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A synchronized dating of three Greenland ice cores throughout the Holocene

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[1] As part of the effort to create the new Greenland Ice Core Chronology 2005 (GICC05) a synchronized stratigraphical timescale for the Holocene parts of the DYE-3, Greenland Ice Core Project (GRIP), and North Greenland Ice Core Project (NGRIP) ice cores is made by using volcanic reference horizons in electrical conductivity measurements to match the cores. The main annual layer counting is carried out on the most suited records only, exploiting that the three ice cores have been drilled at locations with different climatic conditions and differences in ice flow. However, supplemental counting on data from all cores has been performed between each set of reference horizons in order to verify the validity of the match. After the verification, the main dating is transferred to all records using the volcanic reference horizons as tie points. An assessment of the mean annual layer thickness in each core section confirms that the new synchronized dating is consistent for all three cores. The data used for the main annual layer counting of the past 7900 years are the DYE-3, GRIP, and NGRIP stable isotope records. As the high accumulation rate at the DYE-3 drill site makes the seasonal cycle in the DYE-3 stable isotopes very resistant to firn diffusion, an effort has been made to extend the DYE-3 Holocene record. The new synchronized dating relies heavily on this record of ~75,000 stable isotope samples. The dating of the early Holocene consists of an already established part of GICC05 for GRIP and NGRIP which has now been transferred to the DYE-3 core. GICC05 dates the Younger Dryas termination, as defined from deuterium excess, to 11,703 years before A. D. 2000 (b2k), 130 years earlier than the previous GRIP dating.

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1. Introduction

[2] The vast Greenland ice sheet is an outstanding archive of past northern hemisphere atmospheric conditions. During the past decades, several ice coring efforts have been made in order to retrieve continuous records for the study of past climatic conditions [*Dansgaard and Johnsen*, 1969; *Langway et al.*, 1985; *Johnsen and Dansgaard*, 1992; *Dansgaard et al.*, 1993; *Meese et al.*, 1994; *North Greenland Ice Core Project Members*, 2004].

[3] To fully exploit the wealth of information provided by the ice cores, an accurate dating of the records is essential [e.g., *Hammer et al.*, 1978]. Having ice cores from different parts of the ice sheet, cross dating of records is of great importance, because thoroughly cross dated records allow studies of local climate differences [*Rogers et al.*, 1998]. Furthermore, it is possible to retrieve more accurate regional climatic signals by stacking the cross dated records [e.g., *Vinther et al.*, 2003].

[4] Here we present a new counted timescale for the DYE-3, Greenland Ice Core Project (GRIP) and North Greenland Ice Core Project (NGRIP) ice cores, spanning the past 11.7 kyrs, the entire Holocene period. The timescale has been cross dated carefully using volcanic reference horizons, detectable in Electrical Conductivity Measurements (ECM) performed continuously on the cores. This new timescale that synchronizes the Holocene parts of the DYE-3, GRIP, and NGRIP ice cores, is part of the ongoing effort to create the Greenland Ice Core Chronology 2005 (GICC05), a counted chronology reaching far beyond the last glacial maximum.

[5] The ice flow properties at the DYE-3, GRIP and NGRIP drill sites are very diverse. At the DYE-3 site the high accumulation rate allows for extremely well preserved annual layers, detectable in all measured parameters. At the same time, however, the high accumulation rate leads to vigorous ice flow which rapidly thins the annual layers with

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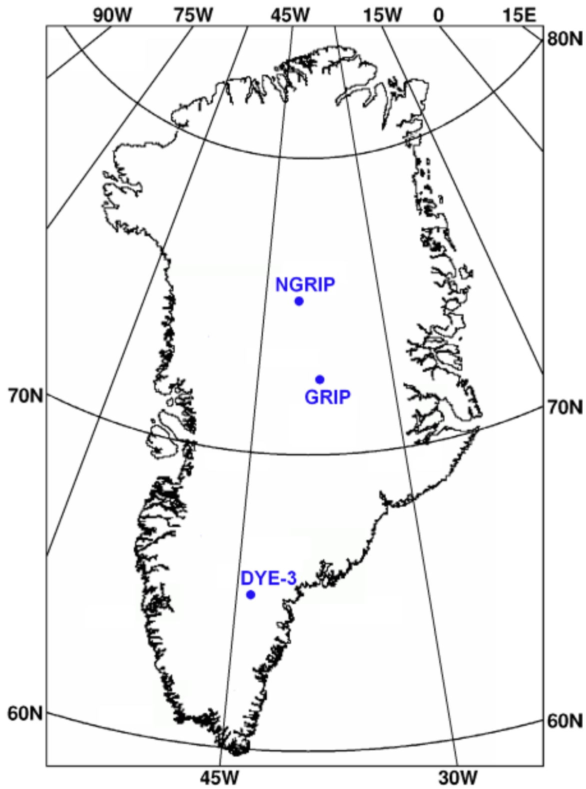

Figure 1. The three Greenland deep ice cores used in the construction of the Greenland Ice Core Chronology 2005: DYE-3, Greenland Ice Core Project (GRIP), and North Greenland Ice Core Project (NGRIP).

increasing depth. The GRIP and NGRIP drill sites, situated at the summit of the Greenland ice cap and on the northern ice divide respectively, are sites with more moderate accumulation and ice flow, which create conditions for slow but steady layer thinning. However, because the NGRIP core has been drilled at a site of the ice cap subjected to bottom melting, the mean annual layer thickness never gets much smaller than the annual melt rate.

[6] The differences between the glaciological conditions at the DYE-3, GRIP and NGRIP drill sites make these three ice cores an ideal combination for dating purposes. Through a large part of the Holocene, the high accumulation rate at DYE-3 allows robust identification of the annual cycles in stable oxygen and hydrogen isotope data. Hence some 12,000 new isotope samples have been cut and measured to complete and extend the DYE-3 stable isotope record. Below the 8.2 ka cold event, thinning of the annual layers makes identification of annual cycles in the DYE-3 stable isotopes difficult. Therefore GRIP Continuous Flow Analysis (CFA) measurements of chemical impurities in the ice have been used for annual layer counting below 7.9 ka b2k (before A.D. 2000).

[7] The dating of the early Holocene using GRIP and NGRIP CFA data (GRIP data 7.9–11.7 ka b2k, NGRIP data 10.3–11.7 ka b2k) has been presented by *Rasmussen et al.* [2006a]. Because of the relatively slow flow-induced thinning at NGRIP and the high resolution of the NGRIP CFA data, annual layers can be identified past the last glacial maximum. An extension of GICC05 down to 42 ka is in preparation (K. K. Andersen, in preparation, 2006; A. Svensson, in preparation, 2006).

2. Ice Core Data

[8] The locations of the DYE-3, GRIP, and NGRIP drill sites are shown in Figure 1, while further information on the cores and drill sites is given in Table 1. An overview of the temporal distribution of the ice core data used for the GICC05 dating can be seen in Figure 2. Descriptions of data from each of the three ice cores are given in the following sections. To facilitate comparison of data availability between the ice cores, the common GICC05 ages of the sections will be used instead of referring to ice core depths.

2.1. DYE-3

[9] An extensive amount of stable oxygen isotope measurements ($\delta^{18}O$) has been carried out on the DYE-3 ice core during the early 1980s [*Dansgaard et al.*, 1982]. 63,000 $\delta^{18}O$ samples at a resolution of 8 samples per year or higher cover the period back to the year 5815 b2k and the time interval from 6906 to 7898 b2k.

[10] In this work an additional 12,000 ice samples from the periods 5816–6905 b2k and 7899–8313 b2k have been cut at a resolution of 8 samples per year in order to complete the DYE-3 stable isotope record and extend it through the 8.2 ka cold event. Stable hydrogen isotope measurements (δD) were carried out on these samples, exploiting the small sample size required for δD measurements using a modern continuous-flow isotope ratio mass spectrometer (CF-IRMS). All 12,000 samples have been measured at the AMS 14C Dating Centre at the University of Aarhus on a GV Instruments CF-IRMS [*Morrison et al.*, 2001]. ECM data are available down through the entire Holocene for the DYE-3 core [*Hammer et al.*, 1980].

2.2. GRIP

[11] Measurements of $\delta^{18}O$ at a resolution of 2.5 cm are available back to 3845 b2k [*Johnsen et al.*, 1997]. This resolution corresponds to 7–10 samples per year (with fewest samples per year in the earliest part of the record due to flow-related thinning of the annual layers). Short sections of $\delta^{18}O$ measurements are available through the rest of the Holocene, but they cover less than 10% of the total time span and do not form a continuous record. ECM data are available for the entire GRIP core [*Clausen et al.*, 1997].

Table 1. Ice Core Specifications and Present Drill Site Characteristics

Ice Core	Elevation, m asl	Latitude, °N	Longitude, °W	Mean Air Temperature, °C	Accumulation, m ice per year	Ice Core, Length, m	Years of Drilling
DYE-3	2480	65.18	43.83	−20	0.56	2037	1979–1981
GRIP	3230	72.58	37.64	−32	0.23	3027	1989–1992
NGRIP	2917	75.10	42.32	−32	0.19	3090	1996–2004

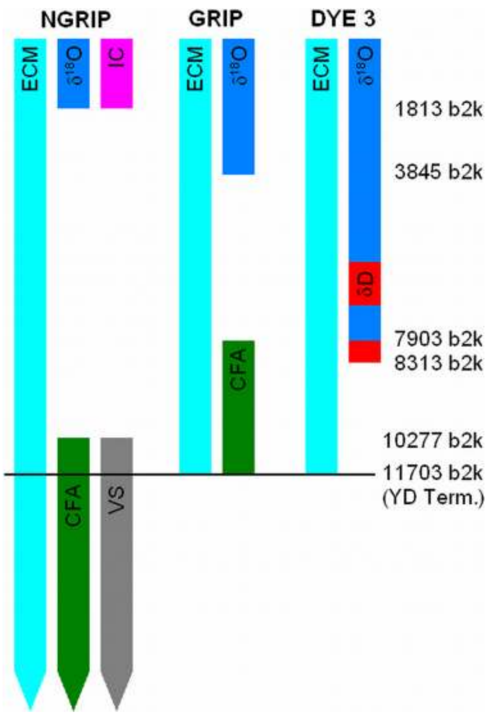

Figure 2. Overview of the ice core data used for constructing the Greenland Ice Core Chronology 2005. The termination of Younger Dryas (YD Term.) is indicated by the black line. ECM is electrical conductivity measurement, IC is ion chromatography data, CFA is continuous flow analysis data, and VS is visual stratigraphy data.

2.3. NGRIP

[12] The $\delta^{18}O$ measurements at a resolution of 2.5 cm are available back to 1813 b2k [*Dahl-Jensen et al.*, 2002]. This resolution corresponds to 7–9 samples per year, again fewest in the earliest part of the record. Ion Chromatography (IC) measurements of impurities have been made (at the Niels Bohr Institute, University of Copenhagen) back to 1813 b2k, at a resolution of 5 cm, corresponding to ~4 samples per year. ECM data exist for the entire NGRIP core [*Dahl-Jensen et al.*, 2002].

3. Methodology

[13] The dating of the three ice cores is carried out in four steps. First the ECM records of the three cores are used to match up volcanic reference horizons. Secondly, between consecutive match points annual layers are counted independently in each core. In the third step it is decided if possible discrepancies in the annual counts between the cores can be resolved. If this is not possible, a return to step 1 (the ECM match) is deemed necessary. The fourth step is to find the number of years which is consistent with all available data, and then impose the resulting dating on all three ice cores. In this step the records showing the clearest annual cycles are given the greatest weight.

[14] The process of going through the four steps is carried out for all parts of the DYE-3, GRIP and NGRIP Holocene records, thereby producing a synchronized timescale valid for all three ice cores. In the next sections we describe the dating procedure and the records used in the different time periods of the Holocene, starting with the uppermost year present in all three cores, 21 b2k (A.D. 1979).

3.1. Time Period 21–1813 b2k

[15] For this period, detailed $\delta^{18}O$ data from all three cores have been used. As diffusion in the snow and firn layers (the upper 60–70 m of the ice sheet) dampens the annual cycle in $\delta^{18}O$ significantly for areas of low accumulation, it has been necessary to use deconvolution techniques [*Johnsen*, 1977; *Johnsen et al.*, 2000] to reestablish the annual oscillations in the GRIP and NGRIP records. Deconvolution is not necessary for the DYE-3 $\delta^{18}O$ data due to the high accumulation rate at DYE-3 (see Table 1).

[16] An example of the matching, deconvolution and layer count is given in Figure 3. It is seen that the NGRIP $\delta^{18}O$ data set is on the limit of safe deconvolution, whereas most annual layers are discernible in the measured GRIP $\delta^{18}O$ data before deconvolution. The measured DYE-3 $\delta^{18}O$ data is seen to exhibit clear annual cycles.

[17] Multiparameter NGRIP IC impurity data are considered in the NGRIP annual layer count and the combined information of the NGRIP IC data and the deconvoluted $\delta^{18}O$ data proved sufficient for annual layer identification. However, during this period most weight is given to the DYE-3 $\delta^{18}O$ data and the deconvoluted GRIP $\delta^{18}O$ data, as the two $\delta^{18}O$ data sets are far better resolved than the NGRIP IC impurity data.

3.2. Time Period 1814–3845 b2k

[18] The NGRIP IC data and the 2.5 cm $\delta^{18}O$ data terminate at 1813 b2k leaving only the NGRIP ECM record with sufficient resolution for dating purposes. As annual cycles are not always clearly represented in the ECM record, almost no weight is given to the NGRIP annual layer count in this section. NGRIP ECM is merely used to transfer the consensus annual layer count from DYE-3 $\delta^{18}O$ and GRIP deconvoluted $\delta^{18}O$ to the NGRIP core. ECM annual layer counting is typically associated with errors of 5–10%. If the discrepancy for a given matched section exceeds this expected error, the underlying match of volcanic reference horizons is reconsidered.

3.3. Time Period 3846–7902 b2k

[19] The GRIP 2.5 cm $\delta^{18}O$ data terminate at 3845 b2k leaving only the GRIP ECM record with sufficient resolution for dating purposes. Therefore almost no weight is given to the GRIP and NGRIP annual layer counts in this section. GRIP and NGRIP ECM data are merely used to transfer the annual layer count from DYE-3 $\delta^{18}O$ and δD data to the GRIP and NGRIP cores. Again, if the discrepancy in a section exceeds the expected error of 5–10%, the underlying match of volcanic reference horizons is reconsidered. Highly resolved GRIP $\delta^{18}O$ data are used in the dating procedure where available. An example of the transfer of the DYE-3 dating to the GRIP and NGRIP cores is given in Figure 4.

3.4. Time Period 7903–8313 b2k

[20] The rapid thinning rate at the DYE-3 site allows progressing ice diffusion to dampen the annual cycle in the DYE-3 $\delta^{18}O$ and δD data (see Figure 5). This dampening

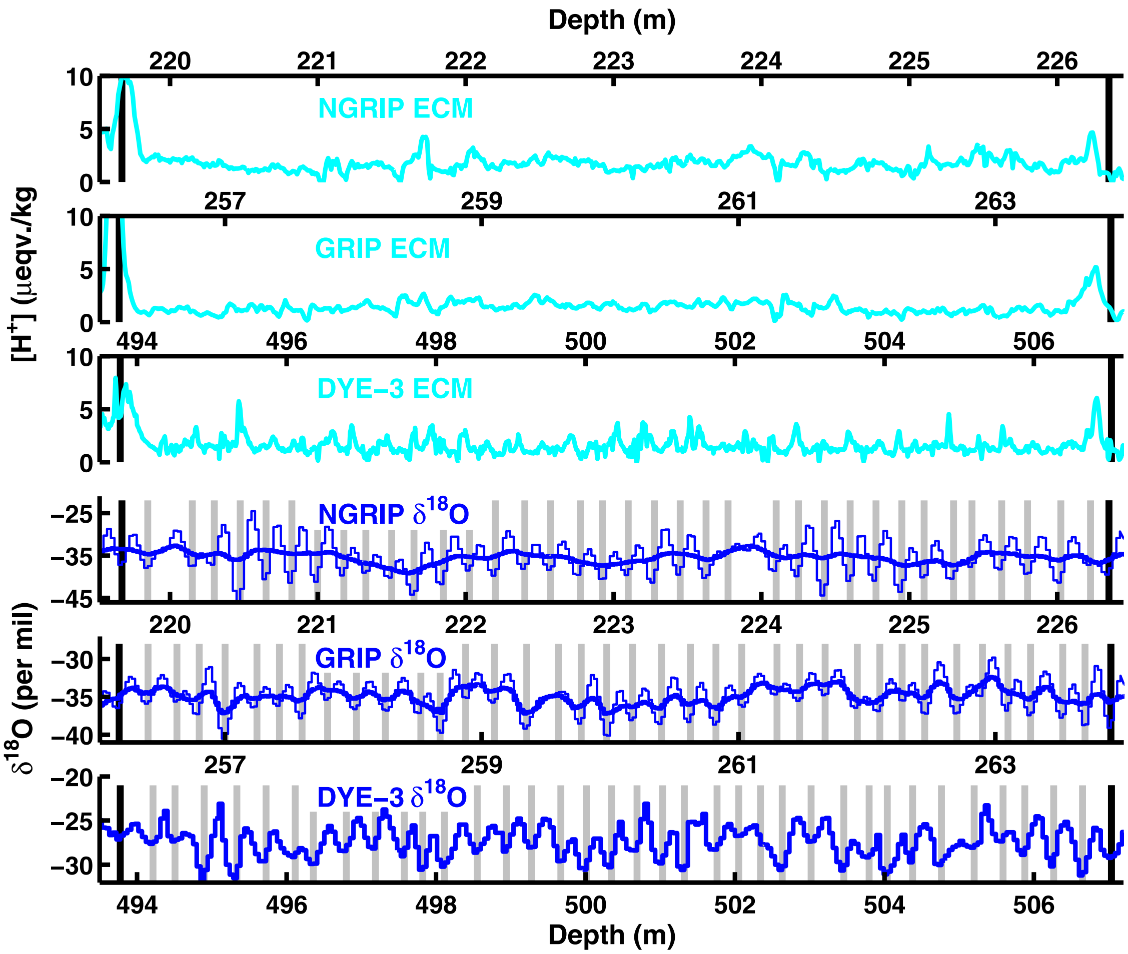

Figure 3. Top three graphs: Matching of the DYE-3, GRIP, and NGRIP ECM records from A.D. 897 to A.D. 934. Reference horizons are indicated by black bars. Bottom three graphs: Detailed comparison of stable isotope records. Thick blue lines are measured data, while thin lines are deconvoluted data, corrected for firn diffusion. Light gray bars indicate single years (winters) identified in the records.

makes identification of annual layers increasingly difficult. Therefore the dating of the GRIP core presented by *Rasmussen et al.* [2006a] is transferred to the DYE-3 core in this section. There are no significant discrepancies between the (less certain) annual layer counts in the DYE-3 δD data and the counts based on GRIP CFA data for any part of the section.

3.5. Time Period 8314–11,703 b2k

[21] Below 8313 b2k the DYE-3 annual layer counting is carried out on the DYE-3 ECM record. The DYE-3 ECM count is merely used to transfer the *Rasmussen et al.* [2006a] dating of the GRIP (8314–11,703 b2k) and NGRIP (10,277–11,703 b2k) cores to the DYE-3 core. Again, if the discrepancies in a section exceed the expected error of 5–10%, the underlying match of volcanic reference horizons has been reconsidered.

4. Dating Uncertainties

[22] A range of issues may lead to uncertainties and errors in ice core timescales based on annual layer counting. The most important ones include: Imperfect core stratigraphy, core loss during drilling/handling of the core, data loss during sampling/measuring of the core, insufficient measuring resolution and misinterpretation of the records [*Alley et al.*, 1997]. During the Holocene, the accumulation rate is known to have been relatively high. Hence the DYE-3, GRIP and NGRIP records should not suffer from any significant imperfections in stratigraphy. The existence of complete years without precipitation is extremely unlikely, especially for the DYE-3 high accumulation site.

[23] Core loss and data loss have been minimal for the DYE-3, GRIP and NGRIP ice cores. Furthermore, having three ice cores available for the dating, any small section of missing data in one core can be studied in two unaffected ice cores. It shall be noted that due to differences in ice flow the time period spanned by DYE-3 brittle zone does not overlap the periods covered by GRIP and NGRIP brittle zones (the brittle zone at a depth of approx. 800–1200 m, is a particularly fragile section of the ice core which is difficult to handle and sample [*Shoji and Langway*, 1982]). The DYE-3 ice is brittle from 1.9–3.6 ka b2k while GRIP and NGRIP brittle zones span the periods 4.0–7.1 ka b2k and 4.7–8.0 ka b2k respectively. A nonbrittle ice core is therefore available for all time periods covered by the GICC05 dating.

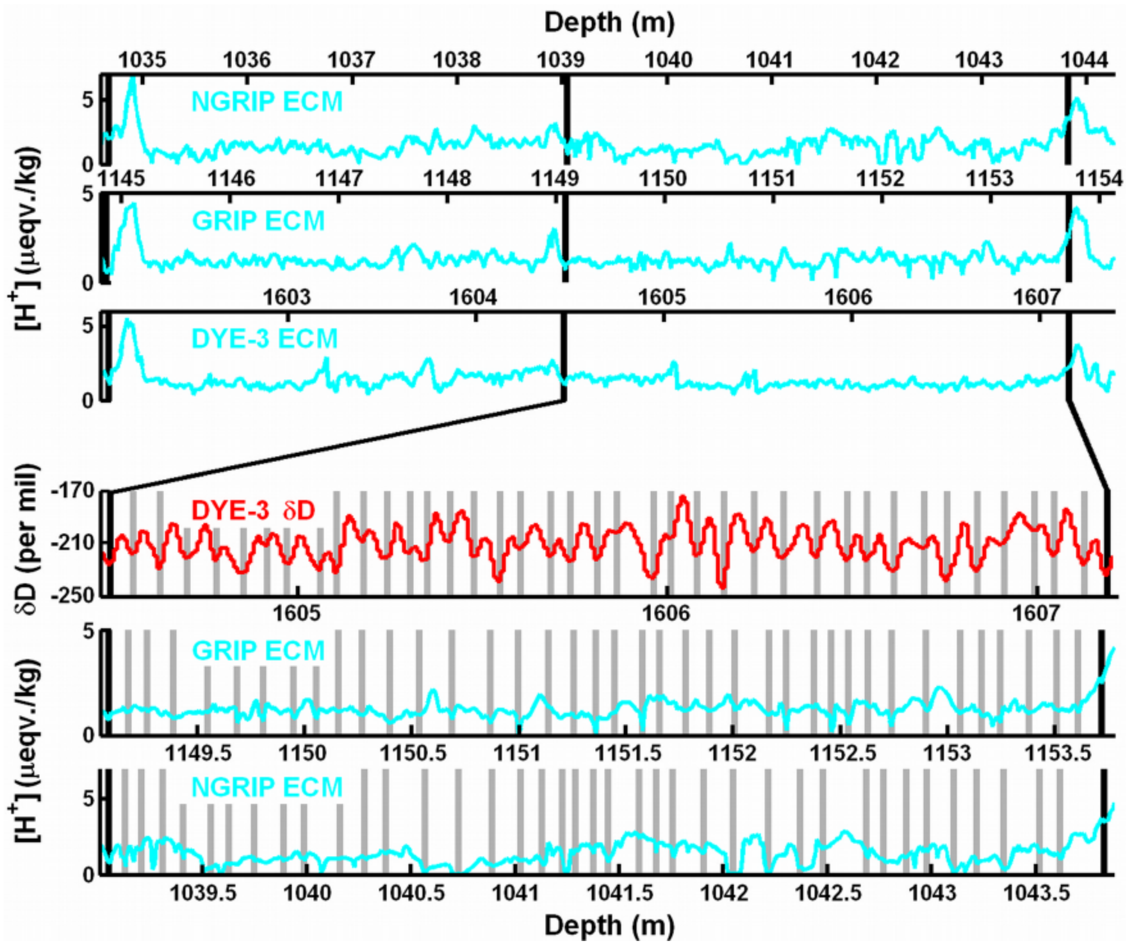

Figure 4. Top three graphs: Matching of the DYE-3, GRIP, and NGRIP ECM records from 6559 b2k to 6632 b2k. Reference horizons are indicated by black lines. Bottom three graphs: Detailed matching of GRIP and NGRIP ECM based dating to the DYE-3 record from 6593 b2k to 6632 b2k. Light gray bars indicate single years (winters) identified in the records.

[24] Having a stable isotope record based on 8 samples per year or better at the DYE-3 site, annual oscillations are resolved during the past 8300 years (see Figures 3, 4, and 5). The sample resolution of the GRIP and NGRIP δ^{18}O data is also sufficient for safe layer counting to be carried out. However, the effective resolution of the GRIP and NGRIP records (and the DYE-3 record below ~6.9 ka b2k) is influenced by diffusional smoothing of the δ^{18}O oscillations. Therefore deconvolution techniques [*Johnsen*, 1977; *Johnsen et al.*, 2000] are applied to the stable isotope records in order to enhance their effective resolution (see Figure 3). The sampling resolution of the NGRIP IC data (~4 samples per year) is some times marginal with respect to resolving annual layers.

[25] The risk of misinterpreting the ice core records is probably the most significant contribution to uncertainties in the Holocene part of the GICC05 dating. Experience from the dating of multiple shallow ice cores (covering the most recent part of the Holocene) does however establish that δ^{18}O and δD data exhibit very reliable annual oscillations due to their close coupling to Greenland temperatures [*Hammer et al.*, 1978]. Deconvolution of the stable isotope data does pose the danger of introducing oscillations of nonannual origin, e.g., the small oscillation observed in the NGRIP deconvoluted δ^{18}O data at a depth of ~224 m in Figure 3. The risk of misinterpreting such oscillations is mitigated by the availability of the DYE-3 stable isotope data, which do not need deconvolution. *Rasmussen et al.* [2006a] offer a discussion of the uncertainties concerning the dating based on the GRIP and NGRIP CFA data.

4.1. Uncertainties and Bias Evaluation for the Annual Layer Counting

[26] In the previous section it has been established that the uncertainties associated with core and measurement related issues are almost negligible. Therefore possible misinterpretation of the ice core records is very likely to be the most significant contributor to uncertainties in the dating of the past 7.9 kyr. Hence several strategies are used to asses this uncertainty. Following the methodology of *Rasmussen et al.* [2006a], features in the ice core records which can neither be dismissed nor confirmed as annual layers using all data available, are recorded as uncertain years. Half of the number of uncertain years is subsequently included in the final timescale, while the other half is discarded. The maximum counting error is then defined as half of the number of uncertain years. This is to say, that uncertain years enter into the dating as 0.5 ± 0.5 year.

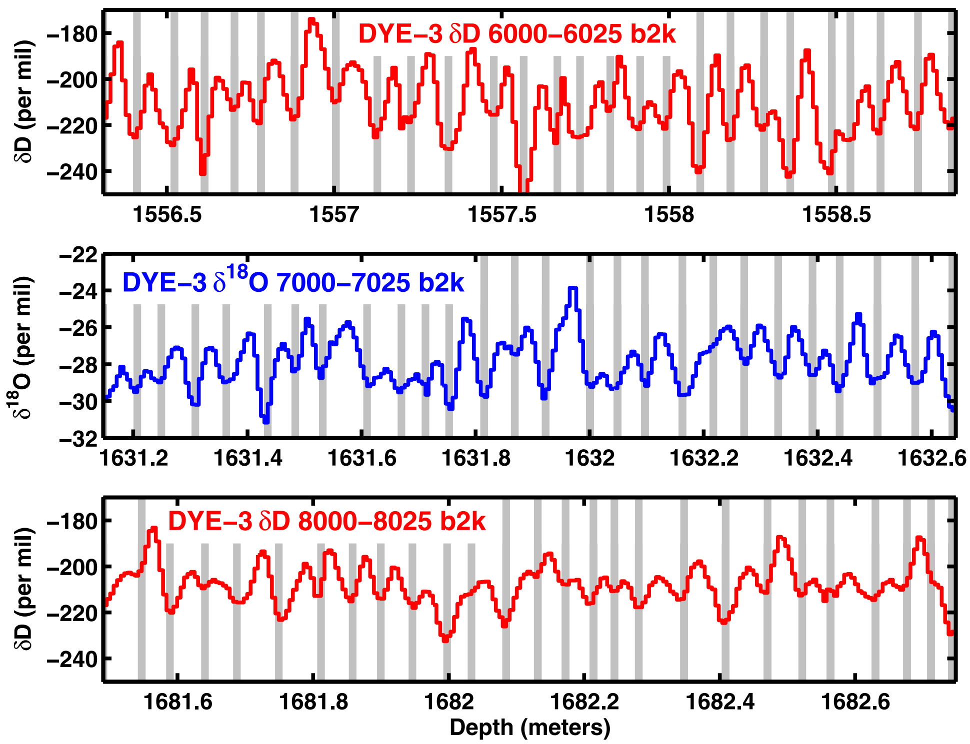

Figure 5. Three sections of the detailed DYE-3 stable isotope profile. The annual cycle is visible in all three sections despite progressive dampening induced by ice diffusion. Light gray bars indicate single years (winters) identified in the records.

Maximum counting errors for different periods of the Holocene are given in Table 2. The error estimates are an expression of the difficulties encountered when interpreting the records, but does not take into account the possibility that the criteria used for identifying annual layers may be imperfect. Thus the maximum counting errors does not reflect possible biases in the annual layer identification process [*Rasmussen et al.*, 2006a].

[27] Direct estimation of the counting bias is possible for the past ~1900 years where historically dated volcanic reference horizons are observed in the ice core records. The period between the A.D. 79 Vesuvius eruption and the A.D. 1362 Öraefajökull eruption has been chosen to evaluate possible biases in the dating technique. Both the A.D. 79 Vesuvius eruption and the A.D. 1362 Öraefajökull eruption have recently been identified in tephra from the GRIP ice core (C. Barbante, personal communication, 2005; V. A. Hall and J. R. Pilcher, personal communication, 2006). Using the DYE-3 and GRIP $\delta^{18}O$ and ECM data a total of 1283 years are counted in between A.D. 79 and A.D. 1362. This is only one year (or ~0.1%) more than the 1282 years known from historical records. It is therefore reasonable to conclude that the bias associated with counting annual cycles in DYE-3 and GRIP $\delta^{18}O$ data is very small, and certainly within the maximum counting error of 0.25% for the period back to 3845 b2k covered by both DYE-3 and GRIP $\delta^{18}O$ data.

[28] From 3846 b2k to 6905 b2k, the DYE-3 stable isotope record is the only data set suited for annual layer counting. The maximum counting error doubles to 0.5% as doubtful features no longer can be investigated in a parallel $\delta^{18}O$ record. A bias estimate when using one record only can be obtained by looking at previous counted timescales for GRIP and DYE-3. According to *Clausen et al.* [1997] the period deliminated by the A.D. 79 Vesuvius eruption and the Minoan eruption of Thera has been independently dated in the DYE-3 and GRIP ice cores. In the GRIP core 1714 years were found, while 1723 years were found in the DYE-3 core. Compared to the new GICC05 dating, that uses both cores, discrepancies are −0.2% and 0.3% respectively. The counting bias introduced when using only one core is therefore within the 0.5% maximum counting error estimate.

[29] The period from 6906 b2k to 7902 b2k is a problematic section in the Holocene part of the GICC05 dating. Progressing ice diffusion gradually smooths the DYE-3 stable isotope data, thereby weakening the annual cycle (see Figure 5). Furthermore, deconvolution techniques are not entirely safe to use, as this part of the DYE-3 record contains some steep gradients in the $\delta^{18}O$ data. The gra-

Table 2. Maximum Counting Errors for the Holocene Part of the Greenland Ice Core Chronology 2005 (GICC05)

Top Year, Age b2k	Bottom Year, Age b2k	Maximum Counting Error, %
21	3845	0.25
3846	6905	0.50
6906	7902	2.00
7903	10276	2.00[a]
10277	11703	0.67[a]

[a]Maximum counting errors from *Rasmussen et al.* [2006a, 2006b].

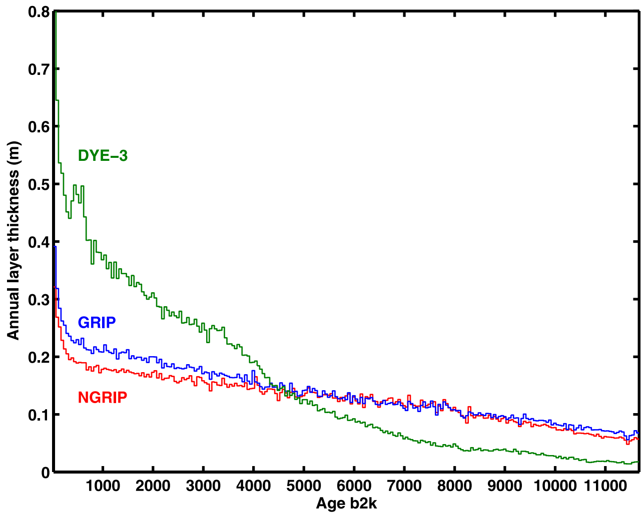

Figure 6. Holocene annual layer thickness profiles for the DYE-3, GRIP, and NGRIP ice cores on the GICC05 timescale.

dients are due to more frequent surface melt during the climatic optimum. Therefore the maximum counting error grows to 2.0% during the 6906–7902 b2k period. This estimate is an average for the entire 997 yearlong period, reflecting that the counting error increases throughout the period as diffusion effects progress.

[30] An independent bias estimation for the 6906–7902 b2k period is difficult to obtain, because the combination of melt layers and progressing ice diffusion is unique to this part of the DYE-3 stable isotope data set. A comparison between annual layer counts in the overlapping period of DYE-3 δD and GRIP CFA data (7903–8314 b2k) indicates a slight bias (0.5–1.0%) toward an overstimation of the number of years in the DYE-3 record. The maximum counting error is, however, 2% for the GRIP CFA record from 7,903–10,276 b2k and ~3% for the DYE-3 record from 7903–8314 b2k. A bias estimate of 0.5–1.0% is therefore below the threshold of safe detection.

[31] As all bias estimates are well within the maximum counting errors given in Table 2, it is considered safe to use the maximum counting errors as an estimate of the total uncertainty associated with the GICC05 timescale back to 6905 b2k. Before 6905 b2k biases are difficult to evaluate and the maximum counting errors are to be used more cautiously. A discussion of the maximum counting errors for the 7903–11,703 b2k period is given by *Rasmussen et al.* [2006a].

4.2. Uncertainties in the Synchronization of the Three Ice Cores

[32] The three ice core records have been synchronized using volcanic reference horizons (see Figure 3 and 4). The risk of mismatching the volcanic reference horizons is low as any such mismatch would create an easily detectable abrupt jump in the derived annual layer thickness record. It is reassuring that no such jumps can be detected in the GRIP and NGRIP annual layer thickness records (see Figure 6). The DYE-3 annual layer thickness record exhibits a peculiar oscillation around 400–800 b2k which is caused by up-stream depositional effects. These effects are due to the DYE-3 drill site being located in an area of vigorous ice flow over a mountainous bedrock leading to a rather uneven surface topography of the ice sheet [*Reeh*, 1989].

[33] The uncertainty in the matching of ECM volcanic reference horizons is estimated to be one year at most, depending on the width and shape of the volcanically induced acidity peaks measured by ECM. Volcanic reference horizons are generally available for every ~50 years linking GRIP and NGRIP, and for every ~100 years linking all three cores [*Clausen et al.*, 1997]. The potential mis-match within matched sections is difficult to asses, but it is believed to be one year at most in the sections where stable isotope data are available for the annual layer counting. When the dating of a core relies only on ECM, the possible maximum mismatch within the matched sections is estimated to 2–3 years. For the part of the DYE-3 core from 8,314–11,703 b2k, which has been synchronized to the *Rasmussen et al.* [2006a] GRIP and NGRIP dating, the maximum possible mismatch is estimated to be slightly higher, 4–5 years, as the mean annual layer thickness in this part of the DYE-3 record amounts to only a few centimeters (see Figure 6).

[34] In order to quantitatively evaluate the ECM match of the cores, correlation coefficients between DYE-3, GRIP and NGRIP annually averaged ECM records have been calculated (see Table 3). As common volcanic signals in the ECM records are expected to correlate (as seen in Figure 3 and 4) the correlation coefficients between the ECM records can be regarded as a measure of the strength of the ECM match. Correlations are presented for the 5 periods of the Holocene outlined in sections 3.1–3.5 and for the three possible core combinations. Table 3 also provides the variances of the ECM records for each core in each section.

[35] From Table 3 it can be seen that correlations vary significantly from section to section, but it is also seen that the variance of the ECM records differ between sections. In fact there is a considerable correspondence between ECM variances and correlations, i.e., the lowest correlations

Table 3. Correlations Between Annually Averaged ECM and Their Variances

Top Year, Age b2k	Bottom Year, Age b2k	Correlation			Variance, μeq/kg^2		
		DYE-3/GRIP	DYE-3/NGRIP	GRIP/NGRIP	DYE-3	GRIP	NGRIP
21	1813	0.24	0.27	0.46	0.25	0.35	0.38
1814	3845	0.23	0.07	0.24	0.15	0.22	0.17
3846	7902	0.27	0.30	0.48	0.23	0.21	0.36
7903	8313	0.19	0.24	0.37	0.08	0.12	0.29
8314	11703	0.40	0.39	0.49	0.21	0.41	0.55

Table 4. GICC05 Dates and Depths for Selected Reference Horizons Observed in the DYE-3, GRIP, and NGRIP Cores

Reference Horizon	DYE-3 Depth, m	GRIP Depth, m	NGRIP Depth, m	Calendar Age, A.D./B.C.	Age, b2k	Maximum Counting Error, years
Öraefajökull[a]	326.70	165.10	142.75	1362	638	0
Hekla[a,b]	429.24	219.55	189.13	1104	896	0
Eldja	493.71	256.15	219.68	933	1066	1
Unknown	635.10	339.83	290.92	529	1471	2
Vesuvius[a]	779.99	429.08	367.80	79	1921	0
Unknown	876.39	493.04	423.15	−252	2251	1
Unknown	1093.53	641.73	555.35	−1077	3076	3
Thera (?)	1227.48	736.47	640.99	−1641[d]	3640[d]	5
Unknown	1443.33	931.78	824.15	−2933	4932	11
Unknown	1555.67	1074.60	964.10	−3993	5992	16
Unknown	1645.10	1225.05	1118.35	−5248	7247	27
8.2k ECM peak	1691.06	1334.04	1228.67	−6237	8236	47
Tjorsà (?)	1708.92	1380.50	1273.45	−6699	8698	57
Unknown	1779.94	1598.91	1470.69	−9307	11306	96
Termination[c]	1786.20	1624.27	1492.45	−9704	11703	99

[a]The Öraefajökull, Hekla and Vesuvius eruptions have been used as historical tie points carrying no uncertainty.
[b]The Hekla eruption commenced in the autumn/winter of A.D. 1104; the signals in the ice cores corresponds to early A.D. 1105.
[c]The termination of Younger Dryas as determined by a shift in deuterium excess values.
[d]GRIP tephra shows that the Thera eruption commenced in 3641 b2k (1642 B.C.). The ECM signals peak in the annual layer 3640 b2k (1641 B.C.).

registered for the NGRIP core is found in the 1814–3845 b2k section, where NGRIP ECM has the lowest variance, whereas the highest correlations for NGRIP is found in the 8314–11703 b2k section where NGRIP ECM variance is at its highest.

[36] The ECM variances provide a good estimate of the strength of the volcanic signals observed in the ECM records, as large ECM spikes (as shown in Figure 3 and 4) will inevitably lead to an increase in the ECM variance. Hence the correspondence between correlations and variances strongly suggests that the differences in correlation

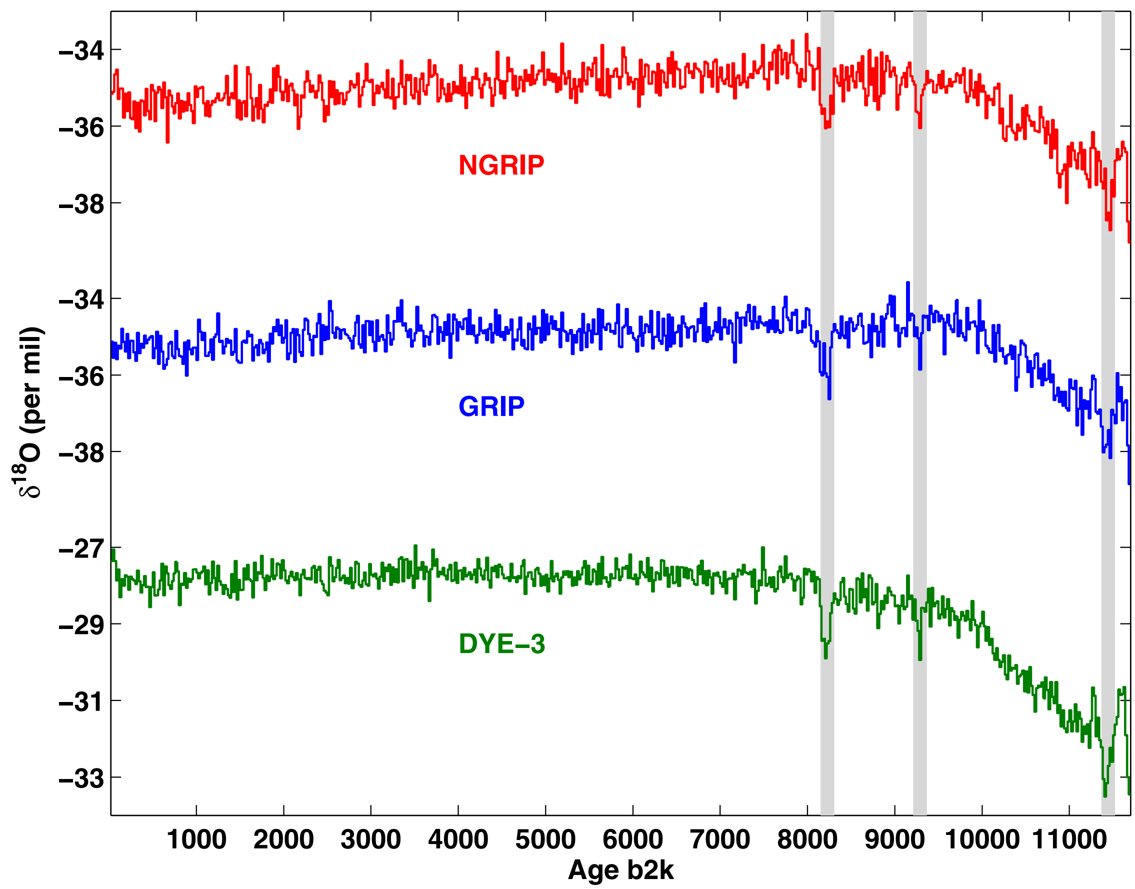

Figure 7. Holocene profiles of δ^{18}O for the DYE-3, GRIP, and NGRIP ice cores on the GICC05 timescale. The 8.2 ka event, the 9.3 ka event, and the 11.4 ka Preboreal Oscillation are indicated by shading.

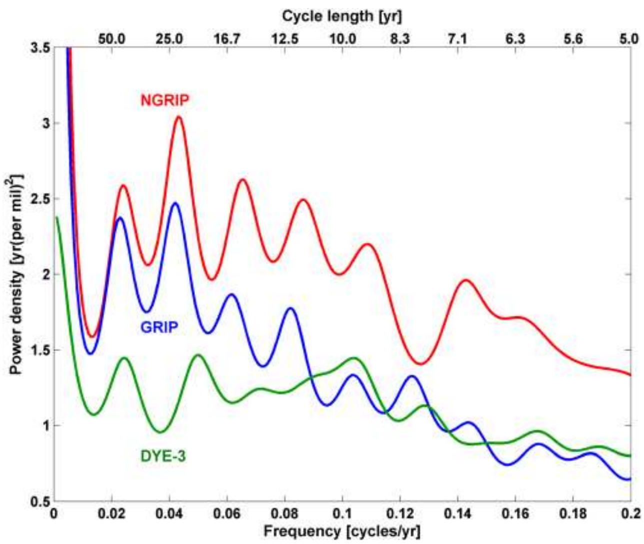

Figure 8. MEM power spectra (AR = 50) for the past 8000 years of the DYE-3, GRIP, and NGRIP annually resolved δ^{18}O records.

between the different sections are predominantly an expression of the frequency and magnitude of volcanic ECM peaks in the sections; not an indication of problems with the ECM matching. That correlations between GRIP and NGRIP are generally higher than correlations with the DYE-3 record reflects the fact, that the GRIP and NGRIP drill sites are much closer to each other than to DYE-3, making it more likely that they contain common volcanic signals. Furthermore melt layers in the DYE-3 core tend to increase the nonvolcanic variability of the DYE-3 ECM record.

5. Results

[37] Table 4 gives depths and ages for selected reference horizons identified in the DYE-3, GRIP and NGRIP ice cores. Maximum counting errors in Table 4 are seen to cumulate before the A.D. 79 eruption of Mount Vesuvius, as this eruption is the oldest historically dated reference horizon in the ice cores. The Minoan Thera eruption [*Hammer et al.*, 1987] is also found in all three ice cores. The GICC05 date for this eruption is 3641 ± 5 b2k (1642 ± 5 B.C.). It should be noted that it has been suggested that an Alaskan volcano, not Thera, was the source of the signals detected in the ice cores [*Pearce et al.*, 2004]. This is, however, extremely unlikely as analysis of the GRIP ice core has established that the tephra from the eruption arrived in Greenland several months before the arrival of the sulphate aerosols [*Hammer et al.*, 2003]. For an Alaskan eruption it would be expected that tephra and sulphate aerosols arrive simultaneously as they are transported to Greenland by the prevailing tropospheric flow (the polar jet). A delay in sulphate arrival can only take place if the sulphate aerosols are transported through the stratosphere, indicative of a highly explosive low-latitude eruption.

[38] Plots of 20-year averages of DYE-3, GRIP and NGRIP δ^{18}O data on the synchronized GICC05 timescale are shown in Figure 7. It can be seen that the past 8000 years are most of all characterized by very stable δ^{18}O values. A slight decline in average δ^{18}O from 8000 b2k to present is, however, discernible in the profiles, most notable in the NGRIP δ^{18}O record.

[39] Before 8000 b2k, the δ^{18}O values are less stable. Significant deviations from the mean DYE-3, GRIP and NGRIP δ^{18}O and annual layer thickness profiles have been found for three events [*Rasmussen et al.*, 2006b]: The 8.2 ka event, the 9.3 ka event and the 11.4 ka Preboreal Oscillation; all clearly visible in Figure 7.

[40] Having three synchronized δ^{18}O records offers the possibility of investigating periodicities without having to speculate whether dating discrepancies shift cycles in between the records. Maximum entropy method (MEM) power spectra using 50 auto regressive (AR) coefficients of annually resolved δ^{18}O data (1–3 year effective resolution) for the latest 8000 years are shown in Figure 8. There is a striking lack of coherency between the three power spectra. A 40–45 year cycle is the only feature common to all three spectra, disregarding the zero frequency general trend peak. As the peak corresponding to the 40–45 year cycle splits up with increasing auto regressive order, it does not seem to represent a strictly periodic component.

[41] It is also worth noting, that no clear imprint of the 11–12 year solar cycle is discernible. It is only because three synchronized records are available for investigation, that the existence of a 11–12 year cycle can be rejected. Looking only at the GRIP or NGRIP spectra one could easily attribute the peaks to the solar cycle.

6. Discussion

[42] Comparisons between the new GICC05 timescale and existing counted GRIP and GISP2 timescales are given

Table 5. Comparison of Counted Timescales for the GRIP and GISP2 Ice Cores at Selected GRIP and GISP2 Reference Horizons

Event	GRIP Depth, m	GISP2 Depth, m	GICC05 Age, b2k	GRIP Age,[a] b2k	GISP2 Age,[b] b2k	GISP2A Age,[c] b2k
Vesuvius[d]	429.08	453.42	1921	1921	1920	1922
Thera (?)	736.47	774.53	3640 ± 5[e]	3635 ± 7	3669 ± 21[f]	3672 ± 21[f]
Unknown	1074.60	1126.04	5992 ± 16[e]	5974 ± 19	6034 ± 68[f]	6039 ± 69[f]
8.2 ka ECM peak	1334.04	1392.66	8236 ± 47[e]	8214 ± 30	8271 ± 113[f]	8298 ± 114[f]
Termination[g]	1624.27	1678.05	11703 ± 99[e]	11573 ± 70	11704 ± 182[f]	11760 ± 183[f]

[a]The counted GRIP timescale presented by *Johnsen et al.* [1992].
[b]The official GISP2 timescale by *Meese et al.* [1997].
[c]GISP2 timescale by *Alley et al.* [1997, personal communication, 2005], based on visual stratigraphy only.
[d]The A.D. 79 Vesuvius eruption has been used as a historical tie point for all timescales.
[e]Maximum counting errors.
[f]Based on error estimate given in Table 2 of *Meese et al.* [1997] (1% error down to 3339 b2k, 2% error below 3339 b2k).
[g]The termination of the Younger Dryas as determined by a shift in deuterium excess values.

Table 6. Comparison of Counted Timescales for the GRIP and GISP2 Ice Cores Between Selected GRIP and GISP2 Reference Horizons

Events Deliminating Period	GICC05 Duration, years	GRIP Duration,[a] years	GISP2 Duration,[b] years	GISP2A Duration,[c] years
Vesuvius to Thera (?)	1719 ± 5[d]	1714 ± 7	1749 ± 21[e]	1750 ± 21[e]
Thera (?) to Unknown	2352 ± 12[d]	2339 ± 12	2365 ± 48[e]	2367 ± 48[e]
Unknown to 8.2 ka peak	2244 ± 32[d]	2240 ± 11	2237 ± 45[e]	2259 ± 46[e]
8.2 ka peak to Term.[f]	3467 ± 52[d]	3359 ± 40	3433 ± 69[e]	3462 ± 70[e]

[a]The counted GRIP timescale presented by *Johnsen et al.* [1992].
[b]The official GISP2 timescale by *Meese et al.* [1997].
[c]GISP2 timescale by *Alley et al.* [1997, personal communication, 2005], based on visual stratigraphy only.
[d]Maximum counting errors.
[e]Based on uncertainty estimate given in Table 2 of *Meese et al.* [1997] (1% error down to 3339 b2k, 2% error below 3339 b2k).
[f]The termination of Younger Dryas as determined by a shift in deuterium excess values.

in Tables 5 and 6. The GICC05 timescale is seen to be in close agreement with the previous dating of the GRIP ice core [*Johnsen et al.*, 1992] for all parts of the Holocene, except for the oldest section (see Table 6). *Rasmussen et al.* [2006a] discusses this issue, and the disagreement is attributed to an erroneous interpretation of the GRIP CFA data during the original GRIP dating effort.

[43] Table 5 shows an astounding agreement between the GICC05 and the official GISP2 dates for the termination of Younger Dryas. However, when comparing different subsections of the GICC05 timescale and the official GISP2 dating [*Meese et al.*, 1997], it is seen that the agreement is less impressive. In the section between the reference horizons of Thera and Vesuvius, the official GISP2 timescale includes 30 more years than observed in GICC05. This is beyond the limits given by the 5 year GICC05 maximum counting error and the 21 year GISP2 uncertainty for that period. The GISP2 dating is hampered by many sections of significant core loss during this period [*Alley et al.*, 1997], while the GICC05 dating is based on complete and highly resolved $\delta^{18}O$ and ECM records from two cores for the entire section in question. It is therefore believed that the 30 year discrepancy mainly stems from the difficulties affecting the GISP2 dating.

[44] The GISP2 sections below the Thera eruption do agree with GICC05 within the uncertainties of the GISP2 dating. It is interesting that the GICC05 dating finds more years than the official GISP2 dating in the earliest part of the Holocene. *Alley et al.* [1997] specifically pointed toward this possibility, as problems with lacking visible annual bands in the GISP2 core hampered the initial dating of this specific core section (GISP2 visual stratigraphy has been used for annual layer counting). As storage of the GISP2 core made annual layers more visible (due to clatherate dissociation), a recount of the annual layers observed in the GISP2 core was carried out a couple of years later (GISP2A in Table 5 and 6) [*Alley et al.*, 1997, personal communication, 2005]. The GISP2A timescale is seen to agree much better with the early Holocene GICC05 dating.

7. Conclusion

[45] A new synchronized counted timescale has been constructed as a contribution to the Greenland Ice Core Chronology 2005 (GICC05). The new timescale is based on annual layer counting in the DYE-3, GRIP and NGRIP ice core records. The three ice core records have been stratigraphically linked by volcanic reference horizons, in order to form a synchronized timescale spanning the Holocene parts of all three cores.

[46] Highly resolved records of stable isotope measurements have been used for the annual layer counting of the most recent 8000 years of the Holocene, while measurements of chemical impurities are used for the dating of the early part of the Holocene. The maximum counting error is 0.5% or less for the past 6900 years, increasing to 2.0% in some of the older sections of the timescale. The Minoan Thera eruption is dated to 3641 b2k (1642 B.C.) with a maximum counting error of 5 years, while a volcanic reference horizon during the culmination of the 8.2 ka cold event is dated to 8236 b2k with a maximum counting error of 47 years. The Younger Dryas termination is found at 11,703 b2k with a maximum counting error of 99 years.

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References

Alley, R. B., et al. (1997), Visual-stratigraphic dating of the GISP2 ice core: Basis, reproducibility and application, *J. Geophys. Res.*, *102*(C12), 26,367–26,381.

Clausen, H. B., C. U. Hammer, C. S. Hvidberg, D. Dahl-Jensen, J. P. Steffensen, J. Kipfstuhl, and M. Legrand (1997), A comparison of the volcanic records over the past 4000 years from the Greenland Ice Core Project and Dye 3 Greenland ice cores, *J. Geophys. Res.*, *102*(C12), 26,707–26,723.

Dahl-Jensen, D., N. S. Gundestrup, H. Miller, O. Watanabe, S. J. Johnsen, J. P. Steffensen, H. B. Clausen, A. M. Svensson, and L. B. Larsen (2002), The NorthGRIP deep drilling programme, *Ann. Glaciol.*, *35*, 1–4.

Dansgaard, W., and S. J. Johnsen (1969), A flow model and a time scale for the ice core from Camp Century, Greenland, *J. Glaciol.*, *8*, 215–223.

Dansgaard, W., H. B. Clausen, N. Gundestrup, C. U. Hammer, S. J. Johnsen, P. M. Kristinsdottir, and N. Reeh (1982), A new Greenland deep ice core, *Science*, *218*, 1273–1277.

Dansgaard, W., et al. (1993), Evidence for general instability of past climate from a 250-kyr ice-core record, *Nature*, *364*, 218–220.

Hammer, C. U., H. B. Clausen, W. Dansgaard, N. Gundestrup, S. J. Johnsen, and N. Reeh (1978), Dating of Greenland ice cores by flow models, isotopes, volcanic debris, and continental dust, *J. Glaciol.*, *20*, 3–26.

Hammer, C. U., H. B. Clausen, and W. Dansgaard (1980), Greenland ice sheet evidence of post-glacial volcanism and its climatic impact, *Nature*, *288*, 230–235.

Hammer, C. U., H. B. Clausen, W. L. Friedric, and H. Tauber (1987), The Minoan eruption of Santorini in Greece dated to 1645 BC?, *Nature*, *328*, 517–519.

Hammer, C. U., G. Kurat, P. Hoppe, W. Grum, and H. B. Clausen (2003), Thera eruption date 1645 BC confirmed by new ice core data?, in *The Synchronisation of Civilisations in the Eastern Mediterranean in the Second Millennium B.C., Proceedings of the SCIEM 2000 - EuroConference Haindorf, May 2001*, edited by M. Bietak, pp. 87–93, Verlag der Österreichischen Akad. der Wiss., Vienna.

Johnsen, S. J. (1977), Stable isotope homogenization of polar firn and ice, in *Isotopes and Impurities in Snow and Ice, I.U.G.G. XVI, General Assembly, Genoble, 1975*, *IAHS-AISH Publ.*, *118*, 210–219.

Johnsen, S. J., and W. Dansgaard (1992), On flow model dating of stable isotope records from Greenland ice cores, in *The Last Deglaciation: Absolute and Radiocarbon Chronologies*, *NATO ASI Ser., Ser. I*, vol. 2, 13–24.

Johnsen, S. J., H. B. Clausen, W. Dansgaard, K. Fuhrer, N. Gundestrup, C. U. Hammer, P. Iversen, J. Jouzel, B. Stauffer, and J. P. Steffensen (1992), Irregular glacial interstadials recorded in a new Greenland ice core, *Nature*, *359*, 311–313.

Johnsen, S. J., et al. (1997), The $\delta^{18}O$ record along the Greenland Ice Core Project deep ice core and the problem of possible Eemian climatic instability, *J. Geophys. Res.*, *102*(C12), 26,397–26,410.

Johnsen, S. J., H. B. Clausen, K. M. Cuffey, G. Hoffmann, J. Schwander, and T. Creyts (2000), Diffusion of stable isotopes in polar firn and ice: The isotope effect in firn diffusion, in *Physics of Ice Core Records*, pp. 121–140, Hokkaido Univ. Press, Sapporo, Japan.

Langway, C. C., Jr., H. Oeschger, and W. Dansgaard (1985), The Greenland ice sheet program in perspective, in *Greenland Ice Core: Geophysics, Geochemistry and the Environment*, *Geophys. Monogr. Ser.*, vol. 33, edited by C. C. Langway Jr., H. Ocschger, and W. Dansgaard, pp. 1–8, AGU, Washington, D. C.

Meese, D. A., A. J. Gow, P. M. Grootes, P. A. Mayewski, M. Ram, M. Stuvier, K. C. Taylor, E. D. Waddington, and G. A. Zielinski (1994), The accumulation record from the GISP2 core as an indicator of climate change throughout the Holocene, *Science*, *266*, 1680–1682.

Meese, D. A., A. J. Gow, R. B. Alley, G. A. Zielinski, P. M. Grootes, M. Ram, K. C. Taylor, P. A. Mayewski, and J. F. Bolzan (1997), The Greenland Ice Sheet Project 2 depth-age scale: Methods and results, *J. Geophys. Res.*, *102*(C12), 26,411–26,423.

Morrison, J., T. Brockwell, T. Merren, F. Fourel, and A. Phillips (2001), On-line high-precision stable hydrogen isotopic analyses on nanolitre water samples, *Anal. Chem.*, *73*(15), 3570–3575.

North Greenland Ice Core Project Members, (2004), High-resolution record of Northern Hemisphere climate extending into the last interglacial period, *Nature*, *431*, 147–151.

Pearce, N. J. G., J. A. Weatgate, S. J. Preece, W. J. Eastwood, and W. T. Perkins (2004), Identification of Aniakchak (Alaska) tephra in Greenland ice core challenges the 1645 BC data of Minoan eruption of Santorini, *Geochem. Geophys. Geosyst.*, *5*, Q03005, doi:10.1029/2003GC000672.

Rasmussen, S. O., et al. (2006a), A new Greenland ice core chronology for the last glacial termination, *J. Geophys. Res.*, *111*, D06102, doi:10.1029/2005JD006079.

Rasmussen, S. O., B. M. Vinther, H. B. Clausen, and K. K. Andersen (2006b), Early Holocene oscillations recorded in three Greenland ice cores, *Q. Sci. Rev.*, in press.

Reeh, N. (1989), Dating by ice flow modelling: A useful tool or an exercise in applies mathematics?, in *Dahlem Konference: The Environmental Record in Glaciers and Ice Sheets*, edited by U. Oeschger and C. C. Langway Jr., pp. 141–159, John Wiley, Hoboken, N. J.

Rogers, J. C., J. F. Bolzan, and V. A. Pohjola (1998), Atmospheric circulation variability associated with shallow-core seasonal isotopic extremes near Summit Greenland, *J. Geophys. Res.*, *103*(D10), 11,205–11,219.

Shoji, H., and C. C. Langway Jr. (1982), Air hydrate inclusions in fresh ice core, *Nature*, *298*, 548–550.

Vinther, B. M., S. J. Johnsen, K. K. Andersen, H. B. Clausen, and A. W. Hansen (2003), NAO signal recorded in the stable isotopes of Greenland ice cores, *Geophys. Res. Lett.*, *30*(7), 1387, doi:10.1029/2002GL016193.

K. K. Andersen, S. L. Buchardt, H. B. Clausen, D. Dahl-Jensen, S. J. Johnsen, S. O. Rasmussen, I. K. Seierstad, M.-L. Siggaard-Andersen, J. P. Steffensen, A. Svensson, and B. M. Vinther, Ice and Climate, Niels Bohr Institute, Juliane Maries Vej 30, DK-2100 Copenhagen Oe., Denmark. (bo@gfy.ku.dk)

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