ARTICLE IN PRESS

Quaternary Science Reviews ▮ (▮▮▮▮) ▮▮▮–▮▮▮

The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records

Anders Svensson[a,*], Katrine K. Andersen[a], Matthias Bigler[a], Henrik B. Clausen[a], Dorthe Dahl-Jensen[a], Siwan M. Davies[b], Sigfus J. Johnsen[a], Raimund Muscheler[c], Sune O. Rasmussen[a], Regine Röthlisberger[d], Jørgen Peder Steffensen[a], Bo.M. Vinther[a]

[a]*Ice and Climate Research, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, Denmark*
[b]*Department of Geography, University of Wales Swansea, Singleton Park, Swansea, SA2 8PP, UK*
[c]*NASA/Goddard Space Flight Center, Climate & Radiation Branch, Mail Code 613.2, Greenbelt, MD 20771, NASA/Goddard, USA*
[d]*British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK*

Received 20 February 2006; accepted 6 August 2006

Abstract

A new Greenland Ice Core Chronology (GICC05) based on multi-parameter counting of annual layers has been obtained for the last 42 ka. Here we compare the glacial part of the new time scale, which is based entirely on records from the NorthGRIP ice core, to existing time scales and reference horizons covering the same period. These include the GRIP and NorthGRIP modelled time scales, the Meese-Sowers GISP2 counted time scale, the Shackleton–Fairbanks GRIP time scale (SFCP04) based on ^{14}C calibration of a marine core, the Hulu Cave record, three volcanic reference horizons, and the Laschamp geomagnetic excursion event occurring around Greenland Interstadial 10. GICC05 is generally in good long-term agreement with the existing Greenland ice core chronologies and with the Hulu Cave record, but on shorter time scales there are significant discrepancies. Around the Last Glacial Maximum there is a more than 1 ka age difference between GICC05 and SFCP04 and a more than 0.5 ka discrepancy in the same direction between GICC05 and the age of a recently identified tephra layer in the NorthGRIP ice core. Both SFCP04 and the tephra age are based on ^{14}C-dated marine cores and fixed marine reservoir ages. For the Laschamp event, GICC05 agrees with a recent independent dating within the uncertainties.

---

1. Introduction

Ice cores from Antarctica and Greenland are unique archives that provide a detailed record of past climate and have an important role in the prediction of climatic changes in the future. However, a correct interpretation of the ice core records, and of many other paleoclimatic records that are linked to the ice cores by reference horizons, relies heavily on the availability of an accurate ice core chronology. Since the start of deep ice core drillings in the late sixties, the development of ice core time scales has, therefore, been an area of great interest.

In most of Antarctica and in parts of Greenland, dating of ice cores is only possible by means of ice flow modelling or by identification of well-dated reference horizons. In some locations, however, the accumulation is sufficiently high to enable a chronology to be built by annual layer counting in a similar way to the methods used in dendrochronology and in the study of varve records. To date, the Greenland ice cores provide the only paleoclimatic archive in which the absolute dating can be performed continuously by counting of annual layers from present day into the glacial period.

Although a Greenland ice core chronology is of utmost importance it has so far not been possible to establish an agreed master chronology reaching back into the glacial period (Southon, 2004). The most commonly used Greenland time scales have been the model-based GRIP time scales and the counted GISP2 time scales, which deviate by several thousands of years beyond 50 ka b2k (before the year 2000 AD).

---

*Corresponding author. Tel.: +45 35320616; fax: +45 35365357.
E-mail address: as@gfy.ku.dk (A. Svensson).

0277-3791/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quascirev.2006.08.003

Please cite this article as: Anders Svensson et al., The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records, Quaternary Science Reviews (2006), doi:10.1016/j.quascirev.2006.08.003

Recently, a new Greenland time scale based on multiparameter counting of annual layers has been developed for the last 42 ka. The Greenland Ice Core Chronology 2005 (GICC05) is based on the Dye-3, GRIP and NorthGRIP ice cores for the 0–10 ka period (Vinther et al., 2006), whereas the NorthGRIP records are solely used for the 10–15 ka period (Rasmussen et al., 2006a) and the 15–42 ka period (Andersen et al., 2006). The NorthGRIP ice core is particularly favourable for dating of the glacial period because several high-resolution records are available and because the layer thinning in the deep ice is less pronounced than in other deep Greenland ice cores (North Greenland Ice-Core Project (NorthGRIP) Members, 2004). This is due to basal melt at the NorthGRIP site, which causes the deepest part of the core to maintain a centimeter-sized annual layer thickness.

One of the strengths of a counted time scale is that it provides very accurate differential dating, whereas a weakness lies in the increasing accumulated error, which—except for the hypothetical case of a perfect counting—often will be biased. On the other hand, time scales based on absolute dating methods, such as radiometric dates, may provide very accurate absolute dates, whereas relative ages typically will be less well determined. Absolute chronologies based on radiometric dating may, however, also be biased, for example if the analyzed material has not been completely sealed off since formation, if there are unknown reservoir ages, or if the decay constants are not precisely known.

As each time scale has different strengths and weaknesses, it is important that the time scales are obtained as independently as possible. Only by comparing independently obtained time scales will it be possible to pinpoint the inaccuracies and their extent within the individual chronologies. For instance, it has been argued that Greenland ice core chronologies may be biased due to the potential risk of ‘missing annual layers’—in particular during cold glacial periods. The only definitive way to test this is to provide an ice core chronology that agrees well with independently dated reference horizons.

Here, we compare GICC05 to a number of other independently obtained chronologies and reference horizons within the time interval 10–42 ka b2k. We refer to the Dansgaard–Oeschger (D–O) events during the last glacial period as Greenland Interstadials (GI) for the mild periods and Greenland Stadials (GS) for the cold periods. We define the Marine Isotope Stage 2 (MIS2) as the period from the onset of GI-3 to the termination of the Younger Dryas, and we use the term Last Glacial Maximum (LGM) for the cold period between GI-2 and GI-3, which is equivalent to GS-3. Ages are specified in units of ‘b2k’ (= before year 2000 AD) or ‘BP’ (= before year 1950 AD) and uncertainties for GICC05 ages are quoted as 1σ, which is equal to half the maximum counting error (Andersen et al., 2006).

2. The NorthGRIP modelled time scale

The existing time scales for the glacial part of the GRIP and NorthGRIP ice cores are mainly based on modelling (see Southon (2004) for a review). The most recent of those models, the ‘ss09sea’ time scale, was constructed for the GRIP ice core (Johnsen et al., 2001) and later applied to the NorthGRIP ice core (North Greenland Ice-Core Project (NorthGRIP) Members, 2004). The model is constrained by two fixed points at 11,554 yr b2k for the Younger Dryas/Holocene transition and at 110 ka b2k for the MIS 5d/5c transition occurring in GS-25. Past accumulation rates are obtained from δ^{18}O by an empirical relation and the thinning of annual layers with depth is obtained from an ice-flow model. The model takes into account past changes in seawater δ^{18}O due to changes in global ice volume.

Between 10–42 ka b2k, the GICC05 and the ‘ss09sea’ model time scales show an overall good agreement with age differences of up to 635 yr (Figs. 1 and 2). An important common feature of the two time scales is a consistently strong correlation between climate (represented by δ^{18}O) and annual layer thicknesses across the D–O events (Fig. 3). The general pattern shows thicker annual layers during warm and mild climates than during cold glacial conditions, a conclusion also reached independently from the NorthGRIP visual stratigraphy alone (Svensson et al., 2005).

The most important discrepancy between the two time scales occurs during MIS2 in the depth range of 1610–1725 m where ‘ss09sea’ predicts generally thicker annual layers than GICC05, which ‘gains’ more than 500 yr compared to the model. Since the model builds on a δ^{18}O-accumulation relationship, the deviation from GICC05 suggests a breakdown of that relationship in that region. Comparison of δ^{18}O profiles of deep ice cores from various locations in central Greenland reveals an unusual dissimilarity in the shape of the profiles between Bølling (GI-1) and GI-2 (Fig. 4). It seems unlikely that this scatter reflects a true climatic variability in Greenland, and, therefore, the δ^{18}O-accumulation relationship is not expected to be valid within this period.

From the LGM and back to 42 ka b2k (1800–2100 m depth) GICC05 generally shows thicker annual layers than the model to which it gradually ‘loses’ some 800 yr. This suggests that the δ^{18}O-accumululation approach of the model is valid for this period but that the model tuning parameters may need adjustment.

3. The GIPS2 Meese–Sowers counted chronology

The glacial part of the GISP2 time scale is based on annual layer counting of visual stratigraphy, laser-light scattering, and electrical conductivity measurements of the solid ice (Alley et al., 1997; Meese et al., 1997; Ram and Koenig, 1997). The uncertainty of the GISP2 time scale in the glacial period back to 40 ka b2k is stated to be about

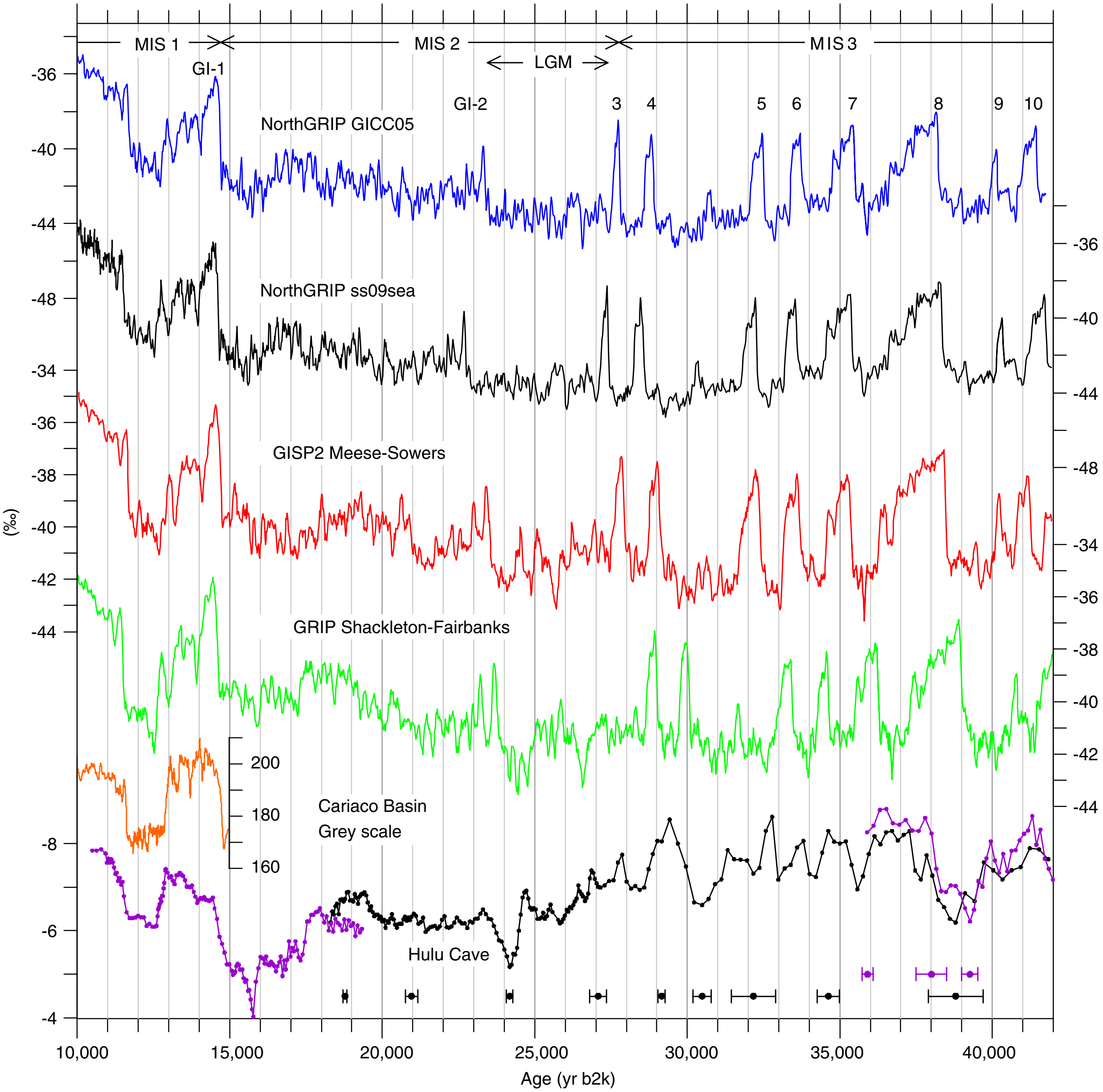

Fig. 1. Comparison of δ^{18}O records and time scales for various sites: NorthGRIP on the GICC05 time scale (Andersen et al., 2006; Rasmussen et al., 2006a, b), NorthGRIP on the 'ss09sea' time scale (North Greenland Ice-Core Project (NorthGRIP) Members, 2004), GISP2 on the Meese–Sowers time scale (Meese et al., 1997), GRIP on the Shackleton–Fairbanks (SFCP04) time scale (Shackleton et al., 2004), grey scale of the varve-counted Cariaco Basin chronology (Hughen et al., 2000), and the Hulu cave record including absolutely dated control points (see Wang et al. (2001) for details). The Marine Isotopic Stages (MIS), the Last Glacial Maximum (LGM), and the Greenland Interstadials (GI) are indicated.

2%, which is comparable to the uncertainty of GICC05 in the same period (Andersen et al., 2006).

As seen in Fig. 1, in general there is a very good agreement between the GISP2 and GICC05 time scales. GICC05 agrees with GISP2 to within 250 yr over the entire period back to 30 ka, and the two chronologies determine the onset of interstadials within 300 yr (Fig. 2). One will notice, however, that the duration of the interstadials/stadials generally appears longer/shorter for the GISP2 time scale than for GICC05 respectively. To investigate this issue in more detail, the annual layer thicknesses of the two time scales are compared in Fig. 5. Because the two cores have different accumulation histories and thinning functions the annual layer thickness profiles of the two cores cannot be expected to match up completely, but one would expect the overall shape of the profiles to be comparable.

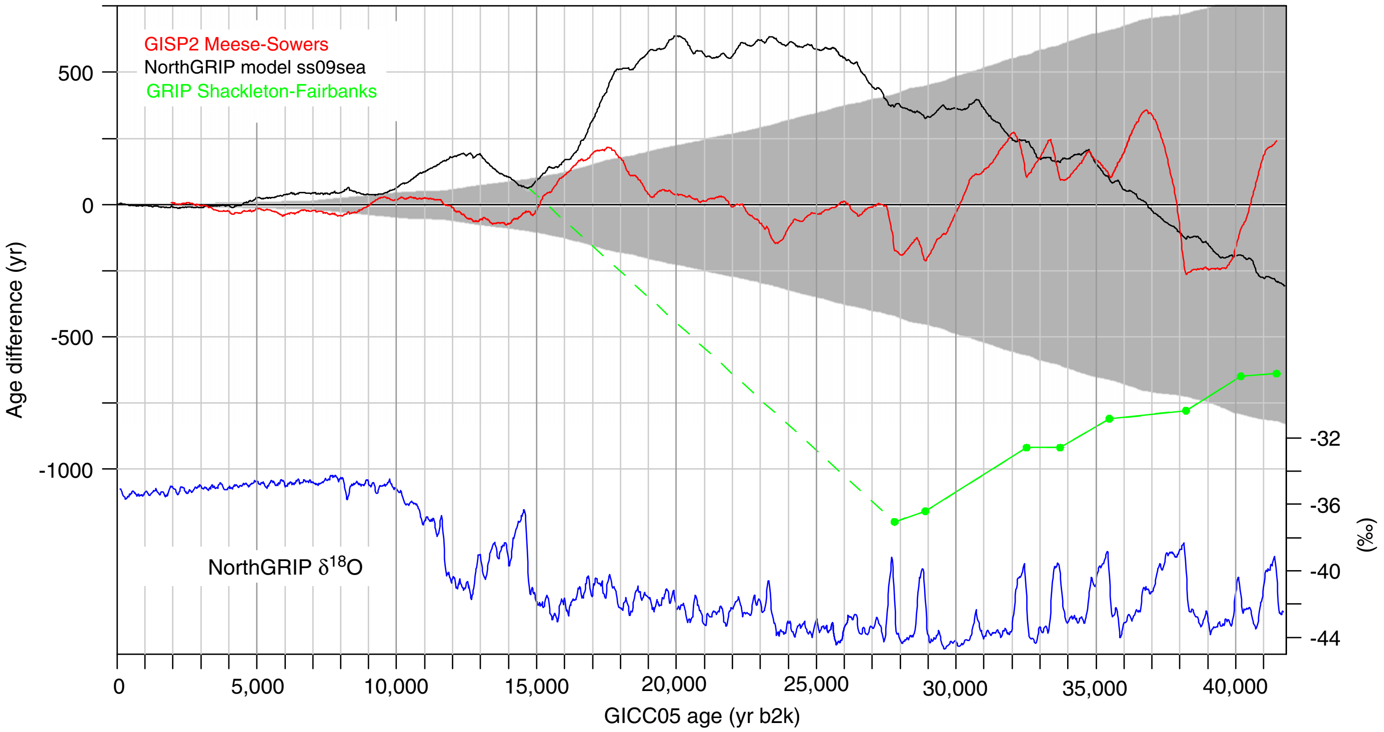

Fig. 2. Deviations of ‘ss09sea’, GISP2, and SFCP04 time scales as compared to GICC05. The shaded area represents the GICC05 1σ uncertainty. The GICC05 and GISP2 records are linked via volcanic reference horizons and other match points back to 32.5 ka b2k (Rasmussen et al., 2006a, b) and by matching of the rapid shifts in δ^{18}O in the remaining of MIS3. SPCF04 is linked to GICC05 by rapid shifts in δ^{18}O only.

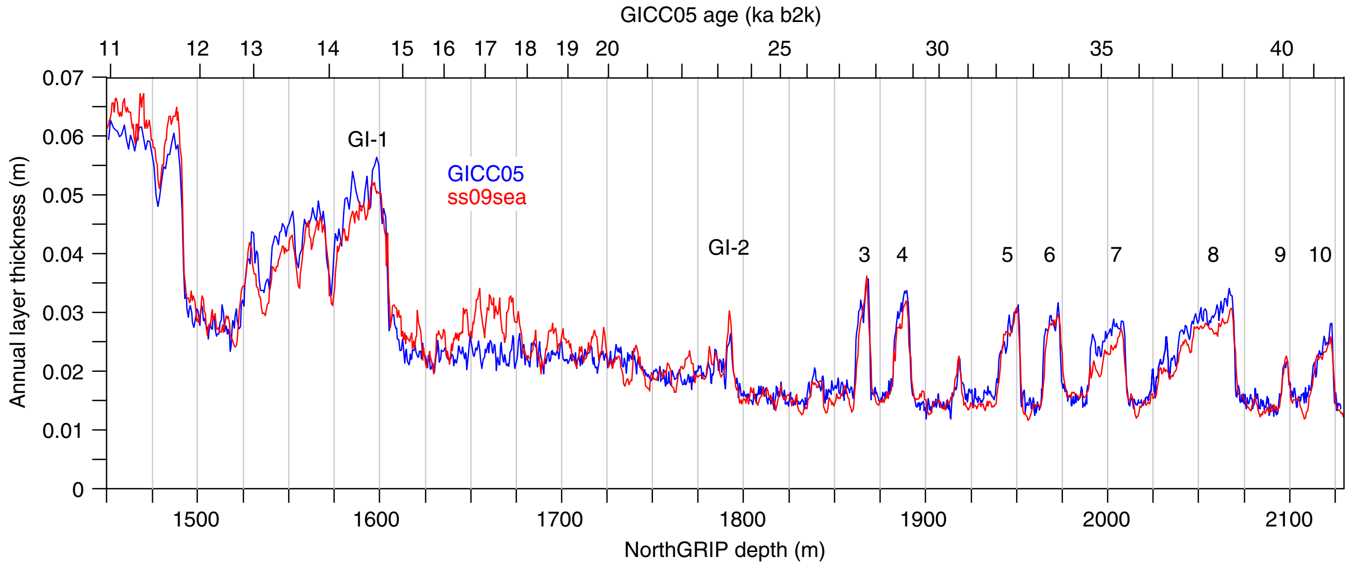

Fig. 3. Comparison of NorthGRIP annual layer thicknesses between the ‘ss09sea’ model and the GICC05 time scales.

However, the detailed comparison in Fig. 5 reveals a significant difference: whereas the GICC05 time scale consistently shows a strong correlation between climate (δ^{18}O) and annual layer thickness, the GISP2 time scale does generally not follow this pattern. The GISP2 time scale has elevated annual layer thicknesses during GI-3, 4 and 7, whereas GI-5 and 6 show no increase in layer thickness compared to the adjacent cold periods and GI-8 appears to be something in between. The change in annual layer thickness across the abrupt climatic changes at the termination of the last glacial period are very well established (Alley et al., 1993; Rasmussen et al., 2006b). Therefore, the lack of coupling between climate and accumulation in Greenland, which is suggested by the

Please cite this article as: Anders Svensson et al., The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records, Quaternary Science Reviews (2006), doi:10.1016/j.quascirev.2006.08.003

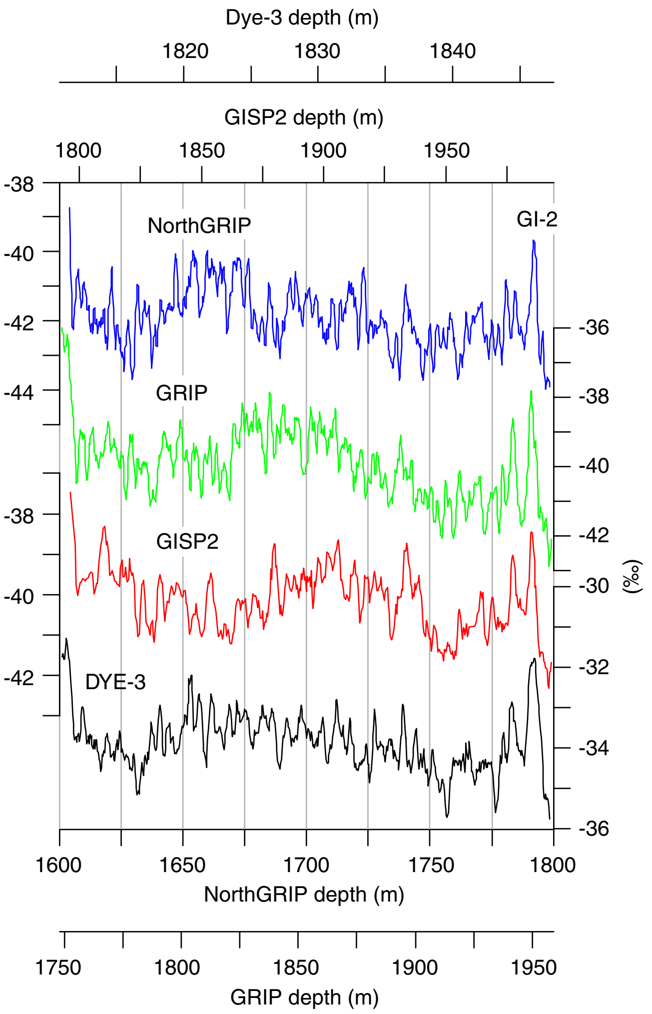

Fig. 4. Comparison of the δ^{18}O profiles for NorthGRIP, GRIP, GISP2, and Dye-3 in MIS2 between Bølling and GI-2. The profiles are shown on their respective depth scales.

MIS3 part of the GISP2 time scale, seems highly unlikely. The reason why the changes in annual layer thickness are not recorded in the GISP2 time scale may be that the GISP2 annual layers become relatively thin in MIS3 and that the counting was made without application of high-resolution chemistry records, which are necessary to identify multiple layers within a year (Andersen et al., 2006). Considering the very significant difference in the annual layer profiles across the D–O events, it is astonishing how well the absolute ages of the GISP2 time scale in MIS3 compare to those of GICC05.

Based on the GISP2 chronology, a number of studies have discussed the existence of temporal periodicities in the ice core proxy data. For example, Ram and Stolz (1999) state that 'the GISP2 dust profile is strongly modulated by ~11 yr, ~91 yr, and ~200 yr periods.' Rahmstorf (2003), Schulz (2002) and many others discuss the existence of a 1470 yr climatic cycle in the stable isotope profiles of the last glacial period. The conclusions of these studies may very well be justified, but we would like to emphasize that the finding of such periodicities obviously relies profoundly on the applied time scale. For example, the existence of the proposed 1470 yr cycle depends on the exact timing and phasing of the onset of D–O events, and, as discussed above, this is exactly where we believe that the GISP2 time scale is inaccurate. A detailed discussion of this topic is, however, beyond the scope of this paper.

4. The Shackleton–Fairbanks marine GRIP time scale

Fairbanks et al. (2005) proposed a 50 ka ^{14}C calibration curve based on paired measurements of ^{230}Th/^{234}U/^{238}U and ^{14}C on pristine corals from various locations. Shackleton et al. (2004) applied this calibration to date foraminifera in marine core MD95-2042 located off the coast of Portugal using a fixed surface reservoir age of 500 ± 100 yr. The oxygen isotope record of planktonic foraminifera in the marine core compares very well with the D–O events observed in Greenland ice cores, and so marine ages for these corresponding events were transferred to the GRIP ice core, and a continuous ice core time scale was obtained by linear interpolation of 'ss09sea' between the fix points. The time scale is named SFCP04.

As seen in Figs. 1 and 2, SFCP04 generally suggests significantly older ages for the glacial ice than those presented in this study. In particular, it places the onset of GI-3 at 29.0 ka BP, which is about 1.2 ka older than the GICC05 age of 27.8 ± 0.4 ka b2k. The two time scales agree at the onset of Bølling (GI-1) within a 100 yr, and thus, the significant age difference accumulates in the interval between GI-1 and GI-3. In other words, if the SFCP04 time scale is correct, it implies that we have been omitting roughly 10% of the annual layers within that section, which is four times the GICC05 uncertainty estimate in the same section (Andersen et al., 2006). We, therefore, believe that the SFCP04 age for the onset of GI-3 is too old. We notice that the Fairbanks et al. (2005) ^{14}C calibration curve around 29 ka BP is based on a few quite distant control points, which are connected by linear interpolation with an almost vanishing curve uncertainty (Fig. 3 in Fairbanks et al. (2005)). In addition, there are significant differences between the various ^{14}C calibration records around this period (Muscheler et al., 2004; van der Plicht et al., 2004). Another possible reason for the discrepancy may be due to uncertain reservoir ages for marine core MD95-2042 in the glacial period.

When comparing SFCP04 to GICC05 at the onset of GI-8, however, we notice that the difference between the two chronologies is reduced to 800 yr and falls within the stated uncertainties. In conclusion, the comparison of the two time scales reveals an inconsistency: either GICC05 contains significantly too few annual layers in the section from GI-1 to GI-3 and too many annual layers in the section from GI-3 to GI-8, or the SFCP04 age for GI-3 is too old.

Please cite this article as: Anders Svensson et al., The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records, Quaternary Science Reviews (2006), doi:10.1016/j.quascirev.2006.08.003

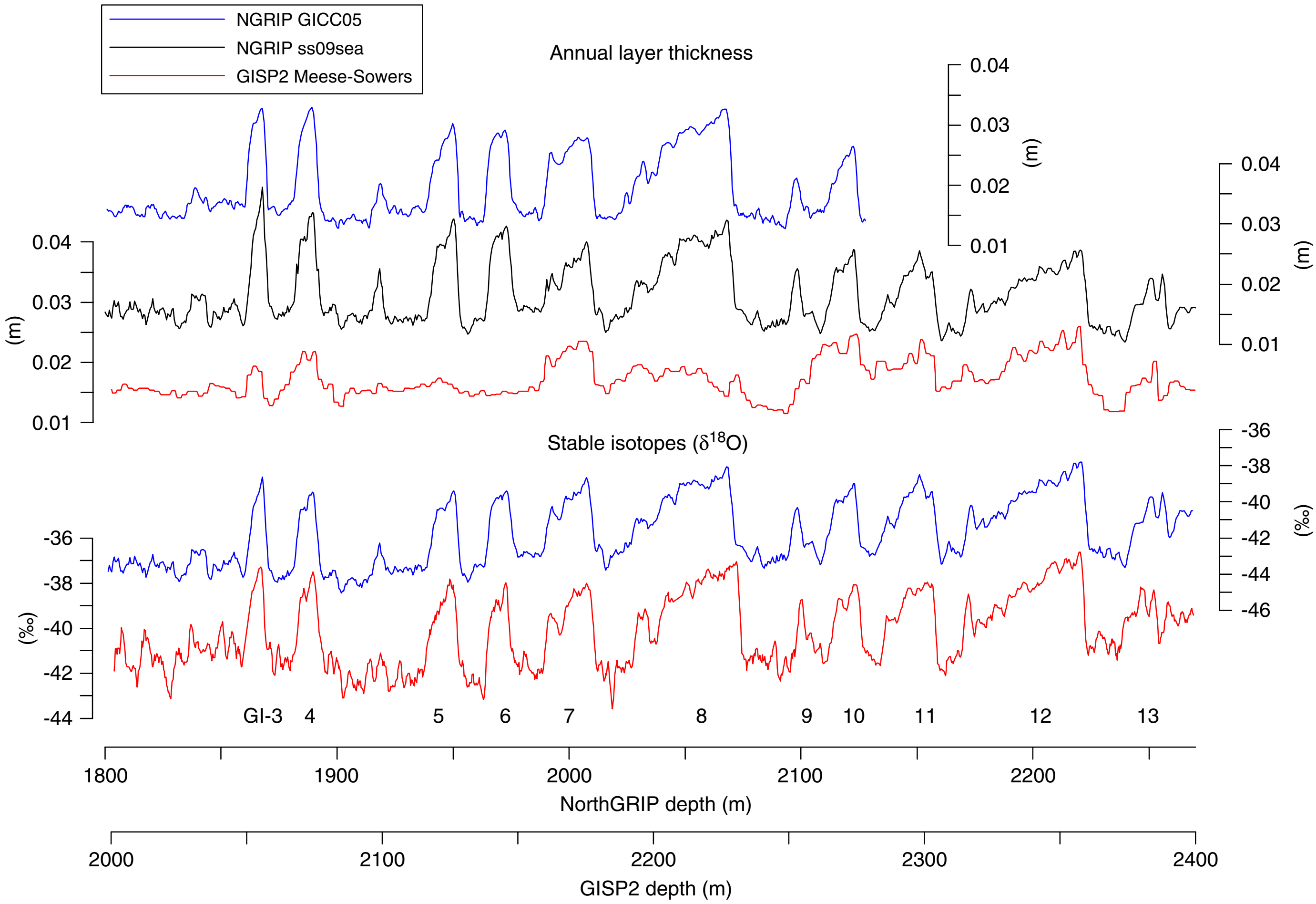

Fig. 5. Comparison of annual layer thicknesses between NorthGRIP and GISP2 time scales in the period from GI-3 to GI-13 (upper three curves). The two cores are shown on their respective depth scales, which are aligned by matching of the δ^{18}O profiles (lower two curves).

5. Cave records

The Chinese Hulu Cave stalagmite record by Wang et al. (2001) has been widely used for dating purposes in the last glacial period due to the absolutely U/Th dates and because the δ^{18}O profile resembles that of the Greenland ice core records. Given the relatively low time resolution of the Hulu Cave record, there is a rather good overall correspondence between the Hulu Cave and GICC05 in MIS3. In particular, the two chronologies apparently agree within the error estimates at the absolutely dated Hulu Cave control points (Fig. 1). It is debatable, of course, if the events seen in the Chinese cave stalagmites actually correspond to the Greenland D–O events. For example, the Hulu Cave peak corresponding to GI-4 is very different from that in Greenland. Even if the events are actually the same in China and Greenland, it is still questionable if the phasing of the events is synchronous at the two locations, and we will, therefore, not focus in detail on this comparison.

Other absolutely dated cave records are available (Spötl et al., 2006; Wang et al., 2004), but the temporal overlap with the current version of GICC05 is limited. The Brazilian speleothem record by Wang et al. (2004) determines the marine Heinrich event 4 (Bond et al., 1993) to occur in the interval 39.6–38.9 ka BP with a duration of 700 ± 400 yr. According to GICC05 this interval occurs in the cold stadial preceding GI-8, where the Heinrich event is supposed to appear, which suggests that the ages are consistent.

6. Reference horizons

Identified volcanic tephra layers in ice cores provide a very important link to other paleoclimatic archives and facilitate the validation of ice core chronologies. If tephra layers have been radiometrically dated by means other than ^{14}C they can be used to validate the ice core chronology, whereas an additional ^{14}C dating links the ice core chronology to the ^{14}C calibration curve.

In the time interval 10–42 ka b2k, three tephra layers with known source and independent age determination have been identified in Greenland ice cores. Two of those are the Saksunarvatn ash layer (early Preboreal) and the Vedde ash layer (Z1, late Younger Dryas), which both demonstrate an excellent agreement between IntCal04

(Reimer et al., 2004) and GICC05 around the last termination as discussed in Rasmussen et al. (2006c). The third tephra layer is the Fugloyarbanki tephra, recently identified in the NorthGRIP ice core at 1848 m depth and about 1 ka after the onset of GI-3 (Davies et al., in preparation). The GICC05 age of the Fugloyarbanki tephra layer is 26 740 ± 390 yr b2k. This tephra layer has been identified and dated in several marine cores from the North Atlantic with ages in the range 22.85–23.3 ^{14}C ka BP and an average of 23.1 ^{14}C ka BP (Rasmussen et al., 2003). A reservoir age of 400 yr has been applied to these ages (T.L. Rasmussen, 2006, pers. comm.). This age goes slightly beyond the IntCal04 calibration curve but is covered by the calibration proposed by Fairbanks et al. (2005). In Fig. 6 it is seen that the Fugloyarbanki tephra data point falls more than 0.5 ka away from the ^{14}C calibration curve, therefore suggesting that either 1) the GICC05 age is too young, 2) the ^{14}C calibration is too old, or 3) the applied marine reservoir age correction is too small. A direct and absolute dating of this and other tephra layers from terrestrial sources is required to eliminate the latter possible source of error.

Another important reference horizon in the Lateglacial period is the Laschamp event, which is a geomagnetic excursion occurring about 41 ka ago that is recorded in many paleoclimatic records. In ice cores, the event can be identified as a peak in the ^{10}Be and ^{36}Cl flux to the ice that is recorded in the GRIP ice core around GI-10 (Yiou et al., 1997; Wagner et al., 2000). The Laschamp event has recently been Ar/Ar and K/Ar dated from the Laschamp and Olby lava flows to 40.4 ± 2.0 ka (Guillou et al., 2004), which compares well to the GICC05 date of 41.25 ± 0.8 ka for the center of the ^{10}Be maximum (Fig. 7).

7. Conclusions

The new Greenland Ice Core Chronology 2005 (Andersen et al., 2006) generally compares well with existing Greenland ice core time scales in the interval 10–42 ka b2k. Comparison with the modelled NorthGRIP time scale 'ss09sea' suggests that the model underestimates the duration of MIS2 by about 500 yr, but that this is compensated for in the period 25–42 ka b2k, where the model has about 800 yr more than GICC05. We conclude that the model approach of establishing an empirical δ^{18}O—accumulation relationship is valid to a first order in the interval 10–42 ka b2k except for the period between GI-1 and GI-2, where the isotope profiles in the Greenland ice cores do not reflect a climatic signal only.

GICC05 agrees very well with the counted GISP2 time scale in late MIS3 and in MIS2, but in MIS3 the GISP2 time scale does not systematically record the important variations in annual layer thickness occurring in phase with the D–O events. Reasons for this may be that the GISP2 annual layers become relatively thin in MIS3 or that the GISP2 counting was based on too few high-resolution records. The resulting inconsistency in the GISP2 time

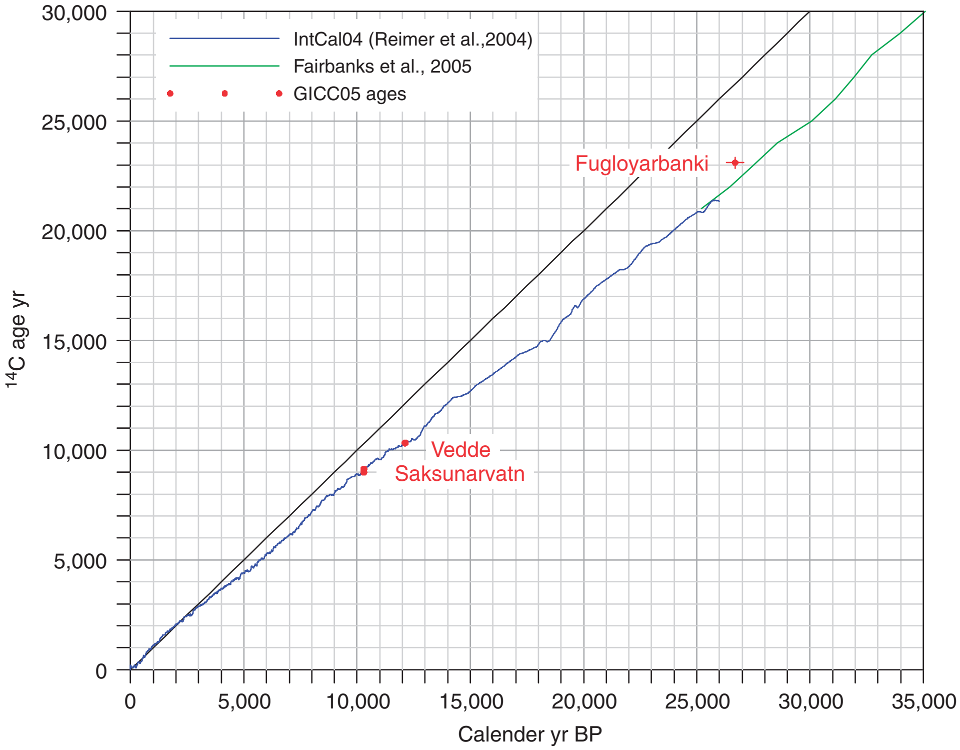

Fig. 6. Comparison of the ^{14}C calibrations of IntCal04 (Reimer et al., 2004) and Fairbanks et al. (2005) with tephra layers in the NorthGRIP ice core which have been dated independently by ^{14}C (Björck et al., 2001; Davies et al., in preparation; Grönvold et al., 1995; Mortensen et al., 2005; Rasmussen et al., 2003; Wastegård et al., 1998). Error bars are 1σ for the ice core ages and representing the span of several measurements for the ^{14}C dates.

Please cite this article as: Anders Svensson et al., The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records, Quaternary Science Reviews (2006), doi:10.1016/j.quascirev.2006.08.003

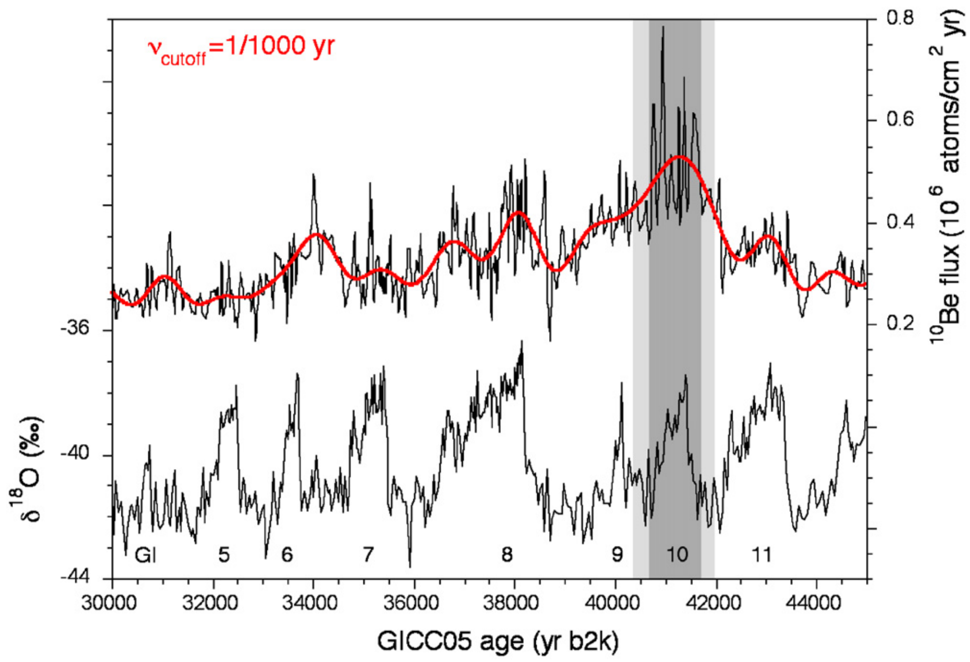

Fig. 7. The ^{10}Be flux increase during the Laschamp geomagnetic field minimum around 41.25 ka b2k (GICC05) and the GRIP δ^{18}O data. The upper panel shows the ^{10}Be flux together a low-pass filtered curve. The maximum in the ^{10}Be increase can be placed around GI-10 (lower panel) but it is not restricted to it. The shaded areas give the expected range of low geomagnetic field values according to the ^{10}Be flux. The light shaded area indicates the full-width half-maximum of the low-pass filtered curve and the darker shading shows the peak width according to the elevated values of the raw data. The GICC05 time scale was extended to older values by use of the 'ss09sea' age model that was shifted by a constant age to obtain agreement between the two time scales around 41.75 ka b2k (the end date of the GICC05 time scale).

scale may have implications for frequency analysis studies applying that chronology.

There is a significant disagreement between GICC05 and the GRIP time scale based on ^{14}C-dating of a marine core (SFCP04) at the onset of GI-3, which gradually decreases towards GI-10, and we suggest that the SFCP04 age for GI-3 is too old by ~1 ka. Due to the potential limitations associated with both marine reservoir ages and ^{14}C calibration, we do not recommend the application of ^{14}C-dated marine cores to improve the dating of Greenland ice cores.

A comparison to the Hulu Cave record reveals a good long-term agreement, but the relatively low time resolution of that record does not allow for a more detailed comparison. A re-analysis of the Hulu Cave record with analytical errors comparable to those of Spötl et al. (2006) would be most valuable.

For the period 15–42 ka b2k, the only widely-distributed tephra layer in the NGRIP ice core is the Fugloyarbanki tephra that falls within the LGM. The calibrated ^{14}C age of that tephra layer, derived from North Atlantic marine cores, is more than 0.5 ka older than the corresponding GICC05 age. If GICC05 is correct within the estimated errors, then the divergence of GICC05 and SFCP04 at the onset of GI-3 and the disagreement between GICC05 and the calibrated age of the Fugloyarbanki tephra both suggest that either the applied ^{14}C calibration records are inaccurate or the applied marine reservoir ages are too low.

We obtain good agreement between the GICC05 age of the ^{10}Be maximum during the Laschamp geomagnetic field minimum and new radiometric datings of this event based on samples from the Laschamp and Olby lava flows. However, because the time span of the ^{10}Be peak in Greenland covers about 1 ka and because the analytical error in the dating of the Laschamp event adds another 2 ka to the uncertainty, the comparison of the two independent Laschamp ages does not constrain the GICC05 uncertainty.

GICC05 provides an independent Greenland time scale that is capable of identifying the causes of the long-lasting discrepancies between the most commonly used Greenland chronologies. This time scale is based on annual layer counting of records with higher resolution than any previously published chronology covering the same interval, and is also in accordance with other independent chronologies in the same time interval, except when ^{14}C calibrated ages from marine cores with fixed marine reservoir ages from the LGM are involved. Therefore, we believe that GICC05 has the potential of contributing to the ^{14}C calibration curve back to 42 ka b2k.

Acknowledgements

This work is a contribution to the NorthGRIP ice core project, which is directed and organized by the Ice and Climate Research Group at the Niels Bohr Institute,

Please cite this article as: Anders Svensson et al., The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records, Quaternary Science Reviews (2006), doi:10.1016/j.quascirev.2006.08.003

University of Copenhagen. It is being supported by funding agencies in Denmark (SNF), Belgium (FNRS-CFB), France (IFRTP and INSU/CNRS), Germany (AWI), Iceland (RannIs), Japan (MEXT), Sweden (SPRS), Switzerland (SNF) and the United States of America (NSF). This work is also a contribution to the Copenhagen Ice Core Dating Initiative, which is supported by a grant from the Carlsberg Foundation.

References

Alley, R.B., Meese, D.A., Shuman, C.A., Gow, A.J., Taylor, K.C., Grootes, P.M., White, J.W.C., Ram, M., Waddington, E.D., Mayewski, P.A., Zielinski, G.A., 1993. Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. Nature 362, 527–529.

Alley, R.B., Shuman, C.A., Meese, D.A., Gow, A.J., Taylor, K.C., Cuffey, K.M., Fitzpatrick, J.J., Grootes, P.M., Zielinski, G.A., Ram, M., Spinelli, G., Elder, B., 1997. Visual-stratigraphic dating of the GISP2 ice core: basic, reproducibility, and application. Journal of Geophysical Research 102, 26367–26381.

Andersen, K.K., Svensson, A., Rasmussen, S.O., Steffensen, J.P., Johnsen, S.J., Bigler, M., Röthlisberger, R., Ruth, U., Siggaard-Andersen, M.-L., Dahl-Jensen, D., Vinther, B.M., Clausen, H.B., 2006. The Greenland Ice Core Chronology 2005, 15–42 ka. Part 1: constructing the time scale. Quaternary Science Reviews, this issue, doi:10.1016/j.quascrev.2006.08.02.

Björck, S., Muscheler, R., Kromer, B., Andresen, C.S., Heinemeier, J., Johnsen, S.J., Conley, D., Koç, N., Spurk, M., Veski, S., 2001. High-resolution analyses of an early Holocene climate event may imply decreased solar forcing as an important climate trigger. Geology 29, 1107–1110.

Bond, G., Broecker, W., Johnsen, S.J., McManus, J., Labeyrie, L., Jouzel, J., Bonani, G., 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. Nature 365, 143–147.

Davies, S.M., Wastergård, S., Rasmussen, T.L., Johnsen, S.J., Steffensen, J.P., Andersen, K.K., Svensson, A. Identification of the fugloyarbanki tephra in the NGRIP ice-core: A key tie-point for marine and ice-core sequences during the last glacial period, in preparation.

Fairbanks, R.G., Mortlock, R.A., Chiu, T.-C., Cao, L., Kaplan, A., Guilderson, T.P., Fairbanks, T.W., Bloom, A.L., Grootes, P.M., Nadeau, M.-J., 2005. Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired ^{230}Th/^{234}U/^{238}U and ^{14}C dates on pristine corals. Quaternary Science Reviews 24, 1781–1796.

Grönvold, K., Óskarsson, N., Johnsen, S.J., Clausen, H.B., Hammer, C.U., Bond, G., Bard, E., 1995. Ash layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land sediments. Earth and Planetary Science Letters 135, 149–155.

Guillou, H., Singer, B.S., Laj, C., Kissel, C., Scaillet, S., Jicha, B.R., 2004. On the age of the Laschamp geomagnetic excursion. Earth and Planetary Science Letters 227, 331–343.

Hughen, K.A., Southon, J.R., Lehman, S.J., Overpeck, J.T., 2000. Synchronous radiocarbon and climate shifts during the Last Deglaciation. Science 290, 1951–1954.

Johnsen, S.J., Dahl-Jensen, D., Gundestrup, N., Steffensen, J.P., Clausen, H.B., Miller, H., Masson-Delmotte, V., Sveinbjörnsdottir, A.E., White, J., 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. Journal of Quaternary Science 16, 299–307.

Meese, D.A., Gow, A.J., Alley, R.B., Zielinski, G.A., Grootes, P.M., Ram, M., Taylor, K.C., Mayewski, P.A., Bolzan, J.F., 1997. The Greenland Ice Sheet Project 2 depth-age scale: methods and results. Journal of Geophysical Research 102, 26411–26423.

Mortensen, A.K., Bigler, M., Grönvold, K., Steffensen, J.P., Johnsen, S.J., 2005. Volcanic ash layers from the Last Glacial Termination in the NGRIP ice core. Journal of Quaternary Science 20, 209–219.

Muscheler, R., Beer, J., Wagner, G., Laj, C., Kissel, C., Raisbeck, G.M., Yiou, F., Kubik, P.W., 2004. Changes in the carbon cycle during the last deglaciation as indicated by the comparison of ^{10}Be and ^{14}C records. Earth and Planetary Science Letters 219, 325–340.

North Greenland Ice-Core Project (NorthGRIP) Members, 2004. High resolution climate record of the Northern Hemisphere reaching into the last Glacial Interglacial Period. Nature 431, 147–151.

Rahmstorf, S., 2003. Timing of abrupt climate change: a precise clock. Geophysical Research Letters 30, 1510.

Ram, M., Koenig, G., 1997. Continuous dust concentration profile of pre-Holocene ice from the Greenland Ice Sheet Project 2 ice core: dust stadials, interstadials, and the Eemian. Journal of Geophysical Research 102, 26641–26648.

Ram, M., Stolz, M.R., 1999. Possible solar influences on the dust profile of the GISP2 ice core from Central Greenland. Geophysical Research Letters 26, 1043–1046.

Rasmussen, T.L., Wastegård, S., Kuijpers, A., Weering, T.C.E.v., Heinemeier, J., Thomsen, E., 2003. Stratigraphy and distribution of tephra layers in marine sediment cores from the Faeroe Islands, North Atlantic. Marine Geology 199, 263–277.

Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.-L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M.E., Ruth, U., 2006a. A new Greenland ice core chronology for the last glacial termination. Journal of Geophysical Research 111, D06102.

Rasmussen, S.O., Seierstad, I.K., Andersen, K.K., Bigler, M., Dahl-Jensen, D., Johnsen, S.J., 2006b. Synchronization of the NGRIP, GRIP, and GISP2 ice cores across MIS 2 and palaeoclimatic implications. Quarternary Science Reviews, submitted for publication.

Rasmussen, S.O., Vinther, B.M., Clausen, H.B., Andersen, K.K., 2006c. Early Holocene climate oscillations recorded in three Greenland ice cores. Quaternary Science Reviews, Submitted for publication.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Intcal04 terrestrial radiocarbon age calibration, 0–26 cal ka BP. Radiocarbon 46, 1029–1058.

Schulz, M., 2002. On the 1470-year pacing of Dansgaard–Oeschger warm events. Paleoceanography 17, 1014.

Shackleton, N.J., Fairbanks, R.G., Tzu-chien, C., Parrenin, F., 2004. Absolute calibration of the Greenland time scale: implications for Antarctic time scales and for Δ^{14}C. Quaternary Science Reviews 23, 1513–1522.

Southon, J., 2004. A radiocarbon perspective on Greenland ice-core chronologies: can we use ice cores for ^{14}C calibration? Radiocarbon 46, 1239–1259.

Spötl, C., Mangini, A., Richards, D.A., 2006. Chronology and paleoenvironment of Marine Isotope Stage 3 from two high-elevation speleothems, Austrian Alps. Quaternary Science Reviews 25, 1127–1136.

Svensson, A., Nielsen, S.W., Kipfstuhl, S., Johnsen, S.J., Steffensen, J.P., Bigler, M., Ruth, U., Röthlisberger, R., 2005. Visual stratigraphy of the North Greenland Ice Core Project (NorthGRIP) ice core during the last glacial period. Journal of Geophysical Research 110, D02108.

van der Plicht, J., Beck, J.W., Bard, E., Baillie, M.G.L., Blackwell, P.G., Buck, C.E., Friedrich, M., Guilderson, T.P., Hughen, K.A., Kromer, B., McCormac, F.G., Bronk Ramsey, C., Reimer, P.J., Reimer, R.W., Remmele, S., Richards, D.A., Southon, J.R., Stuiver, M., Weyhenmeyer, C.E., 2004. NotCal04—comparison/calibration ^{14}C records 26–50 cal ka BP. Radiocarbon 46, 1225–1238.

Vinther, B.M., Clausen, H.B., Johnsen, S.J., Rasmussen, S.O., Andersen, K.K., Buchardt, S.L., Dahl-Jensen, D., Seierstad, I.K., Siggaard-Andersen, M.-L., Steffensen, J.P., Svensson, A.M., Olsen, J., Heinemeier, J., 2006. A synchronized dating of three Greenland ice

Please cite this article as: Anders Svensson et al., The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records, Quaternary Science Reviews (2006), doi:10.1016/j.quascirev.2006.08.003

cores throughout the Holocene. Journal of Geophysical Research 111, D13102.

Wagner, G., Beer, J., Laj, C., Kissel, C., Masarik, J., Muscheler, R., Synal, H.-A., 2000. Chlorine-36 evidence for the Mono Lake event in the Summit GRIP ice core. Earth and Planetary Science Letters 181, 1–6.

Wang, Y.J., Cheng, H., Edwards, R.L., An, Z.S., Wu, J.Y., Shen, C.-C., Dorale, J.A., 2001. A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China. Science 294, 2345–2348.

Wang, X., Auler, A.S., Edwards, L., Cheng, H., Cristalli, P.S., Smart, P.L., Richards, D.A., Shen, C.-C., 2004. Wet periods in northeastern Brazil over the past 210 ka linked to distant climate anomalies. Nature 432, 740–743.

Wastegård, S., Björck, S., Possnert, G., Wohlfarth, B., 1998. Evidence for the occurrence of Vedde Ash in Sweden: radiocarbon and calendar age estimates. Journal of Quaternary Science 13, 271–274.

Yiou, F., Raisbeck, G.M., Baumgartner, S., Beer, J., Hammer, C., Johnsen, S., Jouzel, J., Kubik, P.W., Lestringuez, J., Stiévenard, M., Suter, M., Yiou, P., 1997. Beryllium 10 in Greenland Ice Core Project ice core at Summit, Greenland. Journal of Geophysical Research 102, 26783–26794.

Please cite this article as: Anders Svensson et al., The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records, Quaternary Science Reviews (2006), doi:10.1016/j.quascirev.2006.08.003