The Proceedings of the International Conference on Creationism

Volume 5
Print Reference: Pages 165-174

Article 19

2003

Will Mechanics Allow a Rapid Ice Age Following the Flood?

Mark F. Horstemeyer

Phil Gullett

WILL MECHANICS ALLOW A RAPID ICE AGE FOLLOWING THE FLOOD?

MARK F. HORSTEMEYER, PHD
5074 Pisces Ave, Livermore, CA 94550

PHIL GULLETT, PHD
5333 Lenore Ave, Livermore, CA 94550

KEYWORDS: ice age, fracture, deformation, surging, material behavior, finite element simulations

ABSTRACT

This work presents mechanisms related to the ice age that followed the worldwide Flood discussed in Genesis. Certain parameters related to material properties and environmental conditions are discussed from modern-day field studies, laboratory tests, and numerical simulations to illustrate connections to the past ice age. The goal is to elucidate possibilities of high ice/snow flow rates (surging) that are observed today and speculate if they could have occurred during the ice age that followed the Flood. Field studies indicate that surging, high rate glacial motion, could be caused by five possible mechanisms: soft deformable stratum, “warm” ice, impurities, steep geometric slopes, and large amounts of basal water. To quantify the effects of these five potential surging-enhancement mechanisms, parametric finite element studies were conducted with the following varying 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. Of all the parameters, the finite element analyses show that the ice/ground interface plays the largest role on surging behavior. Furthermore, the mechanisms that cause surging of a glacier could have induced the rapid motion of the glacier/ice sheet that followed the Flood.

INTRODUCTION

One ice age following the catastrophic global Genesis Flood has been asserted from a Biblical frame of reference by Oard [1] and Vardiman [2-4] in contrast to the evolutionary paradigm of multiple ice ages. Warm post-Flood oceans at the mid and high latitudes and volcanic ash and aerosols induced the post-Flood ice age. Subsequent cooling of the oceans and decrease in post-Flood volcanism lead to the end of the ice age. In a mathematical sense, a singularity from the catastrophic Flood caused a massive increase in cold weather and precipitation. This gradually decreased in a nonlinear, non-monotonic fashion to our present day climate. However, interspersed within this nonlinear descent were oscillations that arose from fluctuations of seasonal temperature changes.

In the evolutionary paradigm, one of the arguments for multiple ice ages is related to multiple surges that have been asserted from circumstantial evidences. Clearly, the evidence does point to multiple surges in the past. 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 faster than those asserted in the evolutionary paradigm. Not that evolutionists do not recognize these higher frequency seasonal surges, but they argue for lower frequency surges with much larger amplitudes. These very large amplitudes are what they call the ice ages. Clearly, the large and small amplitude varying frequency surges can be interpreted through the creationist paradigm in a much shorter timeframe. Oard [1] and Vardiman [2-4] provide a framework for such an assessment.

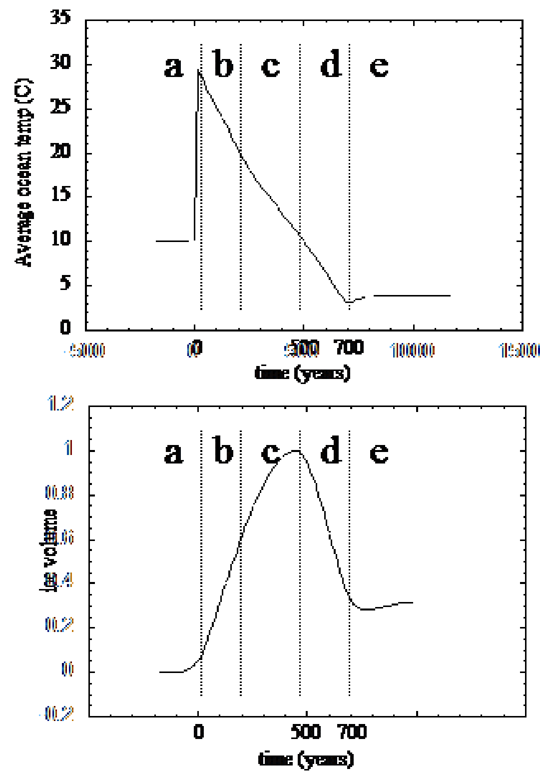

Figure 1. Comparison of average ocean temperature and ice volume versus time illustrating (a) preflood, (b) ice build-up period, (c) maximum glaciation period, (d) some retreating, and (e) coming to equilibrium period. [1].

Taking Oard's estimations of average ocean temperature and ice volume represented through history, Figure 1 shows a breakdown of the different periods. The periods distinguished in Figure 1 are (a) pre-Flood, (b) ice build-up period, (c) maximum glaciation period, (d) glacier retreating, and (e) equilibrium. Although surging and retreating can occur periodically within a year in the different seasons, the demarcation periods mentioned here describe the mean global averages of the glacier. Also, when the term glacier is used, connotations of slow moving large bodies of ice and snow emerge. In relation to the U.S., the paradigm of a large glacier moving from Canada into the U.S. is prevalent. However, Oard [1990] proposed that ice sheets developed in place from a snowblitz following the Flood, except for those regions affected by onshore flow of warm air and on the ice-free corridor east of the Rockies. Whatever the terminology used and whatever the connotations resulting from that terminology, our simulation study does not distinguish between glacier or ice sheet because the varying parameters can represent either a glacier or ice sheet. In any case, we use the term glacier from herein for sake of simplicity. Also, plausible scenarios for the ice volume accumulation could be determined from climatological models. To date, these values have not been ascertained. As such, various assumptions in the finite element simulations for this study will be used.

What has not been analyzed from a biblical paradigm are the mechanics related to fast ice/snow motion. This is relevant to the Biblical creationists, because a fairly short time period (~500 yrs) is required for an ice age. In this study, certain parameters related to material properties and environmental conditions are discussed from modern-day field studies, laboratory tests, and numerical simulations to illustrate connections to the post-Flood snow/ice motion. The goal is to elucidate possibilities of high ice flow rates based upon several parameters. The first parameter is the geometry of the snow/ice pack. The thickness of the glacier or whether the leading-edge has a steep slope or domed slope could affect the leading-edge motion [5]. The second parameter of interest is related to the material properties and microstructures/inclusions that determine the phenomenological response of the material. The various measurable quantities that clearly affect the material response are the grain size and the recrystallization and polygonization of those grains, plasticity, creep, fracture, water content, impurities (volcanic dust, till), density/porosity, texture and deformation history. Each of these can indeed change the stress-strain behavior (rheology or constitutive behavior). The third parameter is the type and magnitude of the boundary condition. As mentioned earlier, we do not really know the accumulation rate of snow/ice, but at least we can assert reasonable guesses and apply those guesses to see if the leading-edge motion of the ice/snow could reach surging velocities. Furthermore, in terms of finite element analyses, it is not clear if pressure, displacement, or velocity boundary conditions are most appropriate. With these finite element simulations, we can apply any of these type of conditions and see if a difference exists in the leading-edge glacier motion. In the end, arguments regarding these questions may be irrelevant, if the simulations show the same order of velocity of glacier motion. A fourth parameter is the temperature. The temperature can affect the snow/ice pack in many ways. In some instances, temperature gradients can drive deformation more than an isothermal case. Higher temperatures can melt the ice and induce hydrolubrication between the ice/ground interface. The temperature can also change the plasticity and creep behavior of the material. As the temperature increases, the work hardening rate and stress level decrease. The final parameter of interest is related to the ice/ground interface, where ablation can occur, freezing/melting [5-6], shearing, and the addition of layers of subglacial till sometimes mixed with water and loose clay particles [7-8].

Oard [1] listed five items that could induce high rate motion related to glacial surging: soft deformable stratum, warm ice, large amounts of impurities, steep slope at periphery, and large amounts of basal water. This list is in general agreement with the previous paragraph. However, some of these are not independent parameters as relations exist between, for example, warm ice and the amount of basal water. In any regard, each parameter can be quantified by finite element analysis.

From each of these parameters, we focus mainly on the leading-edge ice motion and discuss it in terms of its velocity. In particular, surging, or fast ice flow, has been observed in modern glaciers. Not all glaciers experience surging, but quite a few arise, based on the parameters presented. The leading edge of a glacier typically exhibits a non-uniform geometry and sometimes even an oscillatory signature. At different parts of the glacier front, commonly referred to as the margin, retreat, advances, and surges in either direction at different locations and at the same time will occur. The oscillations comprise bed heating from geothermal heating and friction until sufficient thinning occurs. Then rapid cooling can occur to stop the surging and ice builds up again. The cycle continues as the warmer season starts up again. Although this may happen at a local region, it can also happen to the glacier as a whole. Hence, the global glacier mean directions and velocities can also be couched in terms of retreats, advances, and surges. We examine the local leading edge motion and then make inferences related to the global glacial motion.

From laboratory tests, different aspects of the microstructure and material properties will be discussed with a hint towards the material model used in the finite element analyses. The material model [9] is robust enough to capture complex interactions between microstructure and the mechanical properties. Because of the complex microstructures, inclusions, amount of water, and other impurities in ice, studies of this sort are extremely important if large scale numerical simulations of ice flow are to be performed.

FIELD STUDIES

Field studies have brought several observations of high velocity glacial motion [10-11] of modern Ranges from 70 m/yr to 91,000 m/yr have been measured. Clearly, if these rates were experienced over the 500 year time span proposed by Oard, the distances of the forward and subsequent retreat surging could have occurred across North America.

One of the most studied and interesting ice streams is in Antarctica. Ice Stream B shows a number of features that indicate past changes and ongoing changes. In Figure 2 the upstream ends of several ice stream shear margins are highlighted. Figure 2 shows the characteristic crevasse patterns, nicknamed "chromosomes," which mark the ends of several of these margin traces. These features have been shown in some cases to result from upstream migration of the ice stream. The former research camp, UpB (or "Upstream Bravo"), is visible near the center of the northern branch of the stream (south is up in the image). This figure shows a variety of relict features in the ice sheet, attesting to the rapid evolution of ice stream systems relative to most outlet glacier systems. Ice Stream C is flanked by several faint traces marking known or suspected former ice stream shear margins. At the upstream end of the ridge separating Ridge B/C (upper left in the image) several faint traces are intersected by the active shear margin of B, suggesting that flow in this area has recently reorganized.

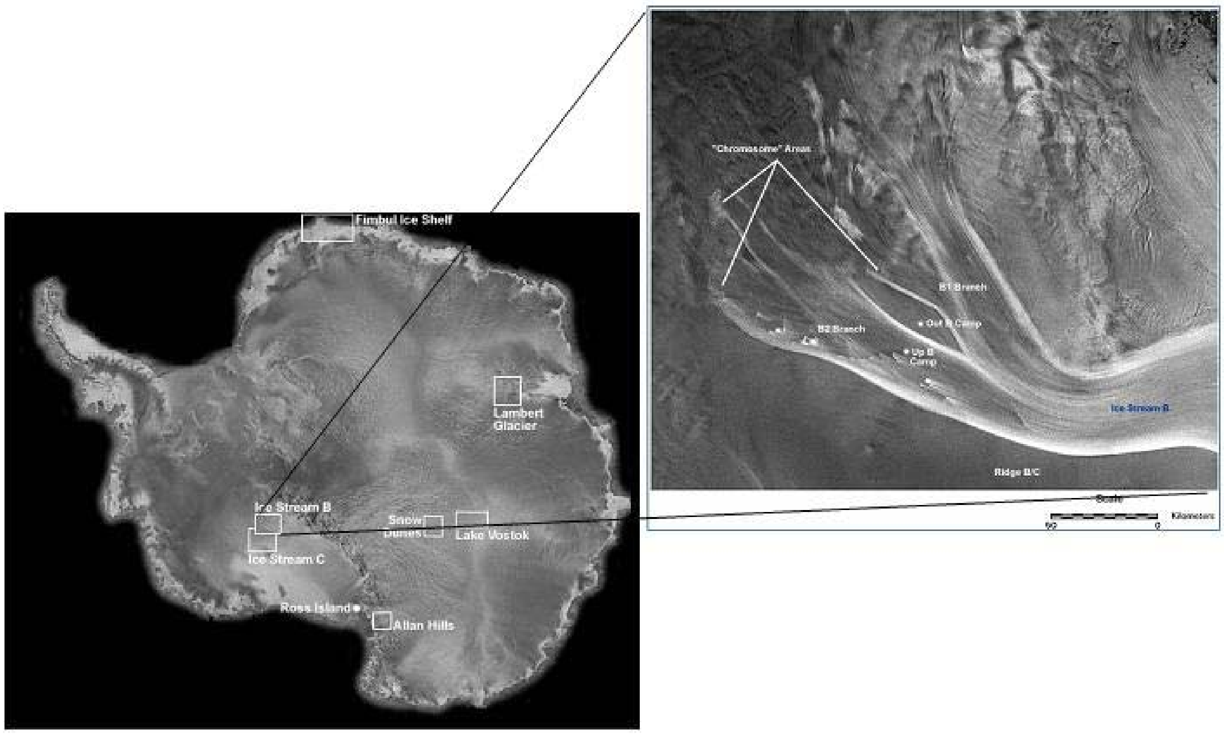

Figure 2. (a) Picture of Antartica with current glaciers and (b) Ice Stream B, a current surging glacier.

Dowdeswell et al. [12] analyzed the Svalbard, Norwegian High Arctic glacier in terms of its surging motions. They asserted that the high velocities arise from internal geometric instabilities and not from external forces. This 120 by 4500 m glacier was analyzed via an energy balance formulation. Their simulations were corroborated with experimental observations and showed by the mass balance that no more surges would be produced without the generation of more snow.

In another study, Muller and Fleisher [13] studied the Bering Glacier in Alaska by gathering aerial photos starting in 1940 up until 1993 and showed that cyclical surges and retreats occurred in various cycles over the years. The interesting find in this study was that debris was found throughout the areas where leading edges had previously been observed. Forces strong enough to grind up bedrock into the glacier as well as knock down forests as uprooted trees were found in various regions.

In finite difference simulations of the ancient Laurentide Ice Sheet, Marshall and Clarke [14] 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 was 480-19150 m/yr and 105-3260 m/yr, respectively, in the Marshall and Clarke [14] simulations. Their results support the plausibility of internally generated instabilities [15-17] 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 [18] 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.

Connections between modern and ancient glaciers have been asserted from field study data. For example, an ancient valley glacier in Black Rapids, Alaska was asserted to have moved in similar fashion as that of the Variegated Glacier, Alaska, measured at a rate of 23 km/year. If this sort of rate could occur in the post-Flood environments, then surging could affect just one glacier to move several hundred km, if not more, if the 500 year post-Flood ice age time is true as described by Oard [1].

Finite element Simulations

Various parameters were evaluated in the simulations. We assumed that an accumulation rate of snow/ice on top of a glacier experienced a fairly high rate of 0.1 km/yr. The rate was applied, and the relative motion of the glacier front edge was monitored. The dimensions of two idealized glaciers were 4 km high by 40 km long and 4 km high by 4 km long. Axisymmetric elements were used so the glacier was a conical dome in nature, and the steep edge glacier employed plane strain elements (cf. Figure 3 for an example of a steep edge). The conical dome dimensions are similar to the Greenland glaciers (Vostok, Byrd, Century, Devon, Mirny, Law Dome, and Ice Stream B) measured today. The finite element code ABAQUS was used for the simulations with the varying parameters.

GEOMETRY: THICKNESS AND SURFACE SLOPE OF GLACIER

Heinrichs et al. [19] claimed that the Black Rapids Glacier, Alaska of 1936-1937 did not change enough in ice thickness and surface slope during the surging and thus cannot be a very important feature to surging in general. However, simulations related to this study indicate that a steep slope will induce fairly high rates of displacement in the top portion of the face as shearing occurs to calve off the ice. Figure 3 shows the steep slope of the leading-edge of a glacier. Figure 4 shows a comparison of the local vertical displacements and shear strains that develop for the steep slope glacier case. These plots show the typical response regardless of temperature, material properties, or type of boundary condition. The steep slope leading-edge rate is higher than the conical dome glacier as illustrated in Figure 5 by plots of the leading-edge displacements (km) as a function of time (year) and the corresponding strain contours.

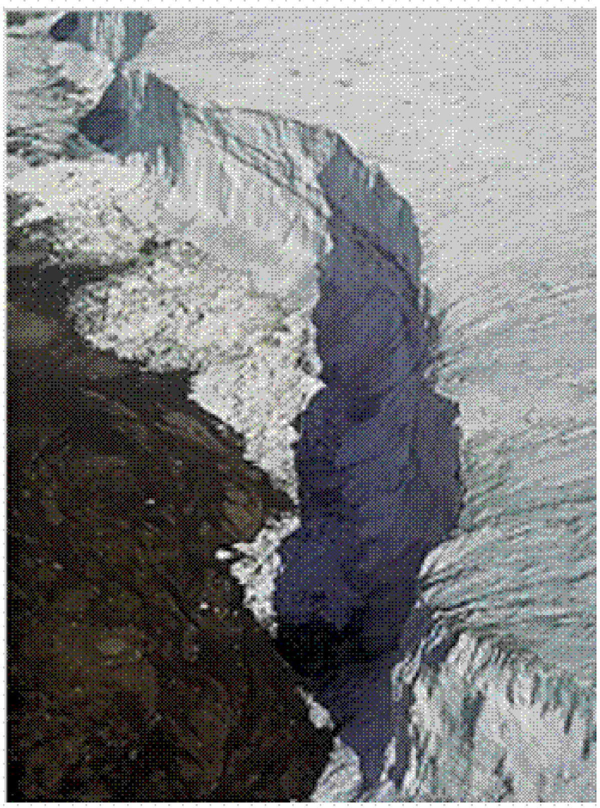

Figure 3. Picture of steep polar glacier showing ice fallen off at leading edge.

As Figure 5 illustrates, the strain localization increases in time in each case: conical dome and steep edge glaciers. In either case, the large strains weaken the ice and the excess falls off and the glacier is free to move forward upon continued deformation. However, the leading-edge displacement rate does differ between the two cases. The dome case gives a nonlinear response and the steep-edge case gives almost a linear response. However, after year 3 in the conical dome case, the gradients are similar yielding approximately a 0.75 km/yr surge rate, which tends toward the lowest surge rate values. Clearly, the geometry of the dome plays a major role in causing various mechanisms/modes of glacier deformation and hence differences in leading-edge glacial motion.

TYPE OF BOUNDARY CONDITION

Simulations with pressure, displacement, dynamic conditions, and quasi-static conditions were performed to observe the leading edge velocity effects. Regardless of the pressure or displacement boundary conditions, as the accumulation rate of snow onto a glacier increased in the simulations, the deformation increased. We varied the snow/ice accumulation rate from 0.001 km/yr to a fairly high rate of 0.1 km/yr. Certainly this is arbitrary and a more accurate applied rate could be achieved as the simulation of immediate post-Flood climatic conditions is realized. Also, since we are trying to show what was physically plausible at the time, this order magnitude of accumulation rate shows that the surging rate could indeed yield surging rates at the low end of the field measured surge rate summarized in Table 1. As the accumulation rate decreases, the curve in Figure 5 would lower thus decreasing the surging rate. As such, one key area of future research would be to calculate this snow/ice accumulation rate resulting from the climatic conditions during and after the Flood. In terms of the parametric study, whether pressure, displacement, or velocity boundary conditions were used, the leading-edge displacements and velocities of the simulated glacier were minimal.

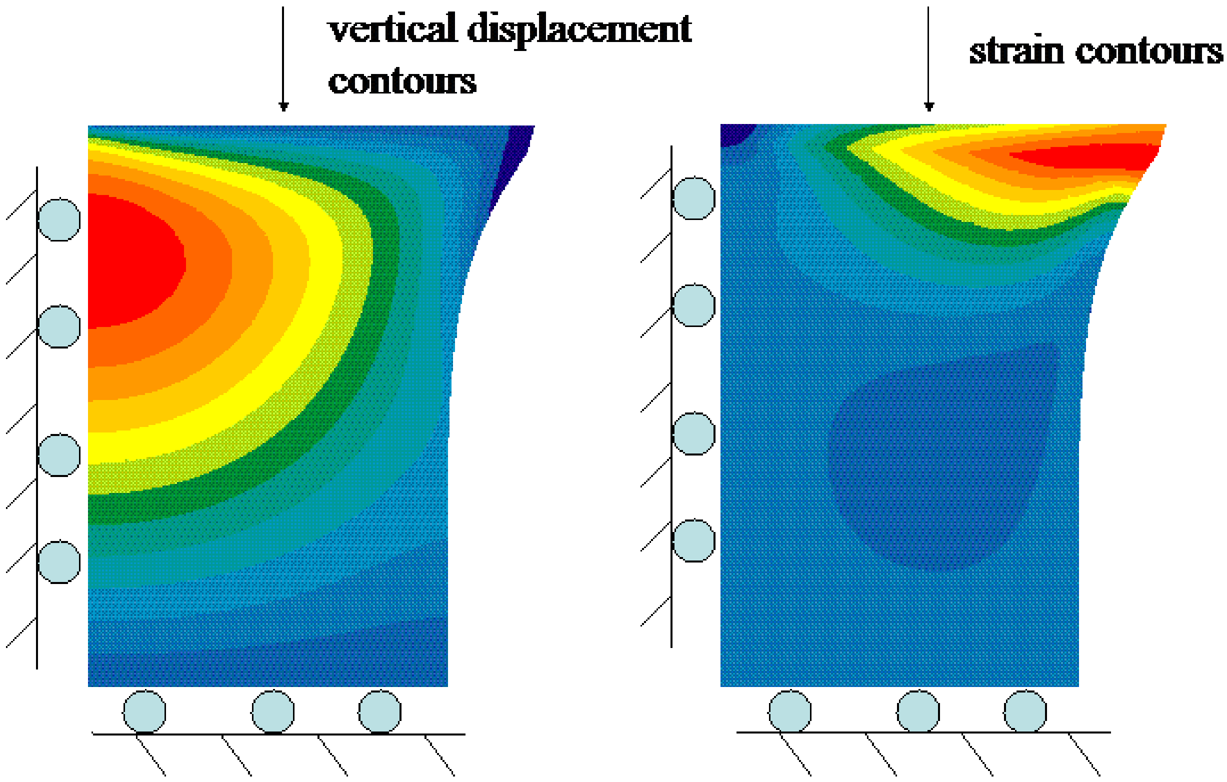

Figure 4. Simulation of steep geometry glacier shows shearing at top that would weaken the glacier and induce higher surging rates.

MATERIAL BEHAVIOR/ GRAIN SIZE/RECRYSTALLIZATION/POLYGONIZATION

The material behavior is reflected in the stress-strain response, which was modeled for various strain rates and temperatures and different genre of snow/ice [9]. Microstructural attributes that affect the stress-strain response are the grain size and the recrystallization and polygonization of grains and subgrains as deformation proceeds and/or temperature changes. Also, porosity, till, and other inclusions could also affect the stress-strain behavior. Sharp [20] showed that high strength gradients of ice through the thickness give nonsurging behavior but low gradients to strengths can give rise to surging behavior as that observed in the Eyabakkajokull, Iceland glacier. This translates to isostress contours throughout the finite element mesh. However, the finite element results of this study indicate that either a stress gradient or isostress initialization do not affect surging behavior. As such, some other mechanism may have induced the surging described in the Sharp [20] studies. Furthermore, when the stress-strain curves were altered as the different levels of temperature were changed, the leading-edge displacements and velocities of the simulated glacier were not much different.

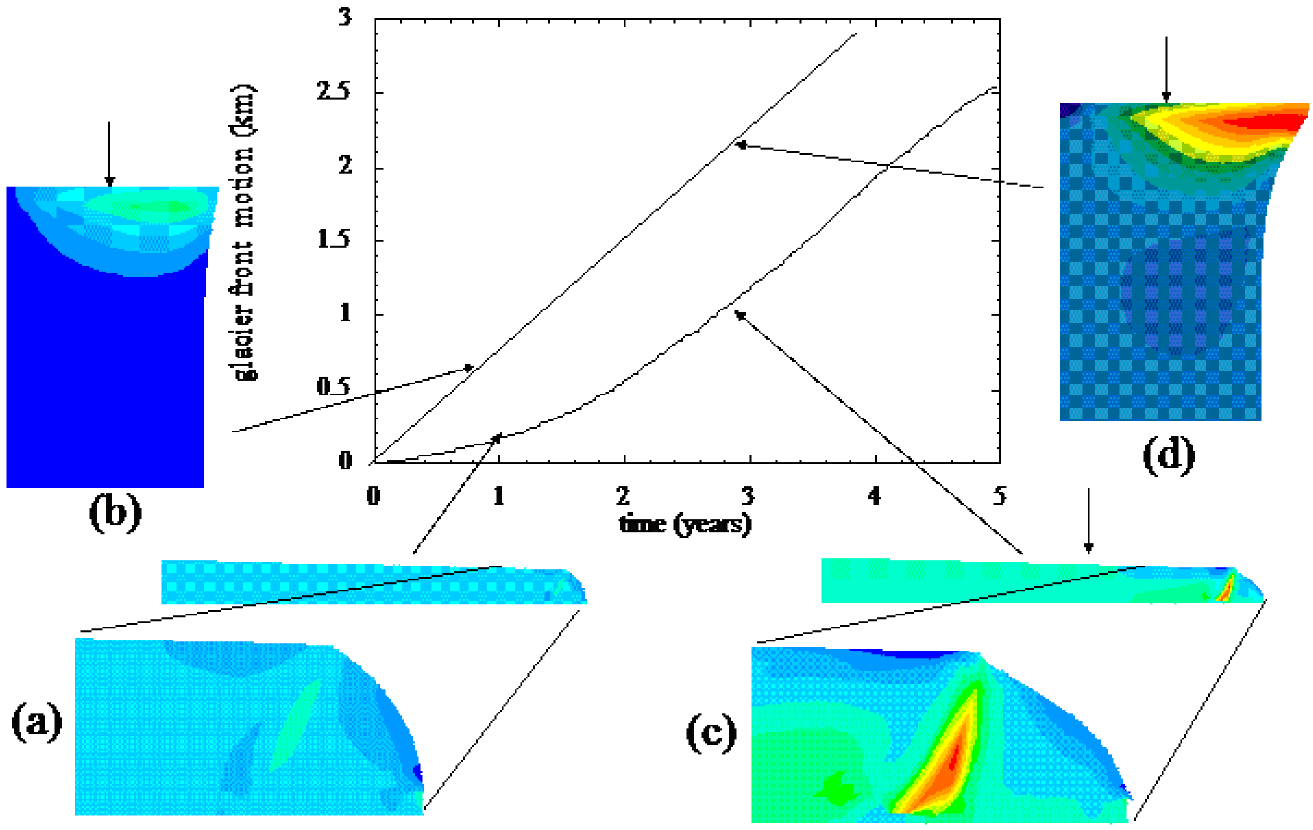

Figure 5.Plot of leading edge distance as a function of time and correlating strain contours at one year and three years for the long dome glacier simulation and steep edge glacier simulation. (a) The peak local strain for the dome at one year was 10% strain and (b) for the steep edge 5% strain. At 3 years, the peak local strains were (c)180% and (d) 50% for the dome and steep edge, respectively.

THERMAL GRADIENTS AND INITIAL TEMPERATURE

Temperature changes can cause surging as summer time appears to admit more surging than winter. Here, we discuss the affect of temperature, not on the melting or recrystallization of the material, which in turn could affect the surging rates, but just upon the deformation of crystalline ice that does not recrystallize. We performed two isothermal simulations with bounding temperatures (220K and 236K) from the Vostok glacier measurements [5] and performed a heat conduction analysis assuming steady state conditions. Ice's thermal properties for the calculations were received from Marshall and Clark [14]: specific heat capacity 2009 J /kg/K, thermal conductivity 2.1 W/m/K, thermal diffusivity 1.15e-6 m^2/s, density 910 kg/m^3. All three simulations gave minimal differences in the glacier leading edge motion indicating that the direct temperature effects do not play a role in surging behavior. However, that is not to speak to the situation if the temperature melts the ice at the ground/ice interface. In all the cases, there was a maximum surge rate of less than 1% difference between all the cases. It doesn't directly affect surging although it might melt the ice or cause recrystallization which could melt the ice.

ICE/GROUND INTERFACE

The debris-rich basal ice layer of glaciers has not had much rheological analysis; however, Knight [21] listed possible rheological effects within this layer. They include 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 could be caused by the pressure from above the ice/basal plane interface that induces normal stresses that increase friction. The friction in turn could produce these phenomena and heat up the interface thus melting the ice. The subsequent water then lubricates and saturates the soil to cause highly nonlinear deformation in the soil.

Some rheological effects have been studied by others. Drewry [22] 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 [1] estimated a 5 cm/yr erosion rate. Erosion is not considered in this study. Verbitsky and Saltzman [18] based upon theoretical analysis and field observations of ice elevation, atmospheric CO_2, and surface temperature believe that frictional and advective heating rather than geothermal heat flux are the likely cause of basal ice melting that led to the Heinrich surging events of the Laurentide Ice Sheet over North America. Water saturated sediment can lubricate glacier beds [23] and hence encourage surging of glaciers.

Kamb [24] 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 ensuing water saturates the soil to cause large nonlinear deformation.

In order to study the ice/ground interface, simulations were performed in which stress-strain curves from Kamb [24] for the ground base were used. In other simulations, we allowed an elastic foundation, friction/no friction between the ice/ground, and changing temperatures. In all of the studies, the ice/ground interface played a much greater role in the leading-edge glacier motion than the other parameters. Figure 6 shows the leading-edge glacier motion comparing no basal motion with basal motion. Figure 6 shows higher surging rates for basal motion than no basal motion. These differences were much greater than those observed by changing the temperature, boundary conditions, material behavior, and temperature. When no ground motion was allowed, ice lobes and slower leading-edge glacier rates were experienced as shown by the strain contour plots in Figure 6. When simulated ground motion and no friction at the ice/ground interface were admitted to model water effects, the leading-edge glacier motion was at its peak and in the range of the surge rates noted in [12-14].

SUMMARY

Field studies and finite element simulations show speeds of ice/snow packs can reach fairly high rates. Marshall and Clarke [14] performed simulations illustrating that the Laurentide Ice Sheet experienced surging oscillations with peak velocities reaching 6.7 km/yr. If this rate lasted the 500 year period that Oard [1] believed followed the Genesis Flood, then surging could have been a major factor that affected the consequential geology. Furthermore, conjectures and interpretations about the periphery of glaciers in the past differ if surging was present. Certainly the Laurentide Ice Sheet did not sustain those velocities over that period but clearly seasonal fluctuations could allow higher local velocities that are plausible for the North American glacier for a 500 year time frame following the Flood. Finite element simulations of various idealized glacier/ice packs show that high surging rates observed today are due mainly to the local ice/ground interface properties and materials. High surging rates that are observed today illustrate the possibility of the post-Flood snow/ice glacial/ice sheet rates. As such, when we consider the observational data and finite element simulations, we see that one ice age with the 500 year period following the Flood comprising multiple seasonal surges projected by Oard seems plausible.

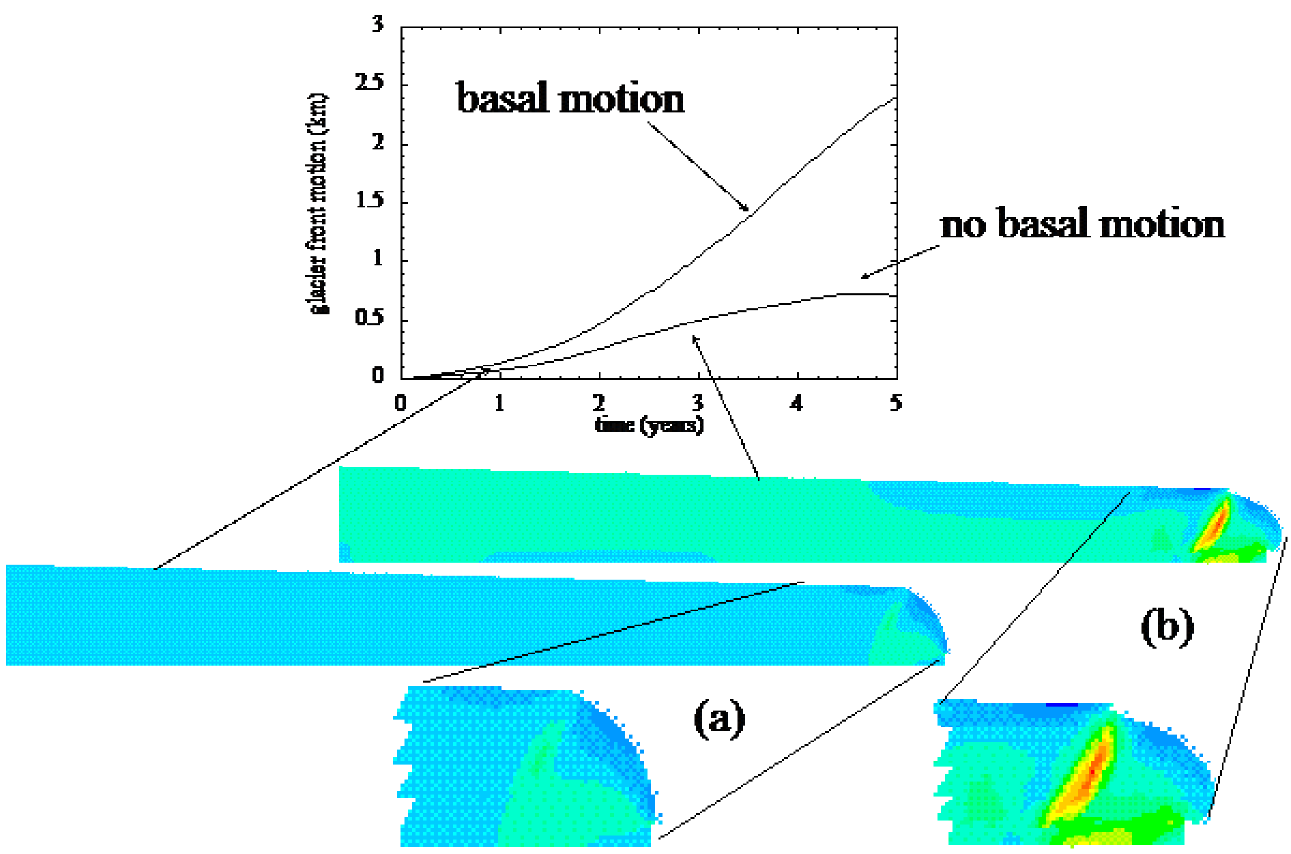

Figure 6. Plot of leading edge distance as a function of time and correlating strain contours at one year and three years for the long dome glacier simulation with ground basal motion and no ground basal motion. (a) The peak local strain for the case with no basal motion at one year was 10% strain and (b) at year three was 214% .

REFERENCES

[1] Oard, M.J. An Ice Age Caused by the Genesis Flood, Institute of Creation Research, El Cajon, Ca (1990).

[2] Vardiman, L. **Out of Whose Womb Came the Ice**, Institute of Creation Research, Impact Article, #254, San Diego, CA (1994).

[3] Vardiman, L. **Cooling of the Ocean after the Flood**, Institute of Creation Research, Impact Article, #277, San Diego, CA (1996).

[4] Vardiman, L. **Cooling of the Ocean after the Flood**, Institute of Creation Research, Impact Article, #294, San Diego, CA (1997).

[5] Paterson, W.S.B. The Physics of Glaciers, 2nd Edition, Pergamin Press, New York (1981).

[6] Sugden, D.E. and John, B.S. Glaciers and Landscape, Edward Arnold, London (1976).

[7] Blankenship, D.D. et al. **Seismic Measurements Reveal Saturated Porous Layer Beneath an Active Antarctic Ice Stream**, Nature, Vol. 322, pp. 54-57(1986).

[8] Alley, Nature, Vol. 322, pp 57-59 (1986).

[9] Horstemeyer, M.F. **Use of History Dependent Material Models for Simulating Geophysical Events Related to the Bible**, Fourth Int. Conf. On Creationism, Pittsburgh, Pa, pp. 303-314 (1998).

[10] Raymond, C.F., Benedict, R.J., Harrison, W.D., Echelmeyer, K.A., Sturm, M. **Hydrological Discharges and Motion of Fels and Black-Rapids Glaciers, Alaska, USA: Implications for the Structure of their Drainage Systems**, J. Glaciology, Vol. 41, No. 138, pp. 290-304 (1995).

[11] Sharp, M. Progress in Physcial Geography, v. 12(#4) pp. 533-559 (1988a).

[12] Dowdeswell, J.A. **Mass Balance Change As a Control on the Frequency and Occurrence of Glacier Surges in Svalbard, Norwegian High Arctic**, Geophysical Review Letters, Vol. 22, No. 21 pp. 2909-2912 (1995).

[13] Muller, E.H. and Fleisher, P.J. **Surging History and Potential for Renewed Retreat: Bering Glacier, Alaska**, Arctic and Alpine Research, Vol. 27, No. 1 (1995).

[14] Marshall, SJ. And Clarke, G.K.C **A continuum mixture model of ice stream thermomechanics in the Laurentide Ice Sheet 2. Application to the Hudson Strait Ice Stream**, Journal of Geophysical Research, Vol. 102, No. B9 pp. 20615-20637 (1997).

[15] MacAyeal, D.R. **Binge/Purge Oscillations of the Laurentide Ice Sheet as a cause of the North Atlantic's Heinrich Events**, Paleoceanography, Vol. 8 pp. 775-784 (1993a).

[16] MacAyeal, D.R. **A Low Order Model of the Heinrich Event Cycle**, Paleoceanography, Vol. 8, pp. 767-773 (1993b).

[17] Payne, A.J. **Limit Cycles in the Basal Thermal Regime of Ice Sheets**, Journal of Geophysical Research, Vol. 100 pp. 4249-4263 (1995).

[18] Verbitsky, M. and Saltzman, B. **A Diagnostic Analysis of Heinrich Glacial Surge Events**, Paleoceanography, Vol. 10, No. 1 pp. 59-65 (1995).

[19] Heinrichs, T.A., Mayo, L.R., Echelmayer, K.A., and Harrison, W.D. **Quiescent Phase Evolution of a Surge Type Glacier: Black Rapids Glacier, Alaska, USA**, Journal of Glaciology, Vol. 42, No. 140 pp. 110-121 (1996).

[20] Sharp, M **Crevasse Fill Ridges – A Landform Characteristic of Surging Glaciers?** Geografiska Annaler, Vol. 67, No 3-4 pp. 213-220 (1985).

[21] Knight, P.G. **The Basal Ice Layers of Glaciers and Ice Sheets**, Quaternary Ice Reviews, Vol. 16 pp. 975-993 (1997).

[22] Drewry D. Glacial Geologic Processes, Edward Arnold, London (1986).

[23] Clarke, G.K.C., Collins, S.G., and Thompson, D.F. **Flow, Thermal Structure, and Subglacial Conditions of a Surge-type glacier**, Can. J. Earth. Sci., vol. 21 pp. 232-240 (1984).

[24] Kamb, B. **Rheological Nonlinearity and Flow Instability in the Deforming Bed Mechanism of Ice Stream Motion**, Journal of Geophysical Research, Vol. 96, No. B10 pp. 16585-16595 (1991).