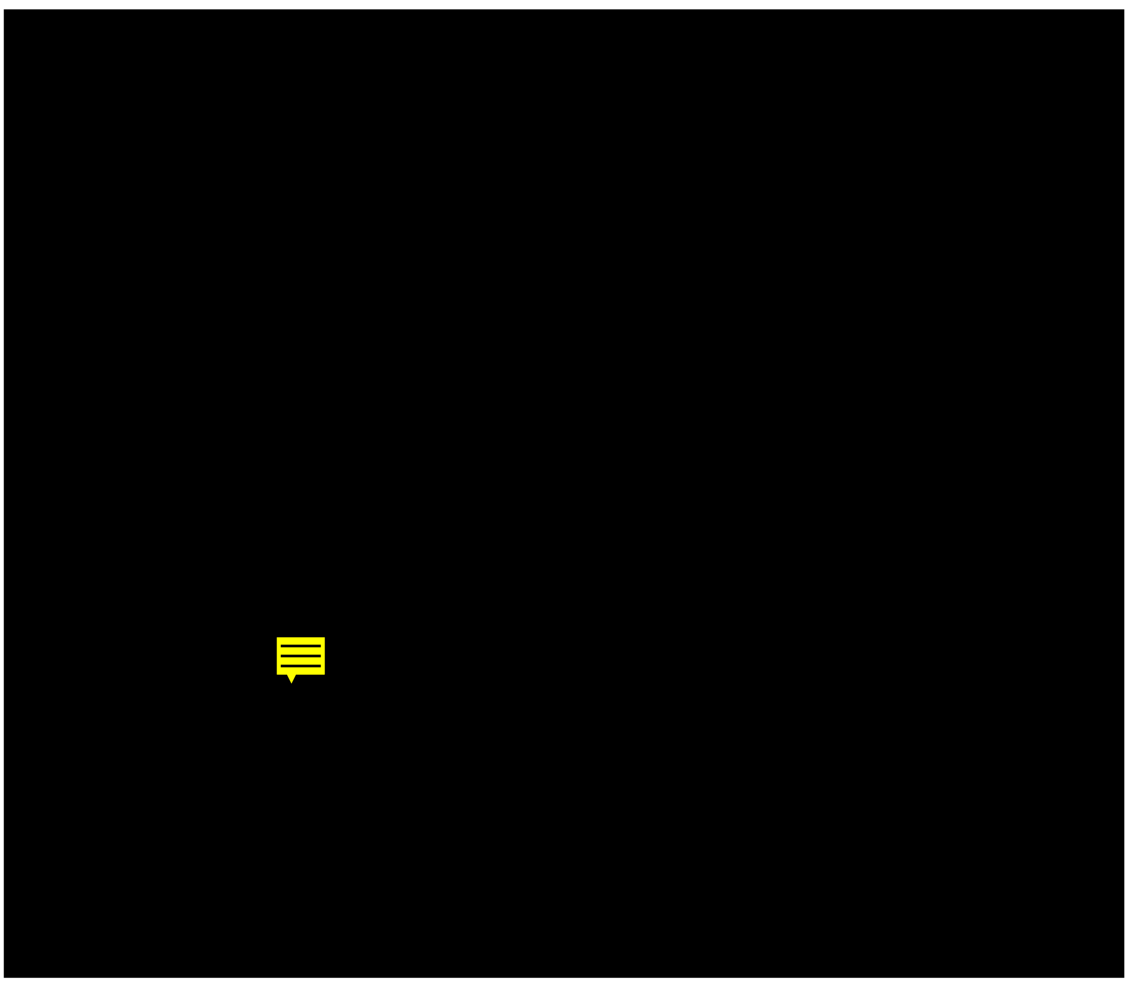

Figure 3. A: CLIMAP Project Members (1981) (maximum) reconstruction of Laurentide Ice Sheet (500 m contour interval, Albers equal-area projection) at last glacial maximum about 18 000 ^{14}C yr B.P. B: Difference map between our reconstruction (Fig. 2) and CLIMAP (maximum) reconstruction of Laurentide Ice Sheet (500 m contour interval, Albers equal-area projection). C: ICE-4G reconstruction of Laurentide Ice Sheet (500 m contour interval, Albers equal-area projection) at last glacial maximum about 18 000 ^{14}C yr B.P. (Peltier, 1994). D: Difference map between our reconstruction (Fig. 2) and ICE-4G reconstruction of Laurentide Ice Sheet (500 m contour interval, Albers equal-area projection).

pare our results is the ICE-4G reconstruction (Peltier, 1994). ICE-4G is significant because it is based on the inversion of relative sea-level observations, rather than ice-dynamics considerations, as in our model. ICE-4G thus illustrates the size and shape of the Laurentide Ice Sheet that are most consistent with these important observations, which otherwise place no constraints on our reconstruction and that by CLIMAP. Comparison of ICE-4G can be considered an important validity test of our reconstruction. If our reconstruction compares favorably with ICE-4G, it suggests that the size and shape of the Laurentide Ice Sheet associated with our assumptions about the glacial geologic record and soft-bed dynamics are consistent with relative sea-level observations.

Our reconstruction shows surface elevations and morphological features similar to those of the ICE-4G reconstruction (Fig. 3C). These include the main ice divide spanning the ice sheet. In both ICE-4G and our reconstructions, surface elevation along this main divide varies between 2000 and 2500 m asl. Other similar surface morphologies include ice domes southeast and southwest of Hudson Bay, over Keewatin, and over Foxe basin, and a ridge crossing the western Canadian Prairies, although this ridge is farther south in ICE-4G than in our reconstruction. Peltier (1994) only reported the ice-volume contribution of combined North American ice sheets (Laurentide, Cordilleran, Innuitian, Greenland, and Iceland), so the Laurentide Ice Sheet contribution is not distinguished from that of its neighbors. In the ICE-3G model (Tushingham and Peltier, 1991), however, the Laurentide Ice Sheet contains 86% of the ice volume ($\sim$55 m of global sea level) of these combined ice sheets. Assuming a similar relation applies in ICE-4G (W. R. Peltier, 1995, personal commun.), then the Laurentide Ice Sheet accounts for $\sim$52.5 m of global sea level, which is within 7% of our reconstruction.

The difference map shows that our reconstruction is generally higher over hard-bedded regions and lower over soft-bedded regions than ICE-4G, although most elevation differences are $<$500 m (Fig. 3D). Our results could be made to more closely match the ICE-4G reconstruction for the soft-bedded regions underlying the western and southern ice-sheet periphery if we were to increase the effective viscosity of subglacial sediments. We are reluctant to make this adjustment, however, because moraine elevations (Mathews, 1974; Clark, 1992) suggest that ice-surface elevations, and thus viscosity, cannot be significantly higher. Ice-sheet loading in the soft-bedded regions of the Great Lakes area and western Canadian prairies is not as well resolved by relative sea-level data as other parts of the Laurentide Ice Sheet (Peltier, 1994; Tushingham and Peltier, 1991). A viscoelastic Earth model (Clark et al., 1994) similar to that used in ICE-4G, however, has constrained the ice-loading history in the Great Lakes region from tilted proglacial-lake shorelines. This independent constraint on low ice-surface elevations is consistent with the glacial geology (i.e., height of moraines) (Clark, 1992). We thus believe that ice cover over the southern and western soft-bedded regions of the Laurentide Ice Sheet was thinner than represented in ICE-4G.

CONCLUSIONS

Agreement between our reconstruction and the ICE-4G reconstruction supports the conclusion that soft-bed ice dynamics is a fundamental control on Laurentide Ice Sheet shape and volume. The ICE-4G reconstruction represents the shape and volume that is most consistent with observations of relative sea-level change and other geodynamic considerations. Our reconstruction is independent of these observations and considerations and is based primarily on glacial geologic indicators of flow direction and simple ice-dynamics considerations that feature enhanced flow over soft beds where subglacial sediments lubricate the ice-bed interface. We believe that our reconstruction and the ICE-4G reconstruction are complementary. Their agreement on a similar reduced topography in comparison to the CLIMAP reconstruction suggests that observed relative sea-level changes on which ICE-4G was based can be attributed to the soft-bed dynamics featured in our model. This conclusion implies that adequate understanding of soft-bed ice dynamics is essential to the development of boundary conditions for use in atmospheric GCM experiments intended for the investigation of ice-age climate dynamics. Of particular importance, given the influence of soft-bed dynamics on ice-sheet surface elevation and the associated blocking of atmospheric winds, will be the identification of feedbacks and control mechanisms that determine when, where, and how soft basal sediments can develop in response to climate forcing.

ACKNOWLEDGMENTS

Supported by National Science Foundation grants SBR-9205322, EAR-9205274, EAR-9405117, and OPP-9218078. We thank P. Bartlein, P. Behling, and J. Kutzbach for providing data, K. Currans for computer expertise, J. Kimerling for cartographic assistance, and J. Andrews and N. Humphrey for reviews.

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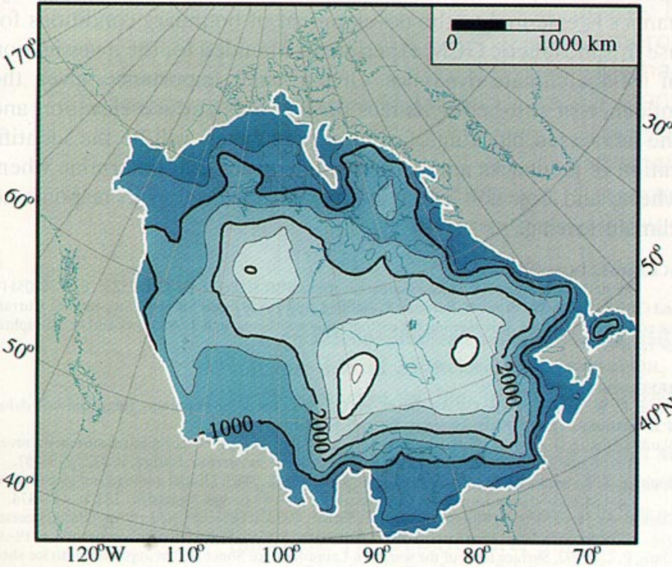
Manuscript received January 8, 1996
Revised manuscript received April 29, 1996
Manuscript accepted May 14, 1996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