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A 60 000 year Greenland stratigraphic ice core chronology

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Abstract

The Greenland Ice Core Chronology 2005 (GICC05) is a time scale based on annual layer counting of high-resolution records from Greenland ice cores. Whereas the Holocene part of the time scale is based on various records from the DYE-3, the GRIP, and the NorthGRIP ice cores, the glacial part is solely based on NorthGRIP records. Here we present an 18 kyr extension of the time scale such that GICC05 continuously covers the past 60 kyr. The new section of the time scale places the onset of Greenland Interstadial 12 (GI-12) at 46.9±1.0 kyr b2k (before year AD 2000), the North Atlantic Ash Zone 2 layer in GI-15 at 55.4±1.2 kyr b2k, and the onset of GI-17 at 59.4±1.3 kyr b2k. The error estimates are derived from the accumulated number of uncertain annual layers and can be regarded as 1σ uncertainties. In the 40–60 kyr interval the new time scale has a discrepancy with the Meese-Sowers GISP2 time scale of up to 2.4 kyr, whereas GICC05 compares well to the dating of the Hulu Cave record with absolute age differences of less than 800 years throughout the 60 kyr period. The new time scale is generally in close agreement with other independently dated records and reference horizons, such as the Laschamp geomagnetic excursion and the Kleegruben speleothem record from the Austrian Alps, suggesting high accuracy of both event durations and absolute age estimates.

1 Introduction

The deep ice cores retrieved in Antarctica and Greenland are becoming increasingly important for the understanding of past climate. The ice cores obtained in Antarctica have provided paleoclimatic records that cover more than 800 kyr of climate history (Jouzel et al., 2007) whereas the Greenland ice cores roughly cover the last glacial cycle, (North Greenland Ice Core Project members, 2004). In order to interpret the climatic signal provided by the ice cores and to enable comparison with other paleoclimatic records accurate time scales are crucial. Because of their high accumulation rates, the Greenland ice cores are well suited for obtaining a chronology based on annual layer counting of the last glacial cycle. In addition, the Greenland ice cores very strongly reflect the abrupt climatic shifts of the last glacial period, the Dansgaard-Oeschger events, and they contain many reference horizons that enable comparison to other paleo-archives.

The most widely applied Greenland ice core time scales are the Meese-Sowers GISP2 stratigraphic time scale (Meese et al., 1997) and the modeled "ss09sea" time scale that has been applied to the GRIP and NorthGRIP ice cores (Johnsen et al., 2001). Those time scales agree within 750 years back to 40 kyr b2k (before AD 2000), but beyond this point the disagreement becomes several thousands of years. So far, there has thus been no consensus for the Greenland ice core time scales in the glacial period (Southon, 2004).

The NorthGRIP ice core covers the past 123 kyr and provides the longest continuous Greenland paleo-climatic record, (North Greenland Ice Core Project members, 2004). This period includes the Holocene, the last glacial period and the termination of the previous interglacial period – the Eemian. The NorthGRIP accumulation history together with basal melting occurring at the drill site cause the annual layers in the glacial ice to be thicker than in all other Greenland ice cores. Flow models thus predict that the NorthGRIP annual layers are of the order of 1 cm at around 100 kyr b2k and the core, therefore, provides an outstanding opportunity to establish an absolute time scale for the entire last glacial cycle.

The Greenland Ice Core Chronology 2005 (GICC05) is a composite stratigraphic time scale based on multi-parameter counting of annual layers in three Greenland ice cores. The 0–7.9 kyr section of the time scale is based on counting of annual layers in $\delta^{18}O$ and δD from the DYE-3, GRIP and NorthGRIP ice cores (Vinther et al., 2006). The 7.9–14.8 kyr interval is established from Electrical Conductivity Measurements (ECM) and Continuous Flow Analysis records (CFA) of the GRIP and NorthGRIP ice cores (Rasmussen et al., 2006), whereas the 14.8–41.8 kyr section is based on counting of annual layers in NorthGRIP ECM, CFA and visual stratigraphy data (Andersen et al., 2006; Svensson et al., 2006). GICC05 provides an uncertainty estimate based on the accumulated number of uncertain annual layers.

The GICC05 time scale was recently transferred to the GRIP and GISP2 ice cores which are tightly synchronized to the NorthGRIP ice core by reference horizons (Rasmussen et al., in press). GICC05 is also transferred to the Greenland Renland ice core and to the Canadian Aggasiz ice cores (Vinther et al., 2007[1]). Furthermore, GICC05 has been applied for tuning of the Antarctic EDC3 and EDML1 ice core age models (Parrenin et al., 2007; Ruth et al., 2007) by matching of ^{10}Be profiles in the Holocene, by methane matching in the glacial termination, and by synchronization of ^{10}Be peaks associated with the Laschamp geomagnetic excursion at around 41 kyr (Raisbeck et al., 2007).

Here we present the extension of the GICC05 back to 60 kyr b2k and we discuss comparison issues to other chronologies for the full 60 kyr period.

2 Methods

The annual layer counting of the 41.8–60.0 kyr section of GICC05 is based on the same NorthGRIP data set that was applied to establish the 10.3–41.8 kyr interval of the time scale and which is thoroughly described elsewhere (Rasmussen et al., 2006; Andersen et al., 2006). In summary, the applied continuous data series are the electrolytical melt water conductivity and the concentrations of the water-soluble ions Ca^{2+}, Na^{+}, NH_4^{+}, SO_4^{2-}, and NO_3^{-} (Bigler, 2004; Röthlisberger et al., 2000), the ECM (Dahl-Jensen et al., 2002) and the visual stratigraphy grey-scale profile (Svensson et al., 2005). The data series are almost complete with only short, insignificant gaps around breaks in the ice

[1]Vinther, B. M., Clausen, H. B., Fischer, D. A., Koerner, R. M., Johnsen, S. J., Andersen, K. K., Dahl-Jensen, D., Rasmussen, S. O., Steffensen, J. P., and Svensson, A. M.: Synchronizing Ice Cores from the Renland and Agassiz Ice Caps to the Greenland Ice Core Chronology, in review, J. Geophys. Res., 2007.

core. For the stadials the dating is based mainly on the records with the highest resolution, namely the visual stratigraphy, the ECM and the conductivity records, whereas the other records play a more important role during milder periods where the annual layers are thicker and the high-resolution records may have multiple annual peaks.

The annual layer thicknesses in the 41.8–60.0 kyr section of the NorthGRIP ice core are comparable to those of the 23–41.8 kyr section, and the applied counting technique is the same as that used for the younger parts of the record (Andersen et al., 2006; Rasmussen et al., 2006). Typical counting examples from just before and just after the onset of GI-14, respectively, are shown in Fig. 1 and Fig. 2. As for the younger part of GICC05, the error estimate is based on identification of "uncertain" annual layers that are counted as $1/2 \pm 1/2$ year (Rasmussen et al., 2006). The accumulated error obtained by summing up the uncertain annual layers is called the Maximum Counting Error (MCE) and is regarded as a 2σ error of the time scale (MCE = 2σ) (Andersen et al., 2006).

The entire 41.8–60 kyr interval has been counted independently by two authors (KKA and AS) and the final dating is a compilation of those two preliminary records. The absolute difference between the two preliminary records is within the absolute error of the 41.8–60 section, although locally the difference sometimes exceeds the final counting error. There is potentially an additional uncertainty in the time scale arising from a systematic bias. Such a bias is, however, difficult to quantify and it is, therefore, not included in the uncertainty estimates given (see detailed discussion of error estimate in Rasmussen et al., 2006).

3 Results

Figure 3 shows the NorthGRIP δ^{18}O and annual layer thickness profiles according to the new time scale. To first order there is a clear correspondence between climate and annual layer thickness throughout the 60 kyr period. However, the high frequency variation in the layer thickness profile appears more dampened than in the δ^{18}O profile.

Generally, in the 41.8–60 kyr interval the annual layers are 1–1.5 cm in cold glacial stadials and 1.5–2.5 cm in mild interstadials. The MCE for the 41.8–60 kyr section is 950 years or 5% which is similar to that of the 14.8–41.8 kyr section.

Table 1 gives the GICC05 ages of important climatic events with the onsets of DO events determined visually from the steepest part of the $\delta^{18}O$ profile. Table 2 gives GICC05 and corresponding radiometric ages of important reference horizons. In the following we compare GICC05 to other independent time scales and reference horizons.

4 Comparison to ice core time scales

One of the most frequently applied Greenland ice core chronologies is that of the GISP2 ice core referred to as the Meese-Sowers time scale (Alley et al., 1997; Meese et al., 1997). The glacial part of this time scale is based on annual layer counting of visual stratigraphy, laser-light scattering, and ECM, and it has an estimated error of 2% back to 40 kyr and 5–10% back to 57 kyr. For the past 40 kyr, there is a good long-term accordance between the GICC05 and the GISP2 time scales (Fig. 4). The major discrepancy in this time interval is due to an inconsistent climate ($\delta^{18}O$) – accumulation relation for the GISP2 time scale, which generally causes the interstadials to appear too long and the stadials to appear too short (Svensson et al., 2006). Beyond 40 kyr, however, GICC05 and the GISP2 time scale start to deviate very importantly and reach a maximum difference of 2.4 kyr at around 52 kyr, which then decreases to 1 kyr at 60 kyr. The GISP2 chronology thus contains respectively 20% more and 20% fewer annual layers in those two intervals compared to GICC05. We will not attempt to identify the cause of this discrepancy, but we notice that no other chronology shows a similar behavior in this period.

The modeled NorthGRIP "ss09sea" time scale is based on an empirical $\delta^{18}O$ – accumulation relationship, an ice flow model, and two fixed points at 11.55 and 110 kyr, respectively (Johnsen et al., 2001). The model also takes into account past changes in seawater $\delta^{18}O$ due to changes in global ice volume and the basal melt at NorthGRIP (Andersen et al., 2006). Except for a significant divergence in the 15–18 kyr interval GICC05 and "ss09sea" agree reasonably well throughout the 60 kyr with a maximum age difference of 800 yrs (Fig. 4). This suggests that the general approach of the model holds throughout the 60 kyr, except for 15–18 kyr interval where the otherwise consistent $\delta^{18}O$ – accumulation relationship breaks down (Rasmussen et al., 2007).

The SFCP04 time scale is based on the marine core MD95-2042 that is ^{14}C calibrated back to 40 kyr using Fairbanks et al. (2005) and matched to the Hulu Cave record (see below) at certain fixed points beyond 40 kyr (Shackleton et al., 2004). Further, SFCP04 was transferred to the GRIP core by wiggle-matching of $\delta^{18}O$ profiles. The GRIP SFCP04 time scale disagrees with GICC05 and with several other records at the onset of GI-3 by more than 1 kyr, but the difference vanishes towards 55 kyr, where SFCP04 is calibrated by the Hulu Cave record (Fig. 4). As described in Svensson et al. (2006) the most likely reason for this difference is that the fix point used for SFCP04 at the onset of GI-3 is too old (by about 1 kyr).

5 Comparison to cave records

A growing number of absolutely dated stalagmite/speleothem records from caves around the world are becoming available. Many of those records have climate records resembling those of the ice core records, which enable comparison under the assumption that the climatic shifts recorded at the two sites occurred simultaneously. This assumption is likely to be valid on the time scales considered here.

The Chinese Hulu Cave stalagmite record (Wang et al., 2001) has become widely accepted as a Northern Hemisphere template for the last glacial period. The stalagmite is ^{230}Th dated at a number of depths and the time scale is linearly interpolated between those depths. It is worth noticing that the NorthGRIP and the Hulu Cave records have very different physical characteristics: whereas the 10–60 kyr section of the ice core record represents 900 m of annual layers the corresponding sections in the stalagmites span just a couple of meters. Because of the absolute dating, the Hulu Cave record has high long-term accuracy, while the duration of shorter time intervals may be less accurately determined due to analytical errors and errors introduced by interpolation. For the stratigraphic ice core time scale the situation is just the opposite. Whereas the absolute ages are potentially inaccurate due to the incremental nature of the ice core dating uncertainty, the duration of shorter periods and events is known with high accuracy.

The Hulu Cave and the NorthGRIP $\delta^{18}O$ profiles can be compared in several ways. Here, we match up the onsets of the glacial interstadials as they are the most clearly defined, at least in the ice core record (Fig. 5). The exception is GI-4 which has very different shapes in the two records. The Hulu cave record has, however, an absolute Th age close to the top of GI-4 which we apply as reference horizon because it can be well correlated to the ice core record. In most other cave records, the shape of GI-4 is narrower than in the Hulu Cave record, as for example the Brazilian Botuverá cave record that places the onset of GI-4 around 29.5 kyr (Wang et al., 2006).

It is encouraging to observe the rather good overall age scale agreement between the Hulu Cave and the NorthGRIP records despite their different nature (Figs. 4 and 5). The largest age difference of 800 years appears at the onset of GI-12, but otherwise the two time scales agree within 500 yrs throughout the 60 kyr period. Such a good agreement would be unlikely if one of the records had a significant dating error. Because of the relatively coarse resolution of the Hulu Cave time scale, we will not attempt to explain the deviation of individual points at this stage. A new high-resolution $\delta^{18}O$ profile and a new high-precision dating of the Hulu Cave record are under way, which will allow for a more detailed comparison.

A recent speleothem record from the Austrian Kleegruben Cave provides a high-resolution record of the 50–57 kyr period covering GI-13 to GI-16 (Spötl et al., 2006). For the events GI-14 and GI-15 that are very well resolved in the speleothem record there is a very good match to GICC05 of less than 300 yrs difference (Fig. 4 and Fig. 6). Towards the ends of the speleothem the age model is less accurate and for the events

GI-13 and GI-16 the comparison to the ice core is less obvious.

The stadials preceding GI-1, 8, 12, and 17, which are concurrent with the Heinrich events H1, H4, H5, and H6, are constrained by absolutely dated Brazilian speleothems (Wang et al., 2004) that support the long-term GICC05 dating (Fig. 5). The onset of GI-17 is constrained by the Villars Cave in France (Genty et al., 2003) and by new Chinese speleothem records from Shanbao Cave (Xia et al., 2007) and Xinya Cave (Li et al., 2007). All those records support both the Hulu Cave profile and GICC05 in this time interval.

The Socotra Island stalagmite record M1-2 from Moomi Cave (Burns et al., 2003; Burns et al., 2004) appears more difficult to fit within the pattern (Fig. 6). Although the M1–2 age of the onset of GI-12 agrees with GICC05 within 350 yrs, the onsets of adjacent interstadials deviate more than 1 kyr from GICC05 and several of the other cave records. This is difficult to combine with the well-constrained event durations of the ice core chronology.

6 Cosmogenic nuclide records

Ice core time scales can be compared to tree ring chronologies through comparison of ice core ^{10}Be and tree ring ^{14}C records. Both ^{10}Be and ^{14}C are cosmogenic nuclides that share a common signal which allows for detailed comparison (Muscheler et al., 2000; Finkel and Nishiizumi, 1997). A recent such comparison suggests that GICC05 is 65 years older than the tree ring chronology at the Younger Dryas – Holocene transition and that there is a major inconsistency between GICC05 and the IntCal04 calibration curve at the onset of the Younger Dryas (Muscheler et al., 2007[2]).

Changes in the geomagnetic field are expressed in the ^{10}Be and ^{36}Cl records of ice cores. Within the 60 kyr time frame there are two major geomagnetic events, namely

[2]Muscheler, R., Kromer, B., Björck, S., Svensson, A., Friedrich, M., Kaiser, K. F., and Southon, J.: A common time scale for ice cores and trees with implications for 14C dating, in review, Nature Geoscience, 2007.

the Mono Lake and the Laschamp events (Table 2, Fig. 7). The most prominent of those is the Laschamp event that is located around GI-10. This event provides an important link between Greenland and Antarctic ice cores that can be synchronized very accurately through comparison of ^{10}Be records (Raisbeck et al., 2007). GICC05 agrees within error estimates with independent radiometric ages of the Laschamp event (Guillou et al., 2004; Ton-That et al., 2001; Svensson et al., 2006). The Mono Lake event that is situated between GI-6 and GI-7 is most strongly expressed in the Greenland ^{36}Cl record (Wagner et al., 2000). This event has been dated in the Pyramid Lake Basin of Nevada to 28 620±300 ^{14}C yr BP (Benson et al., 2003) which compares well to GICC05 when calibrated by the suggested calibration curve of Fairbanks et al. (2005).

7 Tephra horizons

Tephra layers provide a robust method of linking different paleo-records. The number of tephra layers identified in the Greenland ice cores is rapidly increasing (Zielinski et al., 1997; Mortensen et al., 2005), but not all of the ice core horizons have been found in marine or terrestrial records and vice versa. In the 10–60 kyr period there are five tephra layers that provide important tight links to marine and terrestrial records in the North Atlantic region (Table 2). Of those the Saksunarvatn tephra, the Vedde tephra, and the Fugloyarbanki tephra layers have been discussed elsewhere (Svensson et al., 2006; Rasmussen et al., 2007; Davies et al., 2007[3]). A newly identified tephra layer in the ice cores, the so-called Faroe Marine Ash Zone III (Wastegård et al., 2006) (also referred to as the “33 kyr ^{14}C” layer), is situated at 2066.95 m depth in the NorthGRIP ice core. Although the age estimate for this tephra is based on interpolation of AMS radiocarbon dates in marine cores in the Faroes region (Rasmussen et al., 2003), this

[3]Davies, S. M., Wastergård, S., Rasmussen, T. L., Johnsen, S. J., Steffensen, J. P., Andersen, K. K., and 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, Journal of Quaternary Science, submitted, 2007.

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estimate falls well onto a suggested ^{14}C calibration curve (Fairbanks et al., 2005) when compared to GICC05 (Fig. 7). It should be noted that there is an important scatter among the various datasets underlying the suggested ^{14}C calibration curves around this time interval (van der Plicht et al., 2004). One of the most widespread tephra layers in the North Atlantic region is the North Atlantic Ash Zone II or "Z2" layer that appears right at the decline of GI-15 and that has an age of 55 380±1184 kyr b2k according to GICC05. This tephra has been assigned a wide range of ages in the literature (Austin et al., 2004). A recent Ar-Ar age of 54.5±1.0 kyr BP (Southon, 2004) agrees very well with GICC05 (Fig. 7).

8 Conclusions

A new Greenland stratigraphic ice core chronology (GICC05) has been extended to 60 kyr b2k. The maximum counting error of the time scale is on average 1% in the Holocene and 5% in the Glacial leading to an absolute error of about 1.3 kyr 1σ at 60 kyr b2k. The new time scale agrees within 800 yrs throughout the 60 kyr period with most U-Th dated cave records, such as the Hulu Cave record and the Kleegruben Cave record, and with distinct Ar-Ar dated reference horizons such as the Laschamp event and the NAAZ II tephra layer. This excludes the possibility of a significant hiatus in the Greenland ice cores and it supports that GICC05 has no significant long-term bias. In order to keep independency we do, however, maintain the conservative error estimate until new ice core evidence allows for a new estimate.

The strongest discrepancies with GICC05 are for the Meese-Sowers GISP2 time scale that deviates up to 2.4 kyr from GICC05 in the 40–60 kyr interval and for the GRIP SFCP04 time scale that deviates more than 1 kyr from GICC05 at around 28 kyr. Also the M1-2 Socotra Cave record appears to have ages inconsistent with GICC05. Otherwise, we notice that most independent chronologies and absolutely dated reference horizons in the 0–60 kyr period now seem to agree within hundreds rater than thousands of years as was the case until recently. The remaining discrepancies are likely to be reduced as more high-resolution records become available.

The use of ice core cosmogenic isotope records – in particular ^{10}Be – has proven very efficient as a tool for synchronization and comparison of paleo-records. Recently, the Greenland ^{10}Be records have allowed for a detailed comparison to tree ring chronologies and for a synchronization of the Laschamp event in Greenland and Antarctic ice cores. The method could potentially be applied throughout the glacial period at very high resolution, provided there are more high-resolution ice core ^{10}Be and ^{36}Cl profiles available.

For the future, a lowering of the error estimate of the Greenland ice core chronology can be expected when new high-resolution records become available from the NEEM ice core drilling that will soon be initiated. Although the annual layers in the Greenland ice cores do get below critical 1 cm thickness beyond 60 kyr, the annual layers are still countable both in Greenland and in high-accumulation Antarctic ice cores at least back to 80 kyr provided the records have sufficiently high resolution.

The GICC05 time scale is available at www.iceandclimate.dk and at World Data Centre for Paleoclimatology.

Supplemental Material:
http://www.clim-past-discuss.net/3/1235/2007/cpd-3-1235-2007-supplement.zip

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Table 1. GICC05 ages and NorthGRIP depths for climatic events. The locations of the Glacial Interstadials (GI) are indicated in Fig. 3. References: (1) Rasmussen et al. (2006), (2) Andersen et al. (2006).

Climate event	Age ± 1σ (yr b2k)	NorthGRIP depth (m)	Reference
YD/PB transition	11 703±50	1492.45	(1)
Onset GI-1	14 692±93	1604.64	(1)
Onset GI-2	23 340±298	1793.20	(2)
Onset GI-3	27 780±416	1869.12	(2)
Onset GI-4	28 900±449	1891.57	(2)
Onset GI-5	32 500±566	1951.66	(2)
Onset GI-6	33 740±606	1974.56	(2)
Onset GI-7	35 480±661	2009.45	(2)
Onset GI-8	38 220±725	2070.03	(2)
Onset GI-9	40 160±790	2099.62	(2)
Onset GI-10	41 460±817	2124.03	(2)
Onset GI-11	43 340±868	2157.49	This work
Onset GI-12	46 860±956	2222.30	This work
Onset GI-13	49 280±1,015	2256.90	This work
Onset GI-14	54 220±1,150	2345.52	This work
Onset GI-15	55 800±1,196	2366.32	This work
Onset GI-16	58 280±1,256	2402.55	This work
Onset GI-17	59 440±1,287	2420.44	This work

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Table 2. GICC05 ages, NorthGRIP depths, and radiometric ages for volcanic and geomagnetic reference layers. ^{14}C ages are uncalibrated. References: (1) Rasmussen et al. (2006), (2) Svensson et al. (2006), (3) See references in Rasmussen et al. (2007), (4) Davies et al. (2007)[3]; Wastegård et al. (2006) (5) Benson et al. (2003), (6) Wastegård et al. (2006); Rasmussen et al. (2003), (7) Guillou et al. (2004), and (8) Southon (2004).

Reference horizon	GICC05 age $\pm 1\sigma$(yr b2k)	NorthGRIP depth (m)	Radiometric age $\pm 1\sigma$ (yr BP)	GICC05 reference	Radiometric method and reference
Saksunarvatn tephra	10 347±45	1409.83	9000±100	(1)	C-14 (3)
NAAZ I / Vedde tephra	12 171±57	1506.14	10 330±65	(1)	C-14 (3)
FMAZ II / Fugloyarbanki tephra	26 740±390	1848.00	23 100±250	(2)	C-14 (4)
Mono Lake event	34 250±626	1982.70	28 620±300	This work	C-14 (5)
FMAZ III / 33 kyr ^{14}C tephra	38 122±723	2066.95	33 000±1000	This work	C-14 (6)
Laschamp event	41 250±814	2118.66	40 400±1000	(2)	Ar-Ar (7)
NAAZ II / Z2 tephra	55 380±1 184	2359.45	54 500±1000	This work	Ar-Ar (8)

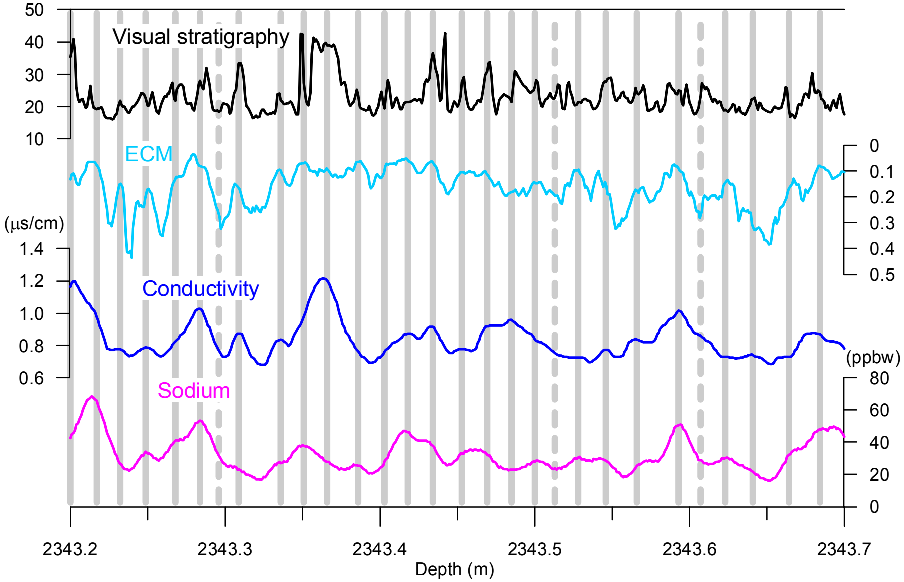

Fig. 1. Example of annual layer counting within GI-14. The records are visual stratigraphy grey scale, ECM, conductivity, and Na^+ concentration. (Uncertain) Annual layers are indicated by (dashed) grey vertical bars. Units of the grey scale and the ECM profiles are arbitrary but comparable to those in Fig. 2.

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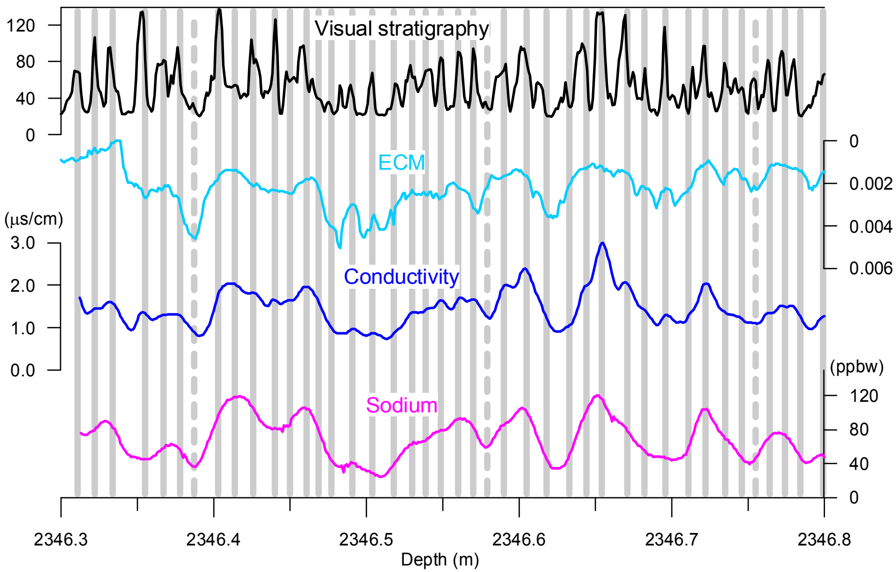

Fig. 2. Example of annual layer counting within the stadial preceding GI-14. Legend as for Fig. 1.

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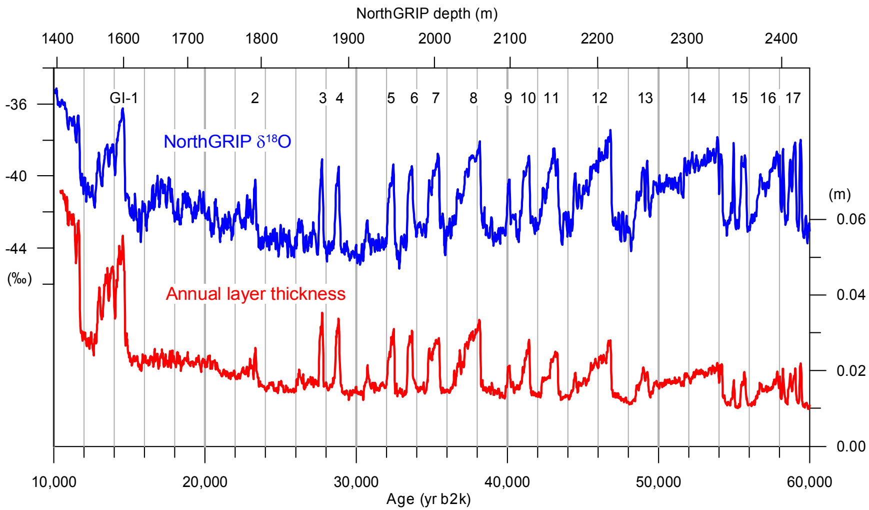

Fig. 3. The NorthGRIP $\delta^{18}O$ profile and the annual layer thickness according to GICC05. The Greenland Interstadials (GI) are indicated.

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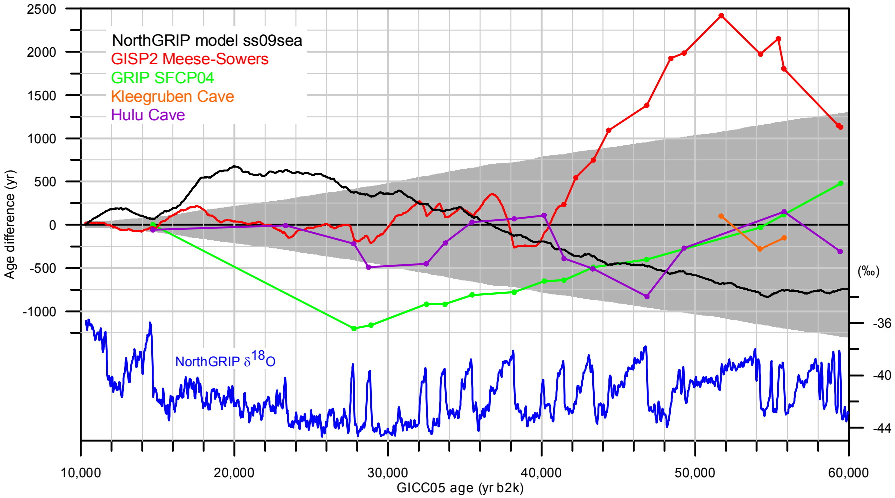

Fig. 4. Comparison between GICC05 and independently dated records: the NorthGRIP model time scale "ss09sea". (North Greenland Ice Core Project members, 2004), the GISP2 time scale (Meese et al., 1997), the GRIP SFCP04 time scale (Shackleton et al., 2004), the Kleegruben Cave record (Spötl et al., 2006), and the Hulu Cave record (Wang et al., 2001). A positive value means that the record is younger than GICC05. The grey shaded area represents the GICC05 counting uncertainty (1σ). The GICC05 and GISP2 records are linked via volcanic reference horizons and other match points back to 32.5 kyr b2k (Rasmussen et al., 2006; Rasmussen et al., 2007) and by matching of the rapid shifts in δ^{18}O in the remaining part. The Hulu and Kleegruben Caves are matched as indicated in Figs. 5 and 6.

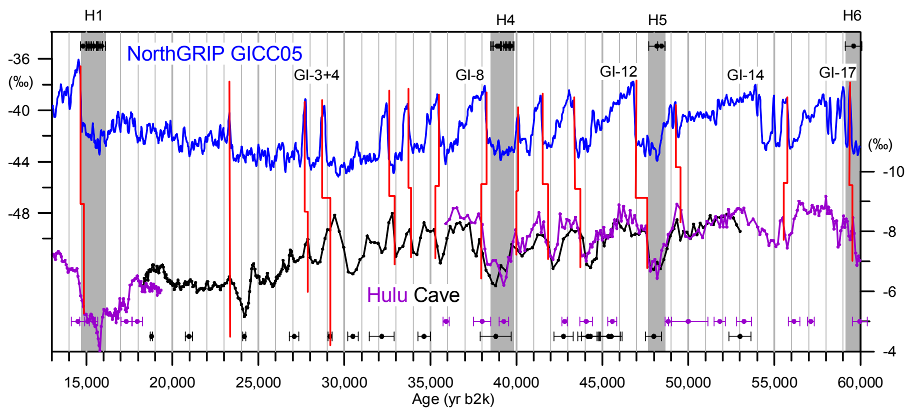

Fig. 5. The NorthGRIP and the Hulu Cave δ^{18}O records on their respective time scales. The red lines indicate the points of comparison applied in Fig. 4. The absolutely dated control points for the Hulu Cave are shown in the lower part of the Figure (Wang et al., 2001). The position of Heinrich events H1, H4, H5, and H6 are indicated as grey vertical bars according to the dating of Brazilian speleothems shown on top of the figure (Wang et al., 2004).

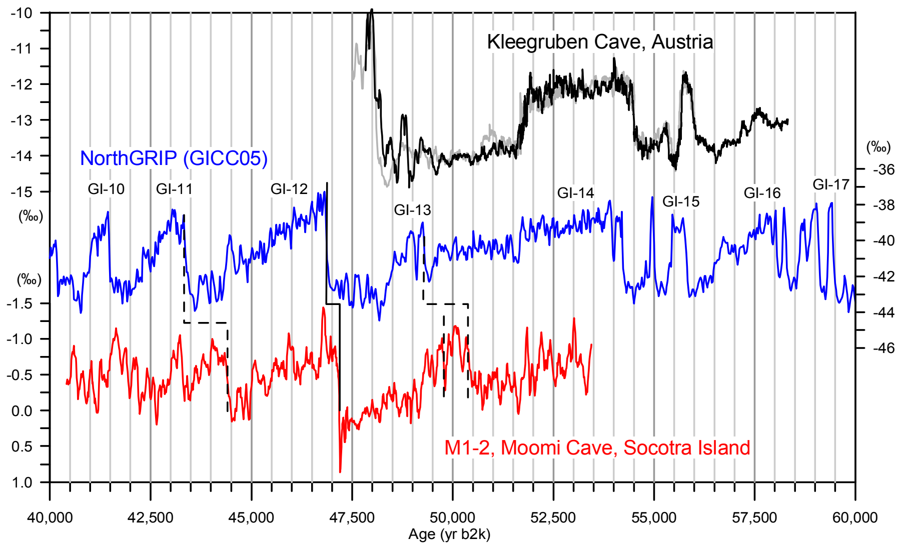

Fig. 6. NorthGRIP $\delta^{18}O$ compared to the Austrian Kleegruben Cave (Spötl et al., 2006) and the Socotra M1-2 Moomi Cave (Burns et al., 2003; Burns et al., 2004) $\delta^{18}O$ records on their respective time scales. Black lines indicate a possible matching of NorthGRIP and M1-2.

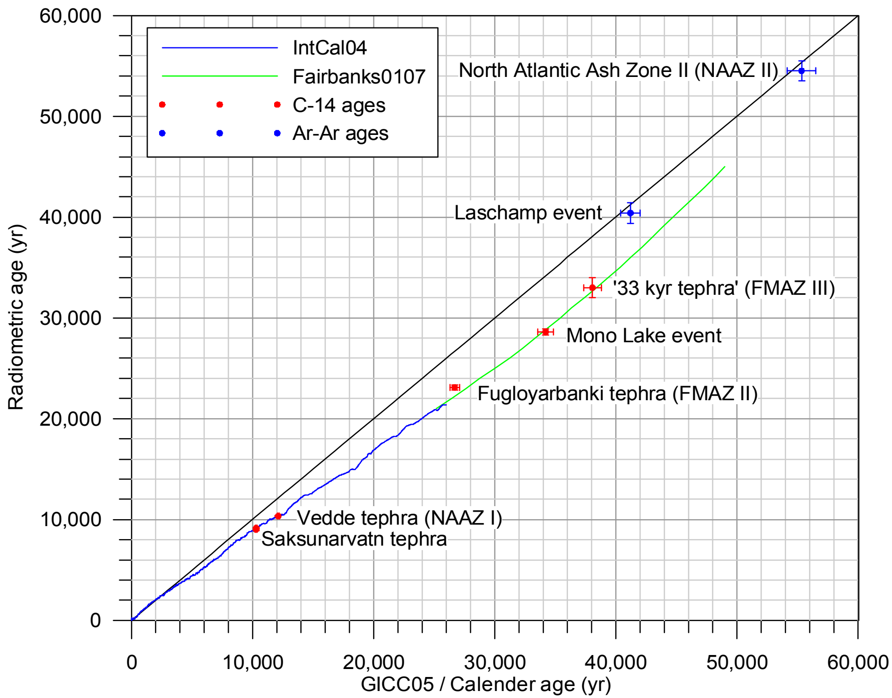

Fig. 7. Comparison between GICC05 and independent ^{14}C and Ar-Ar ages of volcanic and geomagnetic reference horizons identified in the NorthGRIP ice core. The ^{14}C calibrations of IntCal04 (Reimer et al., 2004) and Fairbanks0107 (Fairbanks et al., 2005) are shown. Error bars are 1σ. In case of agreement between radiometric ages, ^{14}C calibration curves, and ice core ages, the ^{14}C data points should fall on the ^{14}C calibration curves, whereas Ar-Ar data points should fall on the 1:1 line. See Table 2 for references.

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