AN ANALYTIC YOUNG-EARTH FLOW MODEL OF ICE SHEET FORMATION DURING THE "ICE AGE"

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KEYWORDS (Flow model, Ice, Ice sheet, Ice Age, Ice cores, Climate, Glaciers, Glaciology)

ABSTRACT

Traditional interpretations of ice layers in polar regions have partially relied upon ice flow models which assume similar accumulation rates as those observed today and accumulation periods exceeding 100,000 years. If the Genesis Flood occurred less than 10,000 years ago and ice began to accumulate afterward at a high rate, decreasing to today's value, a different flow model would be needed and a completely different interpretation would result. This paper describes the development of such an analytic young-earth flow model of ice-sheet formation.

The model assumes that a sheet of ice accumulates snow on its upper surface and grows rapidly following the Flood. The accumulation rate is assumed to be ten times today's rate near the end of the Flood, decreasing to that observed today. The thickness of the ice sheet is then a function of the accumulation rate, the thinning caused by the weight of the accumulated ice, and the time since it was laid down. The thickness of the Greenland ice sheet at Camp Century and the position of annual layers are calculated as a function of time, assuming the Flood occurred 4,500 years ago. The position of ice layers are applied to the oxygen 18 record and compared to the traditional distribution of oxygen 18 versus time.

This alternative young-earth model compresses the Pleistocene record of oxygen 18 into a period of less than 500 years and expands the Holocene record into a period of about 4,000 years. This is in major contrast to the traditional model of hundreds of millennia for the pleistocene and about 10,000 years for the Holocene. If the Flood occurred 4,500 years ago, as assumed in this model, there would have been a quick "Ice Age" of less than 500 years. The oxygen 18 concentration would have decreased from a high value at the end of the Flood to a minimum 200-300 years later. It then would have increased rapidly from the minimum to the stable Holocene period in about 50 years. This latter change is in excellent agreement with the 40-year period of the Younger Dryas to the pre-boreal boundary suggested by several paleoclimatologists.

INTRODUCTION

A commonly used method for identifying the age of ice layers in an ice sheet is to calculate the age-depth relationships of the ice core by developing a mathematical model that incorporates a generally accepted flow theory and reasonable assumptions concerning the parameters that influence it. Dansgaard et al. [5] and Dansgaard et al. [6] have applied this technique to the Camp Century, Greenland core, and Lorius et al. [12,13] to the Dome C Antarctic core.

Fig. 1 shows a vertical section of an ice sheet resting on bedrock. The ice divide (a topographic feature from which ice diverges) is denoted by I-I. The ice deposited on the surface at location I is buried by succeeding snowfalls, and sinks into the ice sheet. At the same time, the layers accumulated annually become thinner by plastic deformation, as the ice flows horizontally outward from the ice divide. The core from Camp Century is shown at C-C. It contains ice formed upstream from Camp Century under similar environmental conditions. The horizontal, upper-surface velocity of the ice at Camp Century is 3.3 meters per year and, therefore, even a 15,000-year-old deep section of the ice core would originate less than 50 kilometers further inland, if it has been moving at a constant rate.

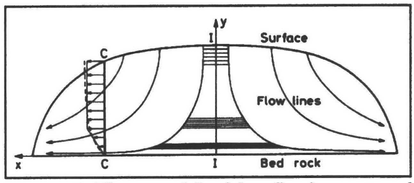

Figure 1 *Flow model of ice flowing outward from an ice divide as described by Dansgaard et al. [6].*

CLASSICAL FLOW MODELS

Several attempts have been made to develop a flow model at Camp Century. Nye [14] derived a simple relationship between the position of a layer in the ice sheet and the time since the snow fell to become ice. He assumed an infinite sheet of ice of uniform thickness with snow accumulating on its upper surface at a constant rate. He also assumed that the horizontal velocity of flow away from the ice divide was constant with depth and the ice sheet was free to slide on the bottom surface. His final result is:

$$\Delta t = -\frac{H\tau}{\lambda_H}\int_H^y \frac{dy}{y} = \frac{H\tau}{\lambda_H}\ln\frac{H}{y} \tag{1}$$

where Δt is the elapsed time since ice at a give depth fell as fresh snow (i.e., the age of a given layer), H is the total thickness of the ice sheet, τ is the accumulation period (typically one year), λ_H is the amount of snow which accumulates over the accumulation period, and y is the height above the bottom of the ice sheet.

Recognizing that Nye's model [14] was inadequate for Camp Century, particularly because of the assumption of sliding on the bottom surface, Dansgaard et al. [6] used a stress-and-strain relationship, called Glen's Law, to develop a more realistic model. The results are:

$$\Delta t = \frac{(2H-h)\tau}{2\lambda_H}\ln\frac{2H-h}{2y-h}\ ; \qquad h \le y \le H \tag{2}$$

$$\Delta t = t_h + \frac{(2H-h)\tau}{2\lambda_H}\left(\frac{h}{y} - 1\right)\ ; \qquad 0 < y \le h \tag{3}$$

where Δt, H, τ, and λ_H are defined in the same manner as Equation 1, h is the height above the bottom of the ice sheet at which the horizontal velocity becomes uniform with height as the ice sheet flows away from the ice divide, and t_h is the age of the ice at height, h.

This flow model can be applied to data acquired from various ice cores to estimate the age of various levels in the ice sheet. Fig. 2 shows the measured values of $\delta^{18}O$ versus depth for Camp Century, Greenland. Note the relatively uniform $\delta^{18}O$ values from the surface to approximately 1000 meters depth. Below 1000 meters, the values decrease suddenly and then slowly increase again to a depth of 1370 meters. The uniform region is typically identified as the Holocene epoch. The maximum extent of the "last Ice Age" calculated to have occurred at about 18,000 B.P. by long-age modelers, is typically identified with the "valley" at the bottom of the record.

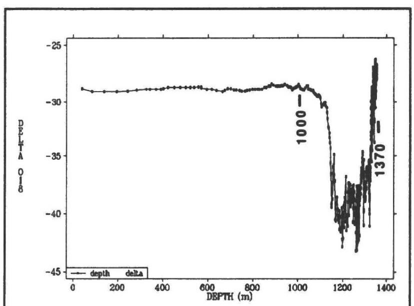

Figure 2 $\delta^{18}O$ *versus depth for Camp Century, Greenland.*

Fig. 3 shows the measured values of $\delta^{18}O$ versus the calculated values of time from Equations 2 and 3. Note how the data between 1000 and 1370 meters have been expanded dramatically in this process. In fact, the data near the bottom are stretched the most, as would be expected from the inverse y relationship in Equation 3. Markers have been placed on Figs. 2 and 3 at 1000 and 1370 meter depths to illustrate the stretching effect of the long-age time model. Time approaches infinity, as y approaches 0. The oldest ice near the bottom of the Camp Century core is estimated by Johnsen et al. [11] to be over 120,000 years old.

Other long-age time models have been developed, but most have very similar characteristics as those of Nye [14] and Dansgaard et al. [6]. Some allow the accumulation rate to vary, but only to a small degree, depending on estimated precipitation formation temperatures derived from $\delta^{18}O$ measurements. One of the most difficult problems the long-age model must explain is how more snow accumulates during an "Ice Age" when the temperature is colder. For example, see Alley et al. [2] where evidence is given that the accumulation rate of snow doubled at the end of the Younger Dryas event when the "Ice Age" was rapidly coming to an end. Colder temperatures lead to lower accumulation rates because of the Clausius-Clapeyron Equation (See Hess [9, p.46]).

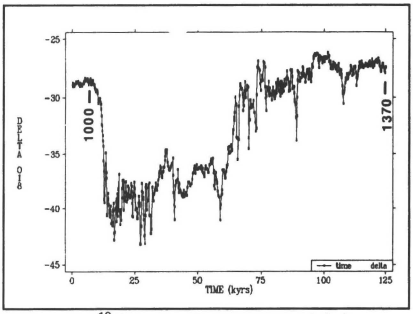

Figure 3 $\delta^{18}O$ *versus long-age model time.*

Recent cores from Greenland have been analyzed with greater precision than earlier cores using stratigraphic techniques. The primary method of estimating the age of layers is to count annual layers. Dansgaard et al. [4] claim to be able to count annual layers downward from the surface back to 14,500 years before present. Validation of these claims must wait for release of the raw data, expected in 1995.

A YOUNG-EARTH FLOW MODEL

In both of the long-age models which we have discussed above, it was assumed that new snow has been accumulating on the top of the ice sheet, at an average rate of λ_H/τ, without interruption or significant perturbation for an infinite amount of time in the past. It is this uniformitarian assumption which gives rise to the very great ages for the bottom ice (infinite age at the very bottom) which these models yield. This assumption of uninterrupted conditions similar to those observed at present is not appropriate for a Biblical, global-flood model of the past. In particular, we would expect the oldest layers of ice to post-date the Flood (i.e. have a finite age), and climatological considerations, based on the work of Oard [15,16], suggest that the annual accumulation of snow would have been much greater than the presently observed value, λ_H, in the early years following the Flood. To illustrate what can happen when assumptions which are more in line with a Flood model are used, consider the following simple flow model, discussed by Vardiman [17].

Assume that a sheet of ice of thickness, H, accumulates snow on its upper surface at a rate of λ/τ meters/year, where λ is the accumulation in meters over a time period τ in years. In this case we will not assume that the ice sheet is in mass balance, but, rather, that it grows rapidly following the Flood, and later slowly approaches the equilibrium condition observed today. This means that λ and H are functions of time, rather than being constant as the uniformitarian model requires. In fact, at the end of this derivation, λ will be assumed to be ten times the accumulation rate observed today and H will be assumed to be 0 at t = 0, the end of the Flood. A more complex model could be considered in the future, in which H is equal to 0 for some period after the Flood, until the temperature is cold enough for snow to begin to accumulate. The thickness of the ice sheet is then a function of the accumulation rate and the rate of thinning. The conventional long-age model developed a flow regime based on a two-dimensional assumption of incompressibility. However, in this model, I will use a linear-thinning function which is calibrated by the observed compression in the upper 4000 layers. In other words, the compression of an ice layer will be proportional to the thickness of the ice sheet.

This simple model can then be expressed as:

$$\frac{dH}{dt} = \lambda/\tau - \delta H \qquad (4)$$

where H is the thickness of the ice sheet in meters as a function of time, t is the time since the Flood in years, τ is the accumulation period in years, λ is the accumulation over the accumulation period in meters, and δ is the thinning ratio in year^{-1}. The thinning ratio is a constant and will be determined by the boundary conditions imposed on Eq. 4.

Eq. 4 says that the rate of change in the thickness of the ice sheet is the difference between the accumulation rate of snow, falling on the upper surface and the compression of the ice sheet which is linearly proportional to its thickness. This model assumes a linear thinning function which may not always be the case, particularly when the stress and strain are outside the elastic limits. Non-linear thinning may occur when the ice is melting, during massive surging, or when the underlying terrain constrains horizontal motions.

Before we can solve Eq. 4, we need to assume a functional form for λ. We have reason to believe, from our Flood model, that immediately following the Flood the oceans were warm and the continents and polar regions cold, compared to that of today as discussed by Oard [15,16] and Vardiman [17, 18]. If this was the case, the precipitation rate likely would have been much greater than that of today, and would have decreased with time. We will assume an exponentially decreasing accumulation function, which approaches today's rate in the limit. For this initial model, we will further assume that the accumulation rate at the end of the Flood was ten times that of today.

The functional form of λ described in the preceding paragraph is:

$$\lambda = \lambda_H (Ce^{-\alpha t} + 1) \tag{5}$$

where λ_H is the accumulation over a period of interest observed today, C is a constant, t is the time since the Flood, and α is the relaxation time for the decrease in accumulation since the Flood. The relaxation time will be determined by the shape of the distribution of layers to be explored shortly. Note that when $t = 0$ in Eq. 5, $\lambda = (C+1)\lambda_H$ and when $t = \infty$, $\lambda = \lambda_H$.

Combining Eqs. 4 and 5 and arranging into a standard form for solution of a linear, time-dependent differential equation gives:

$$\frac{dH}{dt} + \delta H = \frac{\lambda_H}{\tau}(Ce^{-\alpha t} + 1) \tag{6}$$

The solution to this equation is:

$$H = \frac{\lambda_H}{\tau\delta}(1 - e^{-\delta t}) + \frac{C\lambda_H}{\tau(\delta - \alpha)}(e^{-\alpha t} - e^{-\delta t}) \tag{7}$$

Note that Eq. 7 satisfies the boundary condition that $H = 0$ when $t = 0$. By applying another boundary condition, δ can be determined. Assume that $H = 1370$ meters when $t = \infty$, and $C = 9$, so that $C+1=10$ and $\lambda = \lambda_H$. Under this condition, Eq. 7 reduces to:

$$H\ (t = \infty) = \frac{\lambda_H}{\tau\delta} = 1370\ m \tag{8}$$

or:

$$\delta = \frac{\lambda_H}{(1370\ m)(\tau)} = 2.55 \times 10^{-4}\ year^{-1} \tag{9}$$

This value of the thinning function, δ, implies that the thickness of the entire ice sheet decreases by the same amount as the annual accumulation on the surface and an annual layer proportional to its thickness. This thinning function equals $8.09 \times 10^{-12}\ s^{-1}$ when converted to standard SI units.

The thinning function is similar to a strain rate. Strain rates have been measured for ice by Higashi et al. [10] and reported in Fletcher [7, p. 189]. The strain rate in ice at -15°C under a stress of 1 bar (10^6 dynes/cm^2) exceeds $1 \times 10^{-7}\ s^{-1}$. This is over 4 orders of magnitude greater than the thinning function calculated above. In addition, the stress beneath a 1000-meter thick layer of ice is 88 bars, greatly exceeding the test conditions of Higashi [6]. Therefore, the calculated thinning function used in this model is much less than ice would permit under such high stress. It is likely that ice sheets could "thin" even faster than this model indicates and much faster under other hypothetical conditions. "Ice Rivers" moving at rates exceeding 1 km per year have been observed in Antarctica and it has been suggested by several investigators that ice sheets and glaciers could move laterally at high speeds if the edges are moving into deep water. The release of lateral stresses could permit the vertical thinning function to be much greater.

The rapid movement of the edges of ice sheets to form "lobes" and extensions of ice coverage tens or hundreds of kilometers away from accumulation centers is an important element of "Ice Age" research which needs investigation. Rapid accumulation of snow and ice after the Genesis Flood mixed with volcanic particulates and impurities could be a significant factor in thinning of ice sheets and lateral motions. Rapid melting during deglaciation and frequent earthquakes could cause sudden slippage at the base and rapid spreading of ice equatorward. It is conceivable that the polar oceans could have been filled with ice shelves and icebergs from ice sheets sliding rapidly into the ocean during deglaciation.

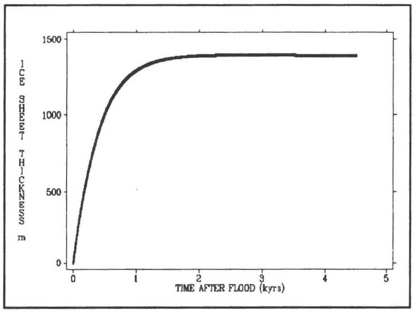

Figure 4 *Thickness of the Camp Century ice sheet as a function of time after the Flood.*

Fig. 4 shows the thickness of the Camp Century, Greenland ice sheet, *H*, plotted as a function of time since the Flood for a certain selection of parameters. In this case, λ_H = .35 m, τ = 1 year, δ = 2.55 × 10^{-4} year^{-1}, α = .0025 ($1/\alpha$ = 400 years), and the time since the Flood t = 4,500 years. Note that *H* starts at 0, increases rapidly, and asymptotically approaches today's thickness of 1370 meters. For larger values of α, the asymptotic approach to today's value is slower.

Fig. 4 illustrates the behavior of the entire thickness of the ice sheet, and deals primarily with the topmost layer. However, when ice cores are drilled down through the ice sheet today, we can measure the position of earlier layers which were formed and then buried. This additional information should help us develop a better estimate of the thinning function.

If we consider a given layer within the ice sheet, can we determine from this model how far it has moved downward since it was formed? If we assume that the rate of movement of an ice layer downward is proportional to the thickness of the ice sheet and the position of a layer relative to the total thickness, we obtain:

$$V_y = \frac{dy}{dt} = -\delta \frac{y}{H_0} H(t) \tag{10}$$

where V_y is the vertical velocity of an ice layer relative to the base of the ice sheet, *y* is the position of a layer, δ is the thinning ratio defined earlier, *H* is the total thickness of the ice sheet as a function of time, and H_0 is the total thickness today.

Now, at first, one might be tempted to define the downward velocity of a layer as proportional to the thickness of ice above the layer. However, it should be noted that the weight of the entire ice sheet is responsible for the movement of a given layer, because the rate at which the ice beneath a layer thins, allowing the layer to move downward, is dependent on the total thickness. Obviously, the preferable manner of deriving V_y would be to have a complete, time-dependent flow model showing the full two-dimensional movement of ice as a function of depth. This is not easily determined, so my model will assume a simple relationship for this first effort.

Eq. 10 says that the velocity of a layer is downward following its deposition and is proportional to the total thickness of the ice sheet. However, the factor, y/H_0, causes the downward velocity to increase linearly from 0 at the bottom of the ice sheet to a maximum at the top. The bottom is assumed to be 0, because it rests on bedrock. The upper layers will subside faster, because of the accumulating compression.

Transposing Eq. 10 results in:

$$\frac{dy}{y} = -\delta \frac{H(t)}{H_0} dt \tag{11}$$

Substituting *H(t)* from Eq. 7 and integrating to find the change in position, *y*, of an ice layer over the period of time since it was laid down, gives:

$$\int_{y_i}^{y}\frac{dy}{y} = -\int_0^{\Delta t}\frac{\delta}{H_0}[\frac{\lambda_H}{\tau\delta}(1 - e^{-\delta\tau}) + \frac{C\lambda_H}{\tau(\delta-\alpha)}(e^{-\alpha t} - e^{-\delta t})]dt \tag{12}$$

where y_i is the initial position of the layer when it was deposited, y is the position of the layer as a function of time after it was deposited, and Δt is the age of the layer.

Solving for y:

$$y = y_i\, e^{-\frac{\delta}{H_0}[\frac{\lambda_H}{\tau\delta}A + \frac{9\lambda_H}{\tau(\delta-\alpha)}B]} \tag{13}$$

where:

$$A = \Delta t + \frac{1}{\delta}(e^{-\delta\Delta t} - 1)$$

$$B = -\alpha(e^{-\alpha\Delta t} - 1) + \frac{1}{\delta}(e^{-\delta\Delta t} - 1)$$

Note that Eq. 13 says that $y = y_i$ for $\Delta t = 0$. This means that the topmost layer, which is deposited today, 4,500 years after the Flood, has not yet begun to subside. Because the first layer at the end of the Flood was deposited at the position, $y_i = 0$, its position, y, will always be equal to 0. Between the Flood and today, each layer will subside a varying amount, dependent upon the total thickness of the ice sheet, its position relative to the bottom of the sheet, and the length of time from its deposition until today.

Fig. 5 shows the position of each annual layer at Camp Century as a function of time since the Flood. As the old top layer is covered by the new winter's snow, the new surface is assigned a higher vertical position. However, with time each layer subsides an amount dependent upon the time since its formation and the total depth of the ice sheet. Fig. 5 is then the height of each annual layer as a function of time after the Flood. The curve shows the greatest rate of change in layer position during the first 1,000 years after the Flood. This is due to the large change in snowfall rate immediately after the Flood. The decrease in accumulation was assumed to be exponential with a 400 year e-folding time. The top layer of the ice sheet will be precipitated at smaller increments above the preceeding layers, and will be particularly noticeable immediately after the Flood. The curve is slightly concave upward during the last 3,000 years or so. This is due to the decreasing period of time available for the ice sheet to thin, as the top of the ice sheet is approached. At the very top, the most recent layer has not had time to thin at all, and its position is the same as the thickness of the ice sheet.

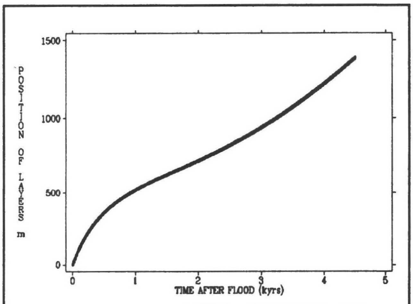

Figure 5 *Position of ice layers at Camp Century as a function of time after the Flood.*

AGE ESTIMATES OF ICE LAYERS

The curve in Fig. 5 can be used to estimate the age of the ice as a function of depth for a measured distribution of $\delta^{18}O$ versus depth, such as in Fig. 2. Unfortunately, Eq. 13, which is the basis of Fig. 5, will not allow Δt, the age of a layer, to be solved analytically. If one wishes to determine the age of a layer at a known depth, either the age must be determined graphically from Fig. 5 or a numerical analysis method must be applied to Eq. 13. The latter method was used in this work.

An iterative numerical approximation method was applied to Eq. 13 to unfold the $\delta^{18}O$ versus depth relationship for Camp Century data shown in Fig. 2 and obtain $\delta^{18}O$ versus time. The result is shown in Fig. 6. Note, that the general shape of the curve of $\delta^{18}O$ versus the young-earth model time has the same general shape as the curve of $\delta^{18}O$ versus depth shown in Fig. 2. This is in major contrast to that of the long-age model shown in Fig. 3, which compresses the data near the top of the ice sheet and dramatically stretches the data near the bottom.

If the Flood occurred 4,500 years ago, as suggested in the young-earth model, there would have been a quick "Ice Age" of about 500 years. This is in good agreement with the estimate of 500 years or so by Oard [15,16] for the formation of the Canadian ice sheets. The $\delta^{18}O$ would have decreased from a high value at the end of the Flood to a minimum about 200-300 years later. The $\delta^{18}O$ would have then increased rapidly from this minimum to the stable Holocene period over a very short time interval. This latter change is in excellent agreement with the 40 year transition period of the Younger Dryas event to the pre-boreal boundary reported by Hammer et al. [8] or even the extremely short 5-year period reported by Alley et al. [3].

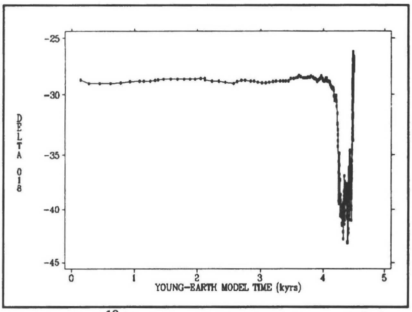

Figure 6 $\delta^{18}O$ *versus young-earth model time after the Flood for Camp Century, Greenland.*

CONCLUSIONS AND RECOMMENDATIONS

Fig. 6 is the result of assuming a relatively high precipitation rate following the Flood about 4,500 years ago. Several additional parameters were incorporated into the model, most of which were determined by given boundary conditions. However, it may be possible to derive an equally valid model with different assumptions. For example, if the Flood is assumed to have occurred 14,000 years ago, as Aardsma [1] has suggested, the model would likely assume a slightly different form.

Detailed confirmation of this model was not attempted in this report. Such an effort would require considerably more research than is reported here. The purpose of this paper is to lay the general framework of an alternative model and demonstrate that a young-earth model can be formulated. One of the next efforts needed to improve this model should be to compare the observable annual layers in the upper portion of the ice sheet with the model predictions. Adjustments will likely need to be made to the parameterization based on the degree of fit between observations and predictions. Another major effort should be the development of a non-steady-state flow model. The current one-dimensional compression model may be correct, but will likely need refinement. Finally, the model should be expanded to explain other sites on Greenland and Antarctica. Of particular interest will be the forthcoming data from the Greenland Ice Sheet Project (GISP2), previewed by Alley et al. [3].

Even with all the caveates about the current model and hopes for improvements in the future, it seems likely that Fig. 6 is closer to reality than the plot of $\delta^{18}O$ versus the long-age time model shown in Fig. 3. At the least, the young-earth model presented here is a legitimate alternative to the long-age model. It is internally consistent and capable of validation or refutation.

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