Past Accumulation rates derived from observed annual layers in the GRIP ice core from Summit, Central Greenland.

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Abstract.

Based on dated reference horizons down to 1623 m an ice flow model has been developed. The model is used to reconstruct past accumulation rates from the sequences of detected annual layers in the upper 2321 m of the 3029 m deep GRIP ice core. Comparison of these past time accumulation rates with the corresponding $\delta^{18}O$ values show a strong correlation. This relationship can be used in a non steady state flow model, in which past accumulation rates, deduced from the continuous $\delta^{18}O$ record, are used to model a time scale. The hereby determined time scale and the modelled annual layers compare well with the observed data.

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Introduction.

The GRIP project at Summit (72°34'N, 37°37'W, elevation 3230 m) in Central Greenland at the crest of the Greenland Ice Sheet is a joint european program with the purpose to drill an ice core to the bedrock. The ice core drilling was started in 1989 and during the 1992 field season bedrock was reached at a depth of 3028.65 m. In addition to the GRIP core the 300 m deep EUROCORE ice core has been drilled at the location, 50 m apart, in 1989.

On the surface the precipitation falls as snow. The snow is gradually compressed to ice and the layers of ice move downwards in the ice sheet with time. The annual layers of accumulation are slowly stretched and thinned under the vertical compression and longitudinal stress from the ice and firn.

An vertically drilled ice core contains a chronology of past annual layers. The present thickness of an annual layer reflects both the original amount of annual accumulation and the vertical compression the layer has been subject to during its life time.

A simple steady state flow model is used to determine the past times annual accumulation rates and thus to determine the relationship between the oxygen isotopes $\delta^{18}O$ (an indication of the surface temperature) and the accumulation rates. A non-steady state model is hereafter used to model a time scale and continuous annual layer thicknesses, λ, with depth at the GRIP bore site, Summit.

Attempts to determine past time accumulation rates have been made using the data from the Dye 3 ice core (south Greenland) (Hammer and others, 1986), from the Camp Century ice core (north west Greenland) and from earlier cores from the Central Greenland region (Hammer and others, 1978), from the Renland ice core (east Greenland) (Johnsen and Dansgaard, 1992) and the Devon ice core (Arctic Canada) (Paterson and Waddington, 1984), from the Dome C ice core (east Antarctica) (Lorius and others, 1979), from the Byrd ice core (Jouzel and others, 1989) and from the Vostok ice core (east Antarctica) (Lorius and others, 1985; Ritz, in press). The advantage of using the GRIP core for this kind of analysis is that the drill site is located on the crest of the Greenland ice sheet, where no upstream corrections are needed, and the accumulation rate is so high, that annual layers λ, can be detected by stratigraphic methods even to the deeper strata of the core (Johnsen and others, 1992).

Data used in the analysis.

At present the isotope oxygen $\delta^{18}O$ ratio has been measured continuously along the GRIP ice core (Johnsen and others,1992). The transition from Holocene to Wisconsin is found at a depth of 1623.60 m and has been dated to 11.550 yrs B.P. (Johnsen and others, 1992). In the upper 770 m detailed $\delta^{18}O$ were sampled (40 samples per meter) and measured in order to resolve the annual cycle. From other stratigraphic data such as dust, nitrate (Hammer and Iversen, 1992), calcium and ammonium measurements (Fuhrer and others, submitted) and from the continuously Electrical Conductivity Measurements (ECM) the annual layers, λ, have been identified in the Holocene and Wisconsin ice; the annual layer thickness decreases from 23 cm of ice eqv. at the top to around 2 cm ice eqv. at a depth of 2321 m. Only data down to this depth is discussed in this paper.

A sequence of dated reference horizons from the GRIP core, shown on figure 1a and 1b, are also used to date the upper 1623.60 m of the ice core. In the upper 1380.5 m the reference horizons are major volcanic eruptions (V) and characteristic $\delta^{18}O$ events (δ). These horizons were observed and dated in several other ice cores (Hammer and others, 1980), especially the Dye 3 core, where a careful dating was made. In the region from 1380.5 to 1623.60 m, the dating of the Summit core deviates from the earlier dating. The reference horizons in this regions are found by counting the annual layers and hereby also dating the Holocene/Wisconsin transition at a depth of 1623.60 m to 11.550 Yrs B.P.

Steady state ice flow model.

In order to use a simple steady state ice flow model to describe the thinning of the annual layers, λ, at Summit a Dansgaard-Johnsen type of model (Dansgaard and Johnsen, 1969) is developed.

The model is based on the following assumptions:

1) The ice thickness of 3028 m has been constant with time. Compression of the firn to ice reduces the ice thickness to 3003 m corresponding to 25 m of air in the upper firn, which is used in the model. The surface and bedrock are assumed to be horizontal.

2) The present annual surface accumulation rate of 0.230 m ice eqv./yr represents the mean annual accumulation rate during the Holocene period (Hammer and Iversen, 1992).

3) The vertical strain rate $\partial v/\partial y$ is assumed to be constant with depth to a distance h above bedrock. Below h the vertical stain rate decreases linearly to 0 at the bedrock, where the ice is below the pressure melting point (Gundestrup and others, in press) and therefore frozen to the bedrock.

4) The model parameter h defined in 3) is assumed to be constant with time.

The parameter h, and hereby also the vertical strain rate $\partial v/\partial y$, is determined in such a way that the flow model depths of the reference horizons, agree to the actual depths in which they are detected in the GRIP ice core. In addition to these reference horizons the transition between Holocene and Wisconsin ice dated to 11.550 yrs. before present and found at a depth of 1623.6 m, which is also used as a reference horizon.

Figure 1a and 1b shows the reference horizons and the modelled age-depth

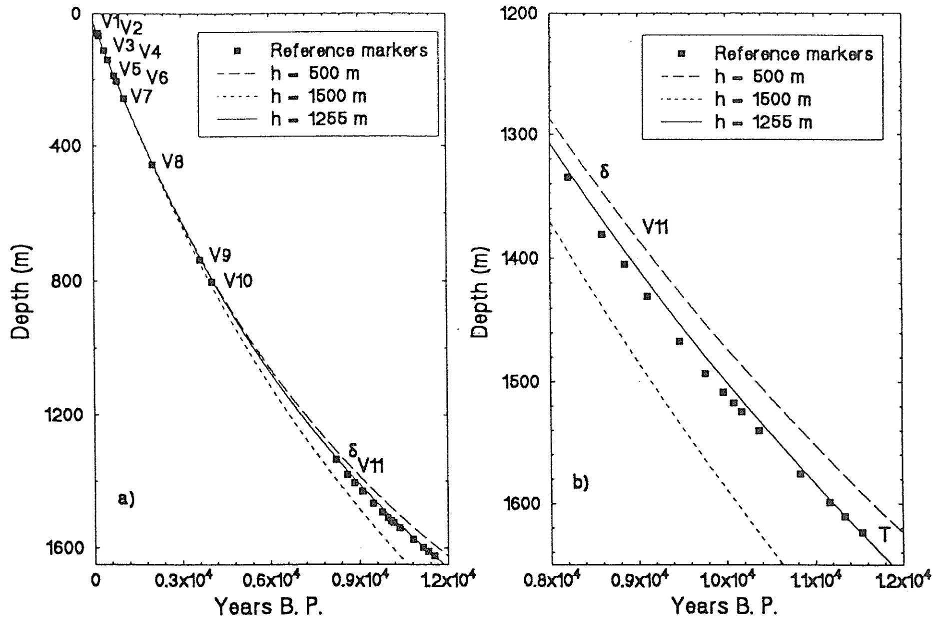

Figure 1a and 1b.
Modelled age-depth curves for different values of the Dansgaard-Johnsen parameter h (Dansgaard and Johnsen, 1969). The dated reference markers shown as points are used to determine h to 1255 m. Figure 1a covers the depths down to 1650 m while figure 1b is an enlargement of the depth range 1200 to 1650 m. The dated volcanic reference points are marked V1 to V11: V1, Tambora, 1816 AD; V2, Laki, 1783 AD, V3, Unknown, 1601 AD; V4, Unknown, 1477 AD; V5, Unknown interhemispheric volcanic marker, 1259 AD; V6, (Katla), 1179 AD; V7, Elgja, 934 AD; V8, Unknown, 49 BC; V9, Thera, 1646 BC; V10, Unknown, 2054 BC; V11, Unknown, 6608 BC. The δ marker is the $\delta^{8}O$ minimum observed in all Greenland ice cores 8210 BP and the T is the transition between Holocene and Wisconsin 11550 BP. The markers between 1380.5 and 1623.6 m are fixpoints from counted annual layers in the GRIP ice core.

relationships for various values of the model parameter h. The best least squares fit gives a value of 1255 m for the parameter h.

Past accumulation rates can be calculated from the sequences of detected annual layer thickness, λ, from the GRIP ice core. The ice flow model, described above, is used to determine the total thinning of the measured annual layer during their

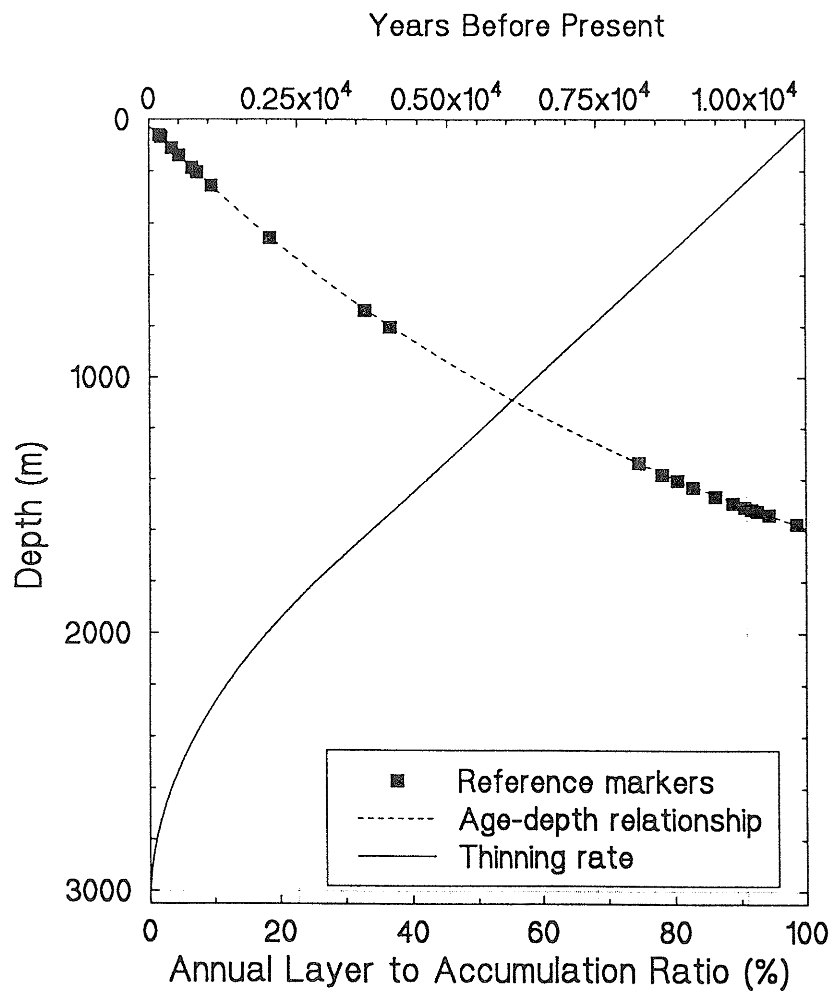

Figure 2
The age-depth curve from figure 1 is shown together with the corresponding thinning rate curve. The thinning rate is the ratio between the annual layer thicknesses and the original accumulation per year of the annual layer. The thinning rate decreases from 100 % at the surface to 0 % at the bedrock.

life span (figure 2). The past accumulation rates can, by use of the thinning rates shown on figure 2, be reconstructed over the intervals of the core, where annual layers

have been observed. This is done for the Holocene ice, where steady-state has been assumed and the model parameters have been determined by a least squares fit to the known reference markers. But also for the Wisconsin ice, down to the depth of 2321 m, the thinning rates can be used to reconstruct past accumulation rates by assuming that the model parameter h has been unchanged back in time. The reconstructed accumulation rates as function of depth are shown on figure 3a and 3b together with the measured annual layer thicknesses, λ, from which the past accumulation rates are deduced. In the Holocene ice, the age-depth relationship from figure 2, also dates the past accumulation rates. In the Wisconsin ice the reconstructed accumulation rates are to sparse and therefore not feasible to base a time scale on. Later in this paper a time scale will be established to the Wisconsin ice.

On figure 3a and 3b the accumulation rate in the Holocene is seen to scatter around the present value in agreement with the ice flow model assumption (2). Also, it is seen, that the accumulation rate decreases to 0.10 m ice/yr at the transition depth of 1623.60 m. The low accumulation rates in the Younger Dryas from 11.550 to 12.700 yrs BP (1623.60 to 1661.55 m depth) are followed by the warmer Bölling period 12.700 to 14.450 yrs BP (1661.55 to 1753.40 m depth) where the accumulation rates increase to 0.20 m ice/yr, which is nearly Holocene values. Below the warm Bölling period the accumulation rates again decreases to 0.10 m ice/yr. Only few sequences of annual layers have presently been analyzed in the lower part of the 1991 core. From figure 3a and 3b it can be seen that the annual layer thicknesses, λ, are nearly constant below 1800 m. As the thinning rate decreases with depth the resulting accumulation rates increase with depth below 1800 m.

Stable isotopes and accumulation rates

In figure 3a and 3b the calculated past accumulation rates are compared with the $\delta^{18}O$ values from the same depth intervals and a correlation exists between the $\delta^{18}O$ values and the accumulation rates i.e. low $\delta^{18}O$ values, representing cold climate,

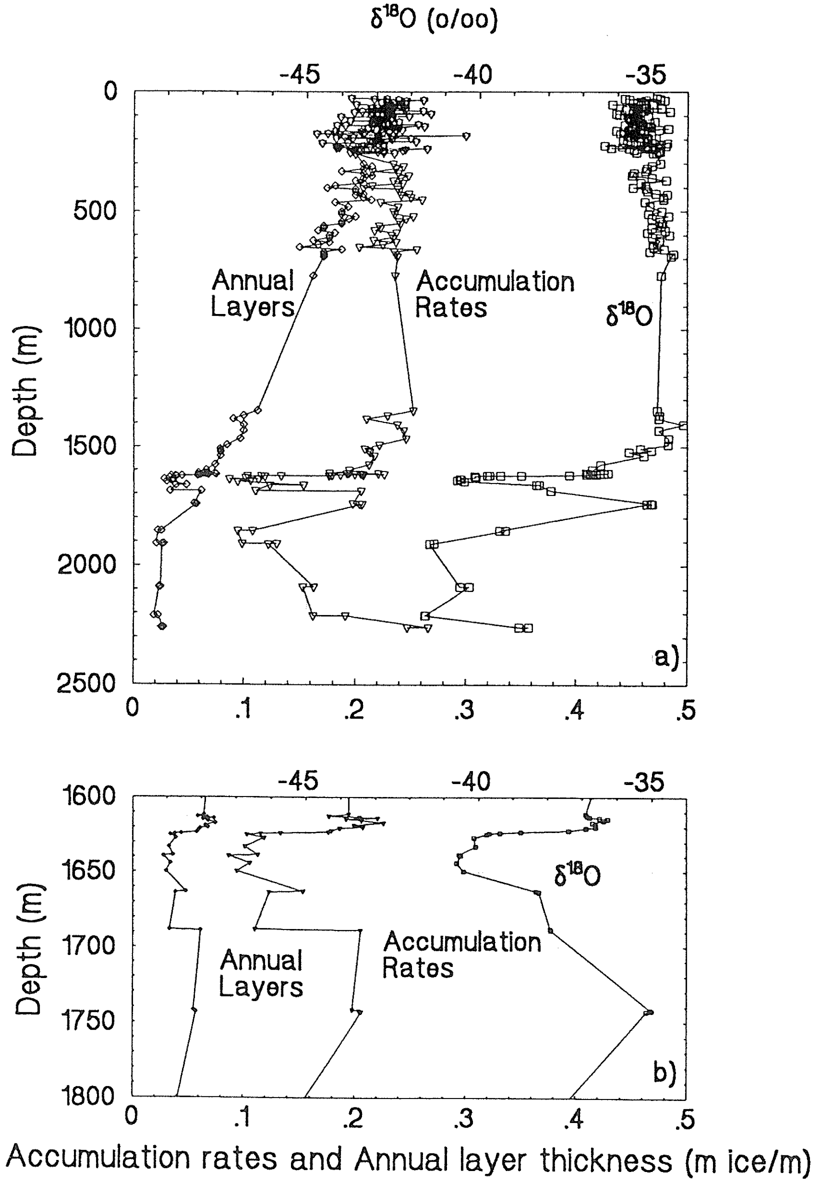

Figure 3a and 3b
The thinning rate from figure 2 is used to reconstruct the accumulation rates (triangles) from the observed annual layers (diamonds). The $\delta^{18}O$ values for the sequences where the annual layers have been detected are shown as squares with an x-axis on the top line of the figures. Figure 3a covers the depths down to 2321 m while figure 3b enlarges the depth interval 1600 to 1800 m in which the Holocene to Wisonscin transition is located at a depth of 1623 m and is preceded by the Younger Dryas cold period.

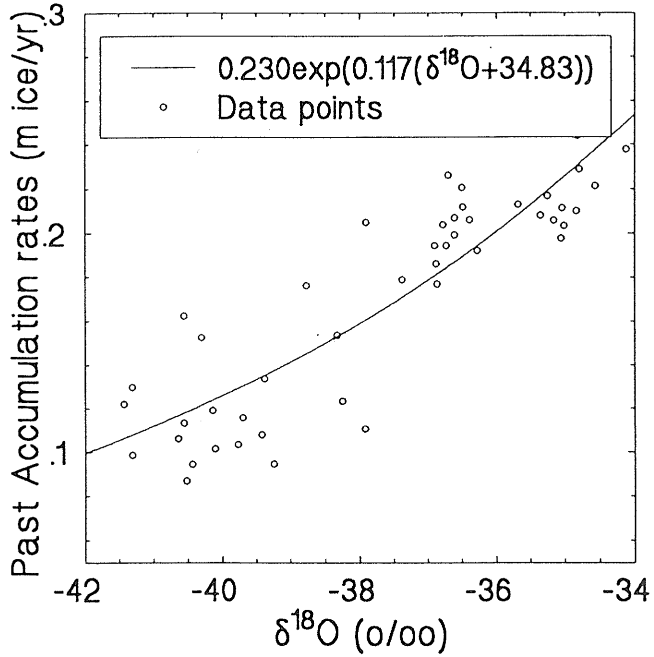

Figure 4
The correlation between the accumulation rates and the $\delta^{18}O$ values both shown on figure 3 gives an exponential curve (solid line).

correspond to low accumulation rates and higher $\delta^{18}O$ values representing a warmer climate correspond to higher accumulation rates. An exponential function is used to relate the data shown on figure 4 as suggested in previous literature (Johnsen and others, 89). A least squares fit to the data gives the following equation:

$$a = 0.230 \exp (0.117 (\delta^{18}O + 34.83))$$

where a is the accumulation rate determined from the corresponding $\delta^{18}O$ value. The exponential relation (figure 4) shows that a 1 °/oo change of the $\delta^{18}O$ values correspond to a 11.7 ± 1.0 °/o change of the accumulation rate. The vapour pressure model used in the paper of Johnsen and others (1989) predict a 9 o/o change for the Summit region. Using the temperature-$\delta^{18}O$ relationship in (Johnsen and others, 1989)

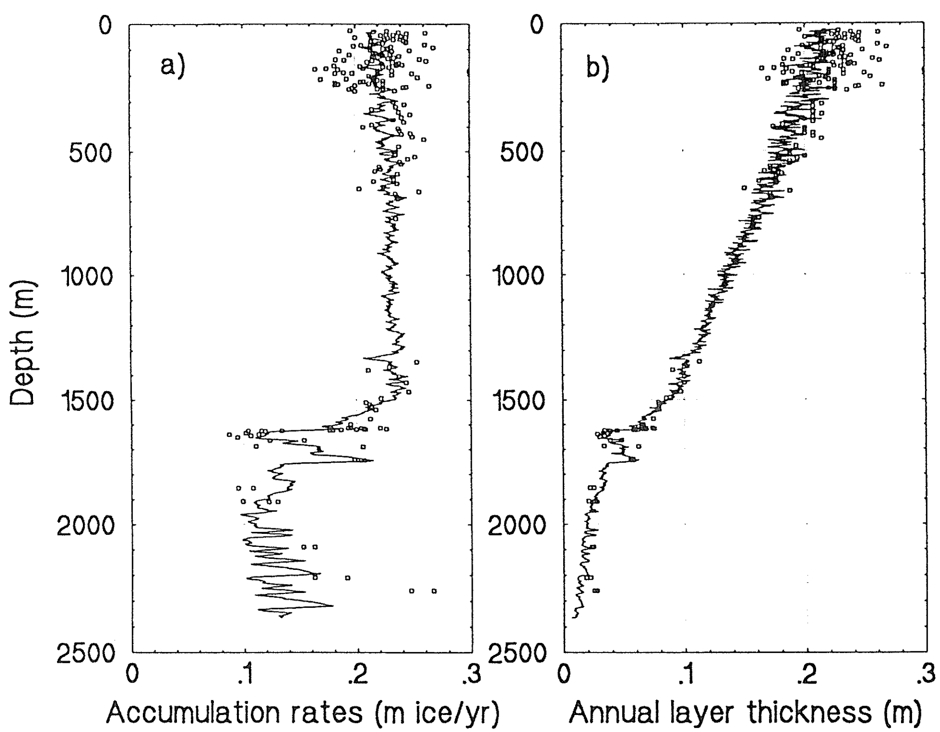

Figure 5a and 5b
a) The correlation between the accumulations rates and the $\delta^{18}O$ values is used to reconstruct a continuous accumulation-depth profile (solid curve) from the continuous $\delta^{18}O$ profile in 0.55 m average depth intervals. The accumulation rates reconstructed from the sequences of observed annual layers are shown as points.
b) The annual layers (solid curve) modelled from the continuous $\delta^{18}O$ profile are compared with the observed annual layers (points).

a 1°C temperature change will correspond to a 7.8 °/o change of the accumulation rate.

Data from a series of 100 m cores in the area south of the summit of the Greenland Ice Sheet has shown to have a similar relationship between the $\delta^{18}O$ values and the accumulation rates: on the average a 1°/oo change of the $\delta^{18}O$ values correspond to a 7-9 °/o change of the accumulation rate (Clausen and others, 1988). Here the vapour pressure model of Johnsen and others (1987) predict an 8°/o change.

The fact that the relationship between the $\delta^{18}O$ values and the past accumulation rates holds even during strongly different climatic periods is remarkable. The observations and the vapour pressure model give slightly different relationships between the $\delta^{8}O$ and the accumulation rate which could be explained by a small change of the precipitation pattern. At present there are around 16 precipitation events each year (Hammer and Iversen, 1992) and a slight change in the seasonal distribution of these events or of the vapour source region would alter the $\delta^{18}O$ to accumulation rate relationship.

The $\delta^{18}O$ depth-profile is continuous so the relationship provides us with a continuous depth profile of the past initial rates of accumulation. The reconstructed accumulation rates are shown on figure 5a in 0.55 m depth interval averages. The top part is very noisy because each 55 cm segment only represents few years. This noise reduces with depth because each 55 cm segment contains an increasing amount of years.

It should be noted that the accumulation rates reconstructed from the $\delta^{18}O$ values show big long term variations in the Wisonsin ice below 1623.60 m depth compared to the variations in the overlying Holocene ice. The accumulation rates do, however, not increase with depth below 1800 m as the few accumulation points, produced from observed annual layers, do. In order to compare the calculations directly with the observed annual layers figure 5b shows the annual layers reconstructed from the $\delta^{18}O$ values together with the observed sequences of annual layers.

Non steady state ice flow model

In order to date the past accumulation rates a non-steady state ice flow model has been developed. The model assumptions 1),3) and 4) as described in the steady state ice flow model section are still valid. Instead of assumption 2) the surface accumulation rate now changes with time. As described in assumption 3), the form of the vertical strain rate is a constant value down to a distance h above the bedrock, and

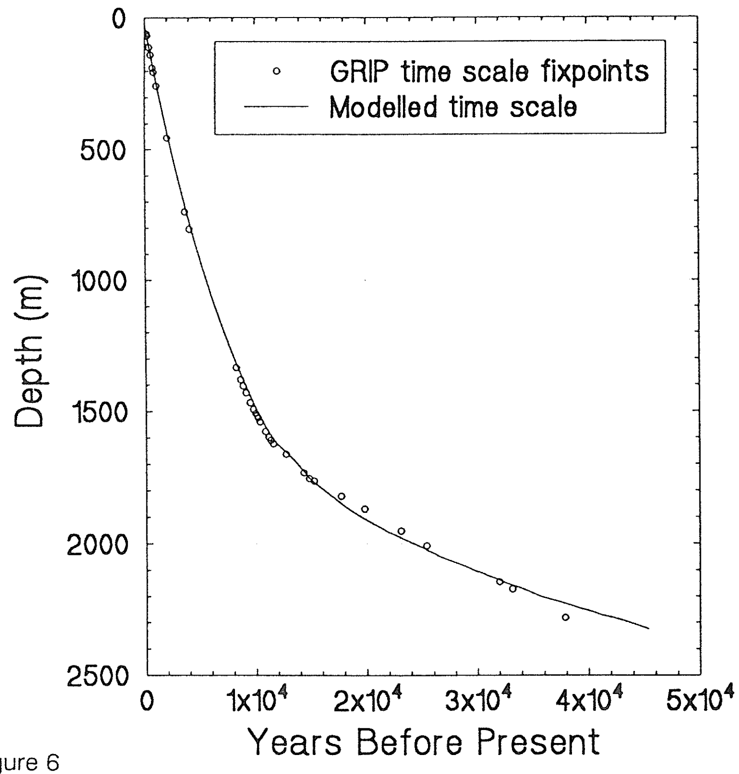

Figure 6
The non steady state ice flow model and the continuous $\delta^{18}O$ profiles are used to model a time scale down to 2321 m (solid line). The stratigraphic determined time scale is shown as points (from table 1, Johnsen and others, 1992).

below h a linear decrease to 0 at the bedrock. The constant value of the vertical strain rate is proportional to the surface accumulation value and therefore changes with time. The constant value of h is 1255 m as determined in the previous section. The depth profile of the $\delta^{18}O$ values and thereby also the past surface accumulation rates are given in 0.55 m depth interval averages down to 2321 m depth.

In order to reconstruct the age intervals of the 0.55 m depth intervals, the flow model is used running "backwards" in time. The top 0.55 m have a mean accumulation rate of a_1, determined from its mean $\delta^{18}O$ value. The flow model is run backwards in time until the bottom of this layer is the new surface. The age interval of this first layer is thus known to be t_1 years. All the underlying layers are also moved up in the core during these t_1 years and their lengths increase from the drilled ice core length 0.55

m. The top of the second layer is now at the surface and the bottom of the second layer is at a depth d_2. With an accumulation rate of a_2, determined from this layers mean $\delta^{18}O$ the whole procedure is repeated until the bottom of the second layer is the new surface. The time used for this is t_2, so the age of the bottom of the second layer is $t_1 + t_2$. The procedure is continued until the bottom of the last layer is at the surface, which occurs after $\sum t_i$ for i= 1 to N

Figure 6 shows the hereby modelled time scale. The age of the ice at a depth of 2321 m is found to be 45 kyrs. The stratigraphical determined time scale for the GRIP core presented in (Johnsen and others, 1992) is also shown on figure 6. The two time scale are not very different, the stratigraphical time scale dating the ice at a depth of 2321 m to 40 ± 2 kyrs BP. The major difference is observed in the lower part where only few annual layers sequences have been analyzed.

On figure 7 the accumulation rates are plotted on the time scale. Observe the different character of the Holocene and the Wisconsin accumulation rates. In the Holocene period the accumulation rate is very stable, while the accumulation rates vary with 50 % in the Wisconsin ice with periods of 1000 to 3000 years.

Discussion and conclusions

The reconstruction of past accumulation rates also in the Wisconsin ice is possible in the GRIP ice core from central Greenland. Only on very few earlier occasions has it been possible to detect the annual layers in Wisconsin ice.

It is possible at Summit partly due to the location of the drill site on the crest and partly to the well suited accumulation rate. The glacial ice is found from a depth of 1623 m so there is 1400 m of ice older than 11.550 years. The ice from the Wisconsin period has annual layer thicknesses up to 7 cm and the ice is far from the bedrock, where special bedrock conditions can cause difficulties in the interpretation. As the ice core is drilled on an ice divide it is believed that there would only be small upstream corrections to the data down to 2321 m even if the dome was located else

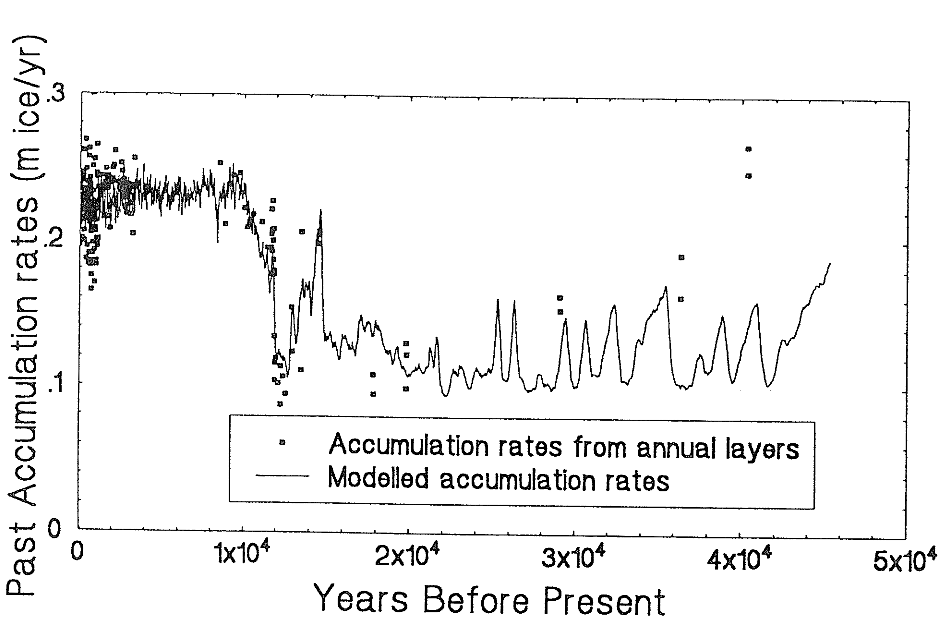

Figure 7
The reconstructed accumulation rates on the time scale from figure 6. Note that the measured data points are very sparse for ice older than 20.000 Years Before Present.

where during glacial times.

Besides from the good location of the Summit region for annual layer studies the detection methods have been refined so the resolution decreases to the order of 1mm for the continuous dust, chemistry and electrical measurements on the GRIP core (Hammer and Iversen, 1992). It is possible to detect annual layers down to the order of 1 cm and diffusion of the chemical concentrations in the ice is in many cases the limiting factor.

The variations of the annual layer thicknesses and hereby also past accumulation rates around the Holocene/Wisconsin transition and during the Allerød and Bölling time periods have been observed in great detail. There is a relationship between precipitation variations and changing climate periods. A time scale for the GRIP ice core must take the varying precipitation into account; especially for the Wisconsin ice, showing big long term variations of the accumulation rates as seen in figure 7, the variations must be included in the calculations of a time scale.

The accumulation rates deduced from the observed annual layer thicknesses correlate with the $\delta^{18}O$ values. This relationship can be used to create a continuous accumulation-depth layer profile which accounts for the changing climate back in time. A flow model can then be used to determine the time scale and a continuous annual layer depth profile.

The amount of data available at the moment is limited for the ice deeper than 1800 m. This study should therefore be seen as a pioneer study of the possibilities that will be available from the Summit ice cores.

When more data is available and the thinning rates and time scale are to be modelled deeper down than done than presented here, a more sophisticated model will be needed. The assumption that the ice in the GRIP ice core has always been deposited on the ice crest is most likely not correct, which means that the model must account for changing flow conditions back in time. The simplest approach would be to allow the model parameter, h, to change with time.

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