*In A. A. Snelling (Ed.) (2008). Proceedings of the
Sixth International Conference on Creationism (pp. 263–273).
Pittsburgh, PA: Creation Science Fellowship and
Dallas, TX: Institute for Creation Research.*

# Simulation Analysis of Glacial Surging in the Des Moines Ice Lobe

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## Abstract

We analyze the Des Moines Ice Lobe of the Laurentide Ice Sheet (a main portion of the glacier that flowed into the United States) using finite element simulations to explore plausible surging scenarios that can reduce ice motion time scales from thousands of years to a couple of decades. We chose the Des Moines Ice Lobe of the Laurentide Ice Sheet, because of its relatively simple geometry. Previous studies considered idealized geometries of continental scale to investigate parameters related to the surging phenomena (cf., Horstemeyer & Gullett, 2003). These continental scale simulations of the Laurentide Ice Sheet provide boundary conditions for our local scale finite element simulations to allow us to examine effects of varying precipitation rates on the larger ice sheet. To further the work of Horstemeyer and Gullett, we performed three dimensional simulations, added a deformable basal till layer, and modified the problem domain from a generic dome to a slab representing the front edge of the Des Moines Ice Lobe. These three dimensional simulation results illustrate clear surging lobing effects that have been observed in nature.

## Keywords

Glacier, Surging, Material modeling, Internal state variable, Des Moines Ice Lobe

## Introduction

In contrast to the uniformitarian paradigm of multiple ice ages, Oard (1990) and Vardiman (1994, 1996, 1997), based a biblical frame of reference, have advocated a single ice age following the catastrophic global Genesis Flood. These authors argue that warm post-Flood oceans at the mid and high latitudes together with high levels of volcanic ash and aerosols induced a post-Flood ice age. Subsequent cooling of the oceans and decrease in post-Flood volcanism, in turn, led to the termination of the ice age. In a mathematical sense, an abrupt rise in ocean temperature resulting from the catastrophic Flood caused high levels of precipitation and ice sheet growth in the high latitudes. This ocean temperature anomaly decreased in a nonlinear fashion to yield our present day climate. However, interspersed within this nonlinear decrease in temperature were oscillations that arose from fluctuations in seasonal temperature.

From an uniformitarian perspective, one of the primary arguments for multiple ice ages is evidence for multiple surges in the main ice sheets. Clearly, the evidence does point to multiple surges. Surging is basically high rate glacial motion. In fact, multiple surging occurs in modern glaciers during the different seasons as the temperature cycles. The frequency of these surges however is much higher than those associated with the uniformitarian paradigm. Not that uniformitarians do not recognize these higher frequency seasonal surges, but they argue for lower frequency ones as well. When a surge has a large amplitude, they call it an ice age. Our calculations show that, both large and small amplitude surges can occur on time scales consistent with the creationist paradigm. Oard (1990) and Vardiman (1994, 1996, 1997) provide a framework for this understanding of glacial dynamics.

Oard's estimates of average ocean temperature and ice volume since the Flood can be divided into the following five intervals: (a) immediate post-Flood period, (b) ice build-up period, (c) maximum glaciation period, (d) glacial retreat, and (e) equilibrium. Although surging and retreat can occur periodically within a year during the different seasons, the periods mentioned here have the mean global averages of glacial ice in view. Our simulation study does not distinguish between glacier or ice sheet, because the varying parameters can represent either a glacier or ice sheet. For simplicity, we shall henceforth use the term glacier for both.

Horstemeyer and Gullett (2003) were the first to analyze the mechanics of glacial surging in terms of a biblical understanding of earth history. They studied certain parameters related to material properties and environmental conditions as derived from modern

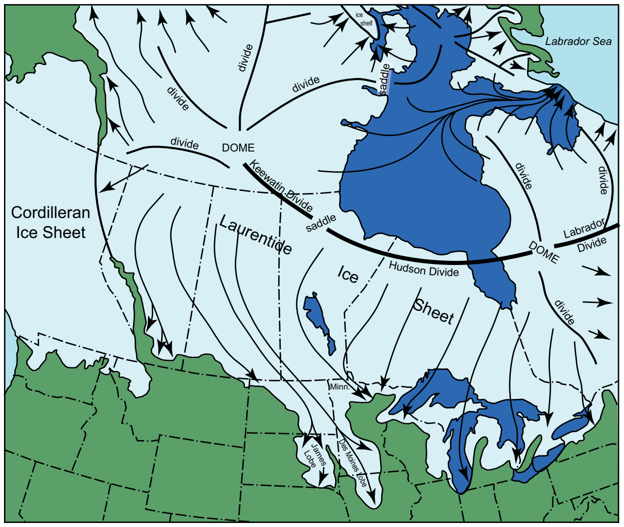

**Figure 1.** Laurentide Ice Sheet and location of Des Moines Ice Lobe.

laboratory studies and field investigations. The goal was to elucidate possibilities of high ice flow rates based upon several parameters: ice/snow material behavior with its microstructure/inclusion features, ice/snow accumulation rates and boundary conditions, temperature effects of the ice/snow pack, geometry of the glacier, and the ice/ground interfaces. Their work showed that the rapid advancement of a glacier, known as surging, could be applied to the post-Flood setting and the biblical time frame, provided precipitation rates were sufficiently high. This work also identified the most important parameters involved with glacial surging, namely, precipitation rate, ice-ground interaction, and material behavior. The Horstemeyer and Gullett (2003) work did not include deformable till beneath the ice. The current work investigates this feature.

From an uniformitarian time frame one of the last ice age periods was the Late Wisconsin Glaciation period. In the Northern Hemisphere the large ice sheet was known as the Laurentide Ice Sheet as shown in Figure 1 and covered approximately an area equivalent to the present Antarctic Ice Sheet (Andrews, 1987). The Laurentide Ice Sheet extended as far south as Illinois, Indiana, and Ohio in the United States. In some locations the ice sheet had small protrusions along the edges, also known as lobes. For this study the Des Moines Ice Lobe is chosen, because of its fairly simple geometry and the availability of literature data that can be used for comparison. The work of Horstemeyer and Gullett (2003) simulated the large scale Laurentide Ice Sheet, but in this study a smaller region is simulated, namely, the Des Moines Lobe.

Few simulations of the Laurentide Ice Sheet have been performed. In finite difference simulations of the ancient Laurentide Ice Sheet, Marshall and Clarke (1997) assumed the leading edge to have a velocity of 41 m/yr. A temperature gradient existed through the vertical thickness ranging from –42°C to 0°C. The surge and quiescent periods of the Laurentide Ice Sheet were 0.48–19.15 km/yr and 0.11–3.26 km/yr, respectively, in the Marshall and Clarke (1997) simulations. Their results support the plausibility of internally generated instabilities (MacAyeal, 1993a, b; Payne, 1995) that induced the surges, and the amplitudes depended upon the ice dynamics and initial temperature configuration. Heinrich events in the Laurentide Ice Sheet have been claimed to produce abnormal iceberg production and surging events. To describe a Heinrich event, Verbitsky and Saltzman (1995) developed a scaling law that has basal melting as the mechanism to induce surging and streaming of the ice. The high rate velocities depend upon the physical properties of the ice sheet, the magnitude of the geothermal heating, the magnitude of frictional heating, and the elevation of the ice sheet.

This study simulates the possibility of glacial surging in the Des Moines Ice Lobe from a creationist time frame. In the following section, we discuss the literature involving the Des Moines Ice Lobe. Then we describe the setup of the finite element simulations of part of the Des Moines Ice Lobe. The boundary conditions for the simulations are taken from the previous work by Horstemeyer and Gullett (2003) who focused on a continental scale analysis similar to the large Laurentide Ice Sheet. The boundary conditions for the Des Moines Ice Lobe are varied for a parametric study on the surging rates. We then discuss our results and offer some conclusions.

## Des Moines Ice Lobe

The Des Moines Ice Lobe was a protrusion of the Laurentide Ice Sheet roughly 500 km long by 300 km wide located in Minnesota and Iowa (Clark, 1992). Its thickness is debated in the literature. Some authors claim the lobe was up to 300 m thick (Clark), while others claim the lobe was as much as 900 m thick (Hooyer & Iverson, 2002). The latter thickness is problematic because till consolidation pressures are in conflict with such thicknesses, and evidence strongly suggests that the ice was thin at the edge of the Laurentide Ice Sheet (Oard, 2004). Therefore, we adopt the 300 m value even though the other could be considered in a later study. The trough-shaped lowlands of Minnesota and Iowa facilitated the formation of this lobe (Patterson, 1998). Its advance was apparently driven by Laurentide ice streams to the north (Patterson, 1997). Patterson offers evidence that the Des Moines Ice Lobe advanced repeatedly during the Late Wisconsin Glaciation. This may indicate that within the biblical time frame after the

Flood the ice lobe advanced and partially retreated several times during that approximately 500 year interval.

Several reconstructions have been offered for the Laurentide Ice Sheet and the Des Moines Ice Lobe. Clark (1980), Mickelson, Clayton, Fullerton, and Borns (1983), and Andrews (1987) did extensive work on reconstructing the ice sheet as a whole. See Andrews (1982) for a thorough review of the subject. The geometry of the lobe used for the study was taken from a combination of the previously cited sources. In our simulations, we assume an increased ice thickness to the north that provides the initial conditions for the surging that occurred southward into the United States.

Glacial geologists have realized the importance of subglacial soil in glacier mechanics. Alley, Blankenship, Bentley, and Rooney (1986) were the first to claim that the ice steam B motion in West Antarctica was due to the deformation of till below the ice. Their work is the basis for the deforming bed model for glacier motion. Later Alley (1991) further suggested the deforming bed mechanism was responsible for deposition of the southern Laurentide till sheets. The glacier community has realized the importance of till, and Van der Meer, Menzies, and Rose (2003) has responded by performing an entire study on formalized till classification. Others have shown that till deformation is the explanation for many features of a number of glaciers (Truffer, Harrison, & Echelmeyer, 2000; Truffer, Echelmeyer, & Harrison, 2001).

## Finite Element Analysis

Finite element analysis (FEA) has previously been applied to simulating glaciers. For example, Hooke, Raymond, Hotchkiss, and Gustafson (1979) analyzed an idealized two dimensional glacier using a plastic material model. In our study, we apply the commercial software ABAQUS (2007) to model the Des Moines Ice Lobe). Our approach is a global-local approach, meaning that a global perspective with a very large territorial domain is first simulated, from which boundary conditions are extracted for a local finite element calculation. The previous work performed by Horstemeyer and Gullett (2003) was a global approach which treated a very large ice dome that represented of the entire continental Laurentide Ice Sheet. The leading edge displacement values found by that analysis were used as the boundary conditions for the local Des Moines Ice Lobe simulation. In particular, the local scale focused upon the leading edge of the Des Moines Ice Lobe. Figure 2 shows the global and local scales in their respective locations.

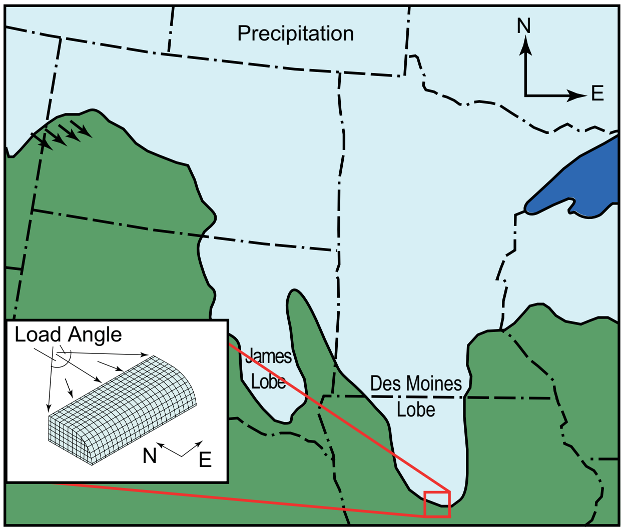

**Figure 2.** Global continental scale picture of the Laurentide Ice Sheet with the local scale Des Moines Ice Lobe Section illustrating the finite element mesh and boundary condition used. The global continental scale was influenced by precipitation rates far north of the local scale. The local scale boundary velocities were retrieved from previous global simulations of Horstemeyer and Gullett (2003) and applied to the back edge of the Des Moines front edge lobe illustrated here.

We varied several parameters to gain understanding of glacial surging dynamics. The key parameters were the upstream ice velocity and the deformation properties of the basal till. Other parameters were the coefficient of friction between the ice and bedrock, the porosity of the ice, and the temperature gradient in the ice sheet. The ice stream velocity employed as the boundary condition for the Des Moines Lobe is directly related to the precipitation rate assumed upstream on the Laurentide Ice Sheet. The global finite element simulations of Horstemeyer and Gullett (2003) assumed a range of precipitation rates from 0.001 km/yr to 0.1 km/yr above the global dome glacier that yielded a maximum edge flow rate of 0.5 km/yr. For comparison, the modern record annual precipitation in the wettest part of Hawaii was equivalent to 0.0176 km/yr. The 0.5 m/yr rate was assumed as the inflow boundary condition for the front edge Des Moines Lobe used in these simulations. For our local simulations we assumed the vertical precipitation on the Des Moines Lobe to be negligible compared to the horizontal ice stream source velocities from the main ice sheet. For the local simulation of the Des Moines Ice Lobe, the maximum applied ice velocity was 0.5 km/yr. This velocity was also corroborated with some modern measurements from Antarctica. The Antarctic Ice Stream B has observed surging rates of 0.8 km/yr (Whillans, Bolzan, & Shabtaie, 1987; Whillans, Jackson, & Tseng, 1993) the Antarctic Rutford Ice Stream surging rate was documented at 0.4 km/yr (Doake, Frolich, Mantripp, Smith, & Vaughan, 1987). We note that Mickelson, Clayton, Fullerton, and Borns (1983) asserted that 7.0 km/yr surging rates occurred on the Quaternary Ice Stream Lobes over Lake Michigan in the Laurentide Ice Sheet ranging over a region of 87,500 km$^2$. These extremely high rates similar to the Marshall and Clark (1997) simulated surging rates related to the Laurentide Ice Sheet appear to occur for a very short season.

Various aspects of the finite element simulations as illustrated in the local mesh shown in Figure 2 will now be discussed. The length of the initial frontal lobe that we are simulating was 10 km; the width was 24 km; and the height was 5 km. The section was split into approximately 9400 finite elements with a 1:1:1 aspect ratio with a thickness of 0.5 km for each element. A mesh refinement study was conducted to ensure the validity of the results with a smaller element thickness of 0.25 km, but this smaller element size increased the lobe front edge displacements by only 0.2%. This implies that the mesh shown in Figure 2 was adequate for this study. The sides of the leading edge were free from tractions so that transverse displacements could be allowed to show three dimensional lobing. The northern back section of the Des Moines Ice Lobe was the location of the ice stream velocity boundary condition. A load angle was applied in-plane to the back northern side of the mesh with different angles (22.5° and 45°) to examine the transverse lobing effect. The bottom layer of the mesh comprised deformable till for several of the simulations; otherwise it was ice. Bedrock was modeled as a rigid, non-deformable analytical surface. Most of the upper layers comprised polycrystalline ice. In all cases whether it was till or ice touching the bedrock, sliding was allowed to occur. The interaction between the ice and the till was idealized for this analysis as completely tied together. The top of the till was connected to the bottom part of the ice glacier. Future simulations should allow the ice to slide over the till as authors have pointed out the importance of this basal layer of till-ice mixture (Knight, 1997; Wu & Hutter, 1999). When no till was present, the ice had either no friction or friction with a coefficient of friction of 0.2 at the bedrock interface.

The materials used in this simulation were ice and till (glacial sediment). The material model used was the Bammann internal state variable (ISV) model (Bammann, Chiesa, Horstemeyer, & Weingarten, 1993). This ISV model has been historically used for metals but has fairly recently has been applied to geomaterials (Horstemeyer, 1998; Horstemeyer & Gullett, 2003). The experimental data used for till was taken from Hubbard and Maltman (2000) and Kamb (1991). The Hubbard data contained both low and high pressure water-till content, whereas, the Kamb data contained only high pressure water-till content. Till is permeable so water will diffuse from the ground into the subglacial material and this can affect the glacier flow (Eyles, 2006).

**Table 1.** Material constants for till and ice for Bammann internal state variable model.

| Material Constant | High Pressure Till | Low Pressure Till | Polycrystalline Ice |
|---|---|---|---|
| $C_1$ (MPa) | 0 | 0 | 3.02E-05 |
| $C_2$ (K) | 0 | 0 | -2744 |
| $C_3$ (MPa) | 0.3 | 0.3 | 9.56 |
| $C_4$ (K) | 0 | 0 | -478.9 |
| $C_5$ (1/sec) | 1.00E-05 | 1.00E-05 | 1.00E-05 |
| $C_7$ (1/MPa) | 235.5 | 1275 | 0 |
| $C_9$ (MPa) | 87.45 | 60.5 | 0 |
| $C_{13}$ (1/MPa) | 1178 | 6300 | 0 |
| $C_{15}$ (MPa) | 33.46 | 105.4 | 1.0 |

As mentioned previously the Bammann Internal State Variable (ISV) (Bammann, Chiesa, Horstemeyer, & Weingarten, 1993) material model was used for this study. This ISV model can capture nonlinear, large deformation effects with varying temperatures, strain rates, and deformation paths. One advantage to this model is the physically based meanings of the model constants that can be correlated to experimental stress-strain data. The Kamb (1991) experimental data was converted to stress-strain behavior for model calibration. See Bammann et al. (1993) for details on the description of the constants and the complete explanation of the model. The constants were experimentally correlated with the use of a nonlinear least squares method. Table 1 contains the model constants for the high pressure till, low pressure till, and polycrystalline ice. The experimental stress-strain data and the model correlations for the high pressure till and the low pressure till are shown in Figure 3. The high pressure

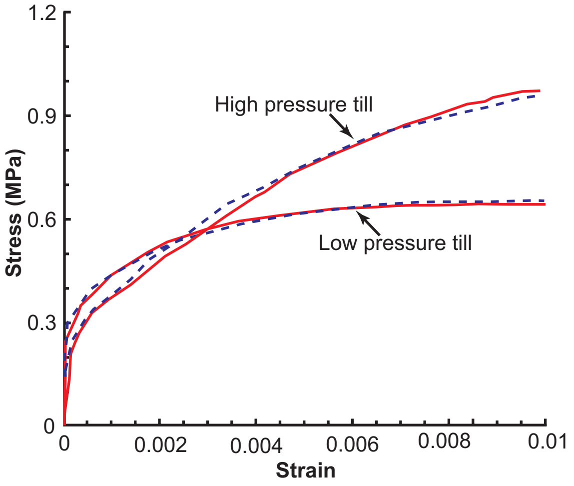

**Figure 3.** Model correlations and experimental stress-strain data for high pressure till and low pressure till. Experimental data are shown in the dashed lines, and the model results are given by the solid line.

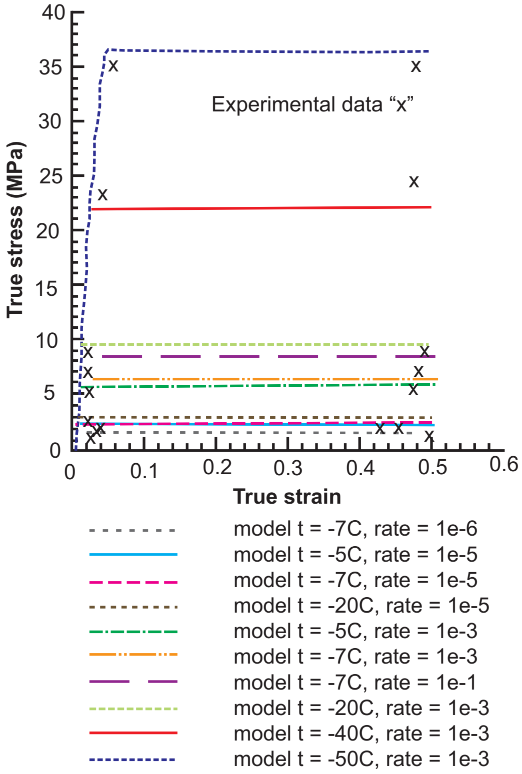

**Figure 4.** Model correlations and experimental stress-strain data for polycrystalline ice.

till data shown in Figure 3 has a greater maximum stress than the low pressure data in Figure 3. This implies the lower pressure till will deform under lower stresses (and loads) than the higher pressure till. We also note that the lower pressure till experienced a saturation stress much sooner than the higher pressure till. This indicates that more hardening will occur in the higher pressure till and thus add more resistance to any possible localization phenomena. The localization phenomena can occur more easily when saturation stresses are reached (c.f., Horstemeyer, 2000). Subsequent to localization is typically a shear banding, which in turn induces a rather sudden movement of material, which is what the glaciologists term “surging” for ice. To complete the discussion of the material model, we show in Figure 4 a plot of the model and experimental data for polycrystalline ice that was reproduced from Horstemeyer (1998). Note that the ice also shows a clear early saturation stress, indicating a great potential for localization and subsequent shear banding.

In order to characterize the influence of different physical attributes of the glacier, we undertook a parametric study. This parametric study focused on the metric of the displacement over a period of time (or velocity) of the front edge lobe. The following items were varied: the applied ice stream velocity in a solid ice glacier, ice porosity, pressure on the till, the applied temperature gradient, the basal coefficient of friction with bedrock, angle of slope to evaluate gravitational effects, and the in-plane load angle from the upstream velocity. For the applied velocity parametric study, the simulations contained only ice, and the ice stream velocity ranged from 0.5 km/yr to 6.5 km/yr. The Horstemeyer and Gullett (2003) study showed precipitation rates from the post flood environment would produce a 0.5 km/yr advancement rate. Marshall and Clarke, (2003) performed simulations that showed that the maximum velocity of an ice stream can approximately reach 6.5 km/yr due to thermodynamic considerations. As such, we employ the 0.5 km/yr and 6.5 km/yr in the present parametric study. The ISV model in this study has the ability to include damage evolution in terms of porosity/crack levels. Initial porosity/crack levels of 0, 0.0001, and 0.01 were simulated. The roll of till was also examined using a high pressure and a low pressure material. We compare these to the simulation with pure ice. Different temperature conditions were also simulated. For one several conditions, we employed a temperature gradient ranging from a surface temperature of 0 Kelvin and 220 Kelvin (Paterson, 1981) to 236 Kelvin at the bottom surface. An isothermal case throughout the lobe at 220 Kelvin was also simulated for comparison. The interaction between the hard ground and the glacier was captured using a coefficient of friction. All the simulations assumed a coefficient of friction of 0.2 except for the parametric study on friction, which included a no friction case. We also varied the slope of the bedrock to 45° to allow analysis of the body force effect arising from gravity. The last parameter that we varied included the in-plane load angle, which we varied from 22.5° to 45°. This load angle directed the up-stream velocity vector that loaded the Des Moines Lobe front edge.

## Discussion/Results

Modeling the debris-rich basal ice layer of glaciers has received little attention. One of the few studies was from Knight (1997), who considered several possible rheological effects within this layer. They included the following: accretion of ice; diagenesis of ice via strain, hydrology, and chemistry; entrainment of debris from bump regelation, structural deformation, cavity squeezing, and vein flow; and thickening by subjacent accretion, folding, and thrusting. All of these can be influenced by the pressure from above the ice/basal plane interface that increases normal stresses and hence friction. The friction in turn heats the interface and melts the ice. (We do not include melting in our study.) The subsequent water then lubricates and saturates the soil leading to highly nonlinear deformation in the soil.

Some of these aspects of the debris-rich basal ice layer have been studied by others. Erosion rates can be related to glacier flow rates. Drewry (1986) observed on Glacier d'Argentiere in the Alps that an erosion rate of 3.6 cm/yr correlated to a glacier flow rate of 250 m/yr. Oard (1990) estimated a 5 cm/yr erosion rate. Erosion is also not considered in this study. Verbitsky and Saltzman (1995), based upon theoretical analysis and field observations of ice elevation, atmospheric $CO_2$, and surface temperature, believed that frictional and advective heating rather than geothermal heat flux are the most likely cause of basal ice melting that led to the Heinrich surging events of the Laurentide Ice Sheet over North America. They asserted that water saturated sediment lubricated glacier beds (Clarke, Collins, & Thompson, 1984; MacYeal 1993a, b) and hence encouraged the surging of glaciers. Kamb (1991) claimed that the highly nonlinear deforming till bed below a glacier (in particular Antarctic Ice Stream B) is what causes the ice streaming through the glacier. The claim is that frictional shear heating melts ice and the resulting water saturates the soil to cause large nonlinear deformation.

Figure 5 shows the shear strain history results from the simulations when friction was included between the ice and bedrock with no till. Clearly the ice front edge lobing shown over this 20 year period illustrates the three dimensionality of the phenomenon. The shear strains on and near the top reach approximately 30% inelastic strains at Year 20. Although not shown in Figure 5, the shear strains on the bottom of the surging ice reach almost 100% strain. Although these strain levels are considered large, much greater strain levels are anticipated as the years progress beyond the 20 year level shown here.

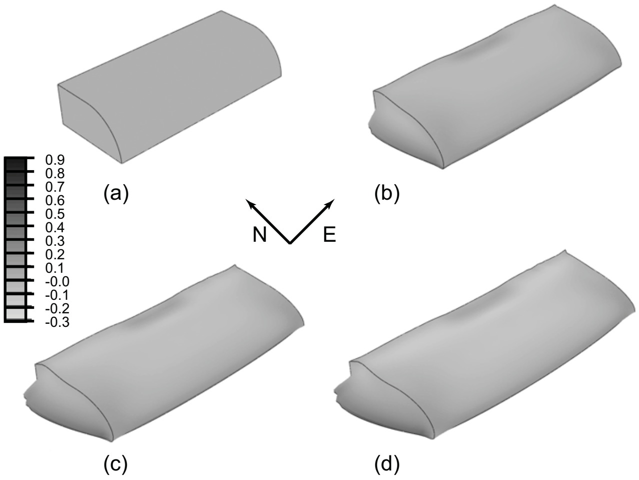

**Figure 5.** Three dimensional shear strain history of ice front edge lobing shown over a twenty year period: (a) start time at Year 0, (b) at Year 7, (c) at Year 14, and (d) at Year 20 with friction with the bedrock and no till.

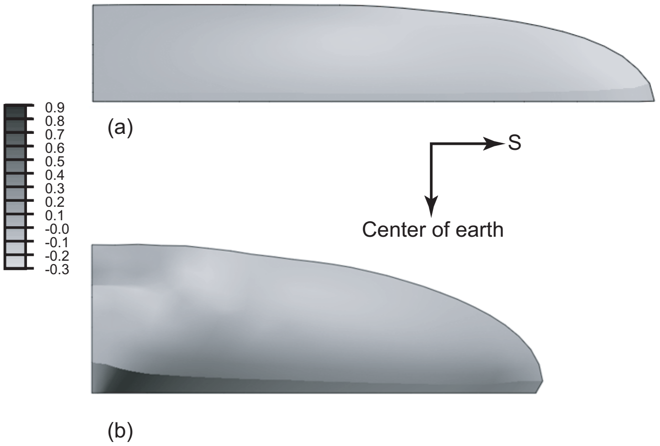

**Figure 6.** Shear strain history contours at Year 20 indicating the difference between (a) a frictionless boundary with bedrock and (b) friction (coefficient of friction was assumed to be 0.2) boundary with bedrock showing the much greater displacements with the frictionless boundary but much greater shear strains with the friction boundary.

Figure 6 shows a two dimensional slice through the center of the three dimensional deformation front edge moving in the southern direction. The shear strain contours shown in Year 20 here depict the differences between the cases when friction and no friction were included in the simulations. Clear trends were evident. The shear strains were much greater within the ice when friction was included at the ice/bedrock interface; however, front edge displacements were greater when no friction was included at the ice/bedrock interface. One can also see a shear band forming in the "friction" case with a much more diffuse shearing in the "no friction" case. From Figure 6, the

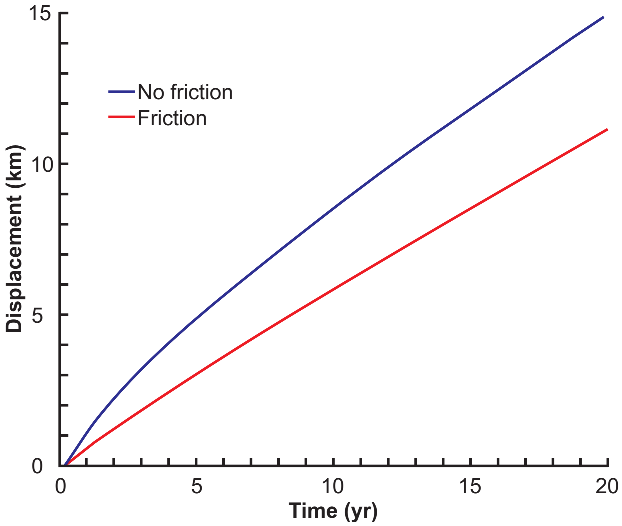

**Figure 7.** Southern displacement versus time for Des Moines Ice Lobe front edge comparing the differences between the case with friction and no friction between the ice and bedrock. Note the gradient (that is, velocity) at Year 20 is approximately 0.6 km/yr for no friction illustrating an increase from the 0.5 km/yr applied velocity due to deformation.

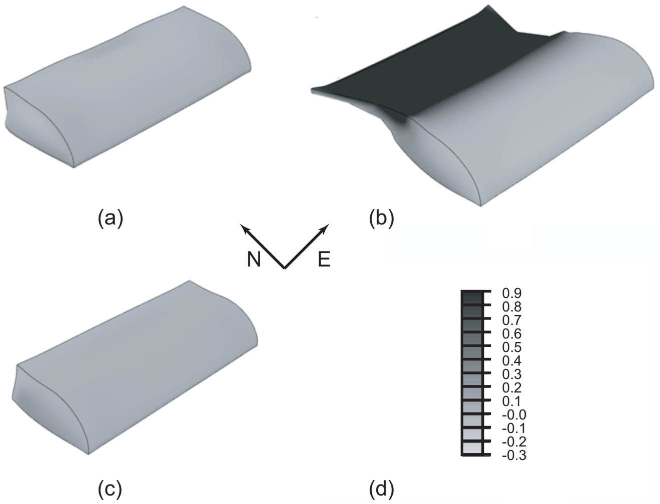

**Figure 8.** Three dimensional shear strain contours at Year 3 comparing the (a) horizontal glacier motion with just an applied upstream velocity, (b) a 45° slope glacial motion with an upstream velocity and a gravitational body force, and (c) a 45° slope glacial motion with just a gravitational body force with no upstream velocity.

associated southern displacement versus time for Des Moines Ice Lobe front edge comparing the differences between the case with friction and no friction between the ice and bedrock is illustrated in Figure 7. Note the gradient (that is, velocity) at Year 20 is approximately 0.6 km/yr for no friction illustrating an increase from the 0.5 km/yr applied upstream velocity due to the ice deformation.

Figure 8 compares three cases related to gravity and the slope of the bedrock under the glacier. Clearly, the deformational pattern was much different when the slope was 45° as opposed to the horizontal (0° slope) condition. The lobe was much more intensified for the greater angle as the body force arising from the gravitational potential energy drove the lobing. In fact, the effect of the body force was greater than the applied velocity from the upstream push. The case with both gravity and the applied velocity showed irregular deformation due to most of the glacier trying to move forward faster than the applied velocity could push. Figure 9 shows a comparison of the displacements for the three cases (45° slope with gravitational body force plus applied velocity, 45° slope with gravitational body force, and horizontal applied velocity, which would be the same as the 45° slope without gravity). Clearly, the effect of the body force due to gravity plays a stronger role than the upstream in-plane velocity.

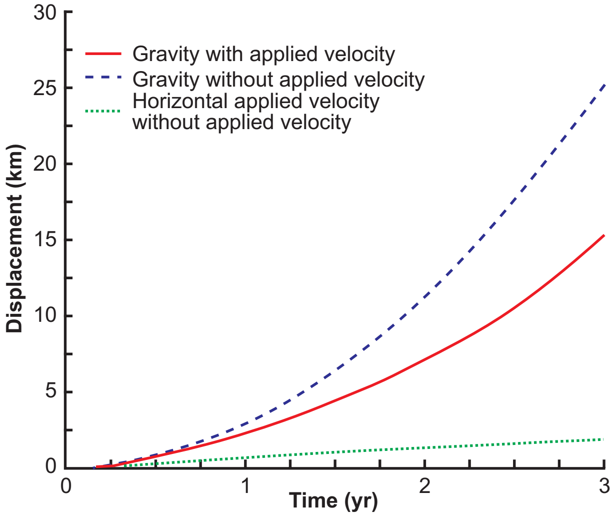

**Figure 9.** Southern displacement of Des Moines Ice Lobe front edge comparing (a) 45° slope with gravitational body force plus applied velocity, (b) 45° slope with gravitational body force, and (c) horizontal applied velocity, which would be the same as the 45° slope without gravity.

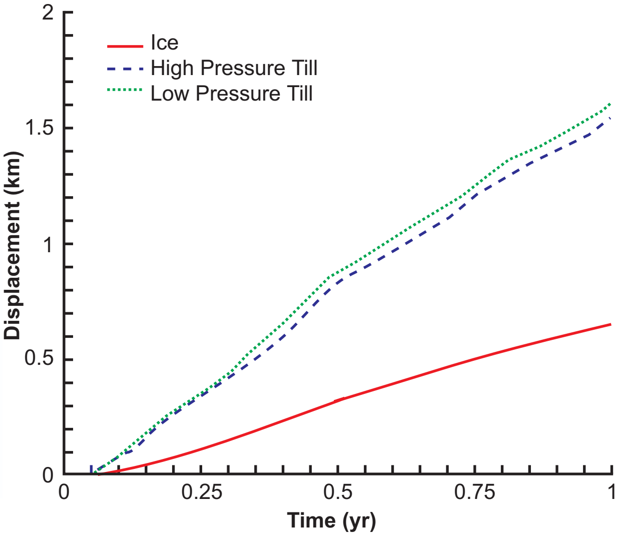

**Figure 10.** Southern displacement versus time for Des Moines Ice Lobe front edge comparing the differences between ice with friction (coefficient of friction was 0.2), low pressure till, and high pressure till at the ice bedrock interface up to year 1. Note the increase of displacement (and hence velocity) of till increasing the rates by approximately three times that of the case when no till is present. Note also that low pressure till admitted even slightly higher velocities than high pressure till.

Figure 10 shows the southern displacement versus time for Des Moines Ice Lobe front edge comparing the differences between ice with friction (coefficient of friction was 0.2), low pressure till, and high pressure till at the ice bedrock interface up to Year 1. Note the increase of displacement (and hence velocity) of till increasing the rates by approximately three times that of the case when no till was present. Note also that low pressure till admitted an even slightly higher front edge velocity than the high pressure till. One could anticipate this result since the low pressure till illustrated a higher ductility and less work hardening rate than the high pressure till as illustrated in Figure 3. When till was included, the

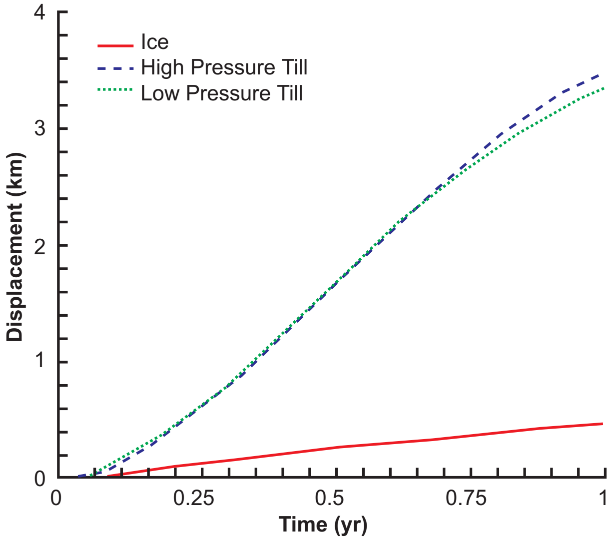

**Figure 11.** East-west displacement versus time for Des Moines Ice Lobe front edge comparing the differences between ice with friction (coefficient of friction was 0.2), low pressure till, and high pressure till at the ice bedrock interface up to year 1. Note the increase of displacement (and hence velocity) of till increasing the rates by approximately seven times that of the case when no till is present.

major deformation occurred within the till and not the ice relatively speaking. Because the low pressure till has a lower saturation stress at a lesser strain than high pressure till, the glacier riding on lower pressure till moved further than when the glacier rode on the high pressure till. This allows the lower pressure till to begin a steady quicker deformation than the high pressure till. This confirms the modern observation that Kamb (1991) claimed in which the highly nonlinear deforming till bed below a glacier (in particular Antarctic Ice Stream B) can cause the ice surging via streaming through the glacier.

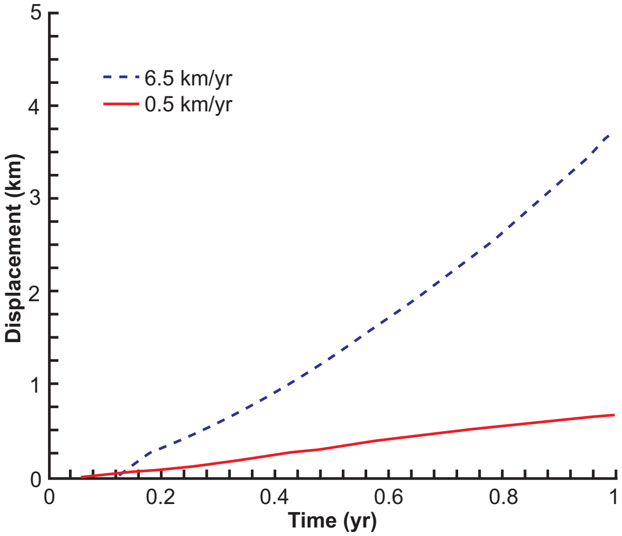

**Figure 12.** Southern displacement of the Des Moines Ice Lobe comparing two different applied velocities showing the nonlinear response of the front edge due to the deformation rheology of the ice with a condition of ice with friction at bedrock and no till. Only in one year, the higher applied velocity was 13 times greater but the displacement rate at the front edge was only eighttimes that of the lower applied velocity.

While Figure 10 shows the southern displacement of the front edge, Figure 11 shows the east-west displacement of the front edge. The lobing clearly has an east-west component and the trend follows that of the southern direction displacements. The low and high pressure till admits greater side edge displacements than just having ice on bedrock. When comparing the transverse east-west displacement with the southern displacements between Figures 10 and 11, one can see that the transverse displacements was approximately three times that of the forward displacement. This indicates that glaciers would have a tendency to spread as opposed to thrusting forward. However, given the ruggedness and constraints from bedrock and mountains, the flow of surging glaciers is (and was) typically not unconstrained. Regardless, many evidences of spreading of glaciers are clear and these particular simulations demonstrate the phenomena.

Figure 12 shows the southern displacement of the front edge the Des Moines Ice Lobe comparing two different applied velocities. The nonlinear response of the front edge is due to the deformation rheology of the ice. After one year of deformation, the higher applied velocity was 13 times greater (6.5 km/yr versus 0.5 km/yr) but the displacement rate at the front edge was only eight times that of the lower applied velocity. One would expect this ratio to change as a function of time, but the applied value of 6.5 km/yr was expected to occur only in a more transient season. However, the extreme upstream velocities show a much greater front edge displacement than the more regulated upstream velocity of 0.5 km/yr. The case of 0.5 km/yr came from the Horstemeyer and Gullett (2003) result and the 6.5 km/yr came from Marshall and Clark (1997) and Mickelson, Clayton, Fullerton, and Borns (1983). Table 2 shows a summary for each of the different cases, and distance if the average rate were extrapolated to 500 years. This is only an assumption for illustrative purposes. There are many other factors that would influence glacial motion in the 500 year advancement. In order to cover the area of the Laurentide Ice Sheet, 2000 km of displacement

**Table 2.** Results of the ice stream parametric study.

| Ice Stream Velocity (km/yr) | Average Displacement Rate (km/yr) | Displacement at 500 yrs (km) |
|---|---|---|
| 0.5 | 0.5 | 250 |
| 6.5 | 4.0 | 2000 |

is needed from the uniformitarian perspective of total displacement of the mass. In the creation model (Oard 1990), the snow falls generally in place and moves according to the laws of physics locally. The ice sheet thickness would be mainly related to the average storm tracks and the closeness to the moisture sources. With the ice stream velocities of approximately 0.5 km/yr, the Des Moines Ice Lobe would have surged locally at its front edge. With the ice stream velocity of 6.5 km/yr the total uniformitarian distance could be reached in the 500 year span.

The idealized simulations in this paper do not consider melting in the ablation zone or seasonal fluctuations of precipitation. These parameters although currently difficult to quantify via numerical simulations, would enhance the velocity rates to a greater rate than what is shown here.

Another variable that was considered in this parametric study was that of temperature. Ice moves faster at warmer temperatures due to deformation and if there existed proglacial lakes ahead of the ice stream. Warmer temperatures can melt the ice at the ice-ground interface, but it is unclear how much the melting affects the leading edge displacement rate. Future work could be done to quantify the influence of melting. The simulations involving the various temperature gradients and isothermal conditions did not affect the front edge displacement rates very much. Horstemeyer and Gullett (2003) also claimed that the temperature effect was a tertiary parameter. However, the reader should keep in mind that melting is currently not used in these simulations.

Porosity/crack evolution was also a parameter studied in this effort, and the front edge displacement percentage difference over a 10 year time span was less than 0.01% for the cases considering an applied upstream velocity of 0.5 km/yr with coefficient of friction of 0.2.

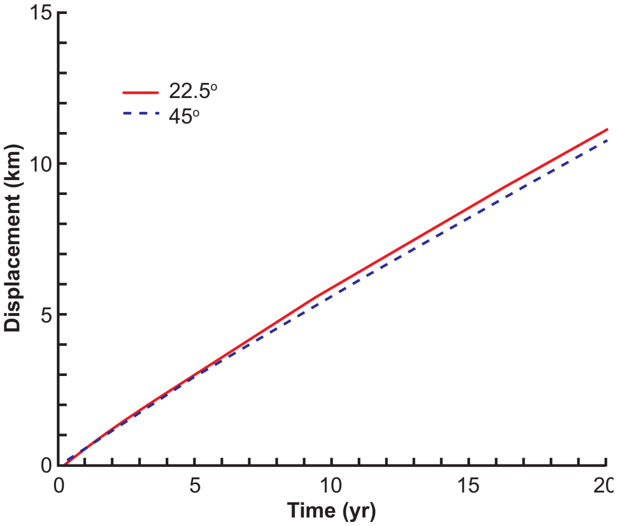

**Figure 13.** Southern displacement of the Des Moines Ice Lobe comparing the load angle changes in the transverse plane arising from the global continental Laurentide Ice Sheet upstream velocity.

Figure 13 shows the difference in the southern displacement of the Des Moines Ice Lobe front edge as the load angle changes in the transverse plane arising from the global continental Laurentide Ice Sheet upstream velocity. One could anticipate different load angles based upon the side constraints of bedrock and/or mountains. Clearly, the angle changes here affect the transverse east-west displacements more than the forward southerly displacements as illustrated in Figure 13.

One should note that all of these simulations are ideal cases of a glacier leading edge motion. The friction between the glacier and the ground does not generate any heat in the simulations. In reality, any friction generates heat which in turn would increase the temperature of the ice and increase the glacier motion. For the till cases the glacier can entrap the till up into the ice and redeposit it farther down as the glacier moved. Another issue is that the simulations ignored the influence of plowing. Plowing is where the till is not deformed, but pushed forward. Some authors argue that the Des Moines Ice Lobe's primary surging mechanism was surface plowing (Hooyer & Iverson, 2002). Some other assumptions made in these simulations about the till were the uniform thickness and a constant pressure. Due to the terrain and complex glacier shape the till may be thick or could not even be present between the glacier and bedrock. The pressures of the basal water can vary considerable depending on the amount of ice above the till and the local water drainage system below the glacier (Eyles, 2006). Even though many simplifying assumptions were made, the simulation results showed qualitatively that the glaciers could have advanced large distances over a short time period.

## Conclusions

Field studies and finite element simulations provide information that illustrates how ice/snow packs can reach fairly fast motion rates. Marshall and Clarke (1997) performed simulations that illustrated that the Laurentide Ice Sheet experienced surging oscillations with peak velocities reaching approximately 6.5 km/yr. If this rate was reached for longer periods of time and lasted the 500 year period that Oard (1990) believed followed the Genesis Flood, then surging could have been a major factor that affected the consequent glaciation. Furthermore, conjectures and interpretations about the periphery of glaciers in the past may be quite different if surging was present. Certainly the Laurentide Ice Sheet did not sustain those velocities over that period but clearly seasonal fluctuations could allow greater local velocities that are plausible for the North American glacier for a 500 year time frame following the Flood. In order to quantify the Laurentide Ice Sheet advance, part of the Des Moines Ice Lobe geometry was simulated to show the feasibility of the rapid advance of the Laurentide Ice Sheet during the single ice age following the flood. The ultimate goal of this parametric study performed in this paper is that no matter what the physical attributes of the glacier, the large ice stream velocities produced by upstream high precipitation rates will cause the glacier to physically move at the high displacement rates. The advance from the previous simulations of Horstemeyer and Gullett (2003) is that this particular study included three dimensional analysis, deformable till into the simulations, different porosity/crack levels, various temperature conditions, various slopes, and different load angles from the upstream glacier. The surging rates show the physical plausibility that the ice sheets could in fact fit the biblical time frame of the ice age.

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