Quaternary Science Reviews 23 (2004) 1513–1522

Rapid Communication

# Absolute calibration of the Greenland time scale: implications for Antarctic time scales and for $\Delta^{14}C$

N.J. Shackleton[a,*], R.G. Fairbanks[b], Tzu-chien Chiu[b], F. Parrenin[c]

[a] *Godwin Laboratory, Department of Earth Sciences, Godwin Institute, University of Cambridge, New Museums Site, Pembroke Street, Cambridge, CB2 3SA, UK*

[b] *Lamont-Doherty Earth Observatory, Columbia University, 61 Route 9W, Palisades, NY 10964-8000, USA*

[c] *LEGOS, 18 Avenue Edouard Belin, 31401 Toulouse, Cedex 9, France*

Received 2 February 2004; accepted 11 March 2004

**Abstract**

We propose a new age scale for the two ice cores (GRIP and GISP2) that were drilled at Greenland summit, based on accelerator mass spectrometry $^{14}C$ dating of foraminifera in core MD95-2042 (Paleoceanography 15 (2000) 565), calibrated by means of recently obtained paired $^{14}C$ and $^{230}Th$ measurements on pristine corals (Marine radiocarbon calibration curve spanning 10,500 to 50,000 years BP (thousand years before present) Based on paired $^{230}Th/^{234}U/^{238}U$ and $^{14}C$ dates on Pristine Corals Geological Society of America Bulletin, 2003, submitted for publication). The record of core MD95-2042 can be correlated very precisely to the Greenland ice cores. Between 30 and 40 ka BP our scale is 1.4 ka older than the GRIP SS09sea time scale (Journal of Quaternary Science 16 (2001) 299). At the older end of Marine Isotope Stage 3 we use published $^{230}Th$ dates from speleothems to calibrate the record. Using this scale we show a $\Delta^{14}C$ record that is broadly consistent with the modelled record (Earth Planet. Sci. Lett. 200 (2002) 177) and with the data of Hughen et al. (Science 303 (2004) 202), but not consistent with the high values obtained by Beck et al. (Science 292 (2001) 2453) or by Voelker et al. (Radiocarbon 40 (1998) 517). We show how a set of age scales for the Antarctic ice cores can be derived that are both fully consistent with the Greenland scale, and glaciologically reasonable.



## 1. Introduction

The two deep ice cores that were recovered at the summit area in Greenland (GRIP and GISP2; Hammer et al., 1997) have been analysed in great detail for the isotopic composition of the ice. The isotopic records have become very well known due to the history of large amplitude ($\sim 10^{\circ}C$) and rapid (within decades) fluctuations in air temperature that has been reconstructed from them. These climatic fluctuations certainly affected the North Atlantic region and appear to have affected a large proportion of the Earth (Voelker et al., 2002). It is difficult to discuss any palaeoclimate record of the last 60 ka (1 ka = 1000 years) without relating it to the Greenland records.

The two summit ice cores have very similar records (except in the ice that was recovered very close to the bedrock) but data from the two cores are usually presented on different age scales because different groups of workers have developed time scales using different approaches. Nevertheless, it is relatively easy to transform records from one age scale to another because there are so many rapid changes in isotope values that can be used as tie points to correlate the records. The GISP2 age scale was developed by annual layer counting (Meese et al., 1997). Uncertainties are estimated at about ±2% to 40 ka beyond which point counting uncertainties become much more significant and the error is estimated at ±5–10% (Meese et al., 1997). The GRIP age scale of Johnsen et al. (1995) is based on layer counting to about 15 ka BP and on glaciological modelling for the earlier part. Back to 15 ka the two age scales are very close, but by 30 ka they already differ by about 3 ka. A more recently published age scale for the GRIP ice core (SS09sea; Johnsen et al., 2001) is closer to the GISP2 scale at 30 ka but diverges from it by about 3 ka at 50 ka. While these divergences are within the uncertainties in the two scales, they are large in

*Corresponding author. Tel.: +44-1223-334876; fax: +44-1223-334871.

*E-mail address:* njs5@cam.ac.uk (N.J. Shackleton).

0277-3791/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quascirev.2004.03.006

comparison with the age uncertainties for good quality radiometric ages in this time bracket; for example $^{230}$Th/$^{234}$U ages may have a precision better than ±100 years, although it is difficult to assess the true absolute age uncertainty in a given measurement. A second and more pressing problem is that the radiocarbon age scale is not adequately calibrated with respect to absolute age. The majority of marine and terrestrial palaeoenvironmental records can only be dated accurately by $^{14}$C, yet $^{14}$C ages differ from calendar ages by several millennia in this period. The calibration of the radiocarbon age scale with respect to the GISP2 age scale has very recently been elegantly addressed by Hughen et al. (2004) for the last 50 ka, using a series of $^{14}$C measurements on an ODP core from Cariaco Basin that has been correlated to GISP2. However, the value of this calibration is restricted by the limitations of the GISP2 age scale itself. Here we obtain accelerator mass spectrometry (AMS) $^{14}$C ages for events that can be closely correlated to the Greenland record, in a deep-sea sediment core taken off Portugal. We calibrate these measurements to calendar ages using a recently analysed set of pristine coral samples that have been $^{230}$Th and $^{14}$C dated using splits of identical samples. This provides a reliable absolute age calibration for events at the young end of Marine Isotope Stage 3 (MIS 3) as recorded in Greenland. Close to the base of MIS 3, there are several reliably dated speleothem records that can be confidently correlated to the Greenland records and that provide a reliable age calibration. By comparing the relative position of identified events in ice cores from both Greenland and Antarctica, we demonstrate that at present it is better to obtain ages for intermediate points by interpolating on a glaciological age model for the ice, rather than to insert additional age control points.

## 2. Methods

Piston core MD95-2042 was collected at 37°48′ North, 10°10′ West in 3146 m water depth. Shackleton et al. (2000) showed that the oxygen isotope record in planktonic foraminifera in this core matches the Greenland ice $\delta^{18}$O record with remarkable fidelity. In Fig. 1 the record is shown correlated to the GRIP $\delta^{18}$O record on the SS09sea age scale (Johnsen et al., 2001). Tie points are placed at stadial–interstadial and interstadial–stadial transitions. The marine record was sampled at 5 cm intervals and at the majority of warming transitions the greater part of the warming occurs between adjacent samples so that at these correlation points the calibration uncertainty is about ±130 years. Inspection of the records suggests that the correlation uncertainty might be twice this value at the cooling transitions. We chose to take samples for AMS $^{14}$C dating at the base of each interstadial, close to the correlation point, so that the uncertainty in the comparison to the GRIP SS09sea age of each sample is not much worse than ±130 years. We chose the interstadial side of each transition in order to reduce the likelihood that the surface water might have been subjected to an uncertain reservoir age. The results are given in Table 1. We use a surface reservoir age of 500±100 years. Bard et al. (1987) carried out $^{14}$C dating in a core from the same area and used a value of 400 years. On the other hand, in well-documented museum samples and in archaeological sites on the Portuguese coast Monges Soares (1993) observed reservoir ages in excess of 600 years. It seems unlikely that the coastal upwelling that his work documents would affect our site to the same extent and 500±100 years gives a conservative estimate of the uncertainty.

Fairbanks et al. (2003) document a suite of pristine coral samples from Barbados and from terraces on the island of Araki which yielded precise $^{230}$Th ages and parallel $^{14}$C ages; we use these to convert each $^{14}$C age to a ‘‘calendar’’ age. Initially, each $^{14}$C age was simply converted to a ‘‘calendar’’ age by interpolation between the closest samples in the calibration data set, and these ‘‘calibrated’’ ages are also shown in Table 1. Fig. 1 shows the record for core MD95-2042 using these ages to generate the age scale. The implied sedimentation rate between each pair of points is shown together with the uncertainties that derive only from the $^{14}$C measurements (we report uncertainties as 1–$\sigma$ throughout this paper). We were unable to make use of the calibrated age for the base of Greenland Interstadial (GIS) 7; either the core age or the closest coral age estimate is in error, or atmospheric $^{14}$C concentration changed rapidly between the two control samples (see below). The implied sedimentation rate is anomalously low at around 45 ka. Here the reason is almost certainly that atmospheric $^{14}$C concentration changed rapidly, because it is known that the Laschamp Event was centred on GIS 10 and that $^{14}$C production was anomalously high at that time, so that the $^{14}$C age of samples above this event is anomalously young.

If we ignore the GIS 7 sample, the calibrated $^{14}$C ages of GIS 3, 4, 5, 6 and 8 are about (1.5±0.34 ka) older than the GRIP SS09sea ages. We propose that this part of the SS09sea age scale should be adjusted in the older direction by about this amount. We note that the improvement in glaciological modelling represented by the transition from the age scale of Johnsen et al. (1992) to that of Johnsen et al. (2001) entailed an increased duration for the last glacial maximum (LGM) interval. This same interval is where our data suggest that time is ‘‘missing’’ in these published time scales. This suggests that it is in LGM conditions that the glaciological modelling is most uncertain.

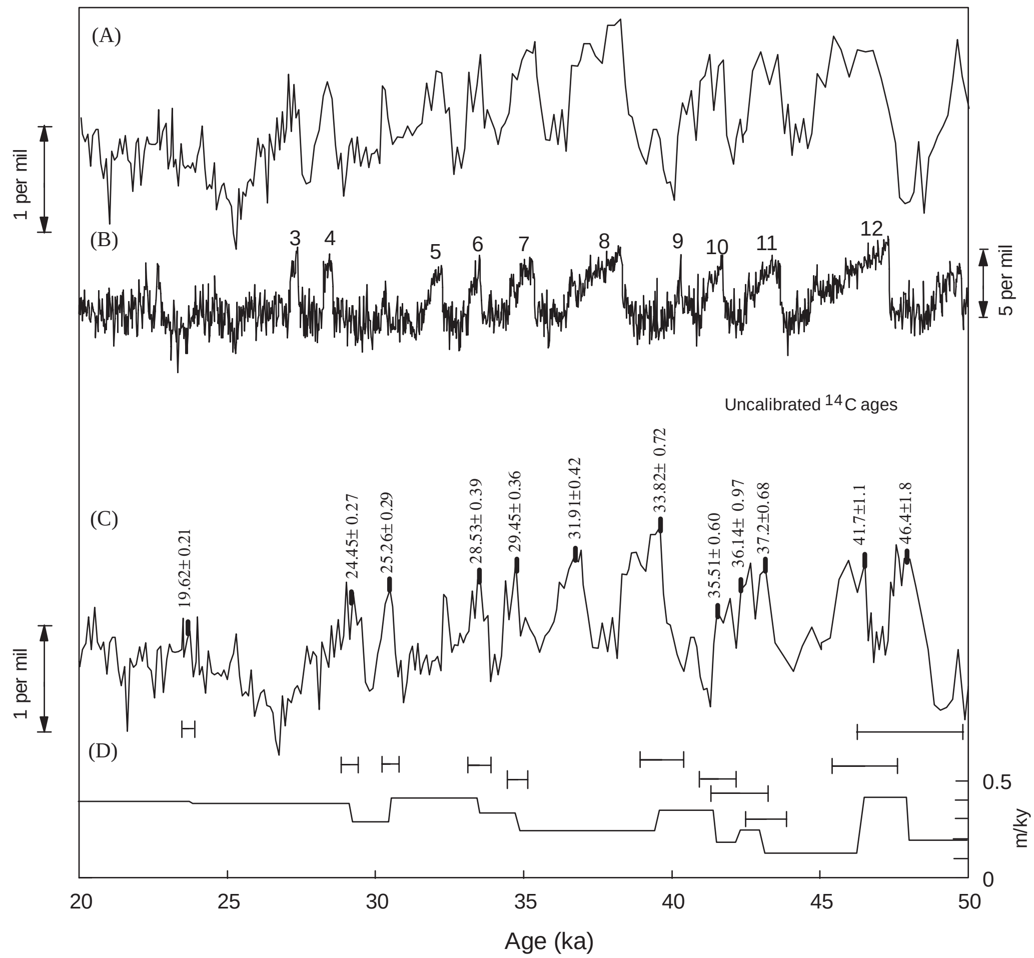


Fig. 1. (A) $\delta^{18}O$ in *Globigerina bulloides*, core MD95-2042, time scale based on a correlation to GRIP on the SS09sea time scale. (B) $\delta^{18}O$ in GRIP ice core, time scale SS09sea of Johnsen et al. (2001). (C) $\delta^{18}O$ in *Globigerina bulloides*, core MD95-2042, time scale using as controls only the $^{14}C$ measurements shown, calibrated as in Table 1. (D) Sediment accumulation rates implied by (C) with above, analytical error (1–$\sigma$) on age controls.

Table 1
AMS $^{14}C$ measurements in core MD95-2042

| GIS no. | Depth (m) | Age SS09sea | $^{14}C$ age[a] | Lab. no. | Calibrated age |
|---|---|---|---|---|---|
| 2 | 8.00 | 22.87 | 19.62±0.21 | GifA100547 | 23.65 |
| 3 | 10.12 | 27.31 | 24.45±0.27 | GifA100548 | 29.14 |
| 4 | 10.48 | 28.42 | 25.26±0.29 | GifA100549 | 30.43 |
| 5 | 11.75 | 32.21 | 28.53±0.39 | GifA100550 | 33.38 |
| 6 | 12.16 | 33.52 | 29.45±0.36 | GifA100551 | 34.72 |
| 7 | 12.67 | 35.18 | 31.91±0.42 | GifA100552 | 38.64 |
| 8 | 13.36 | 38.26 | 33.82±0.72 | KIA14285 | 39.69 |
| 9 | 14.04 | 40.33 | 35.51±0.60 | KIA15625 | 41.43 |
| 9 | 14.16 | 40.79 | 36.14±0.97 | KIA14284 | 42.07 |
| 10 | 14.39 | 41.66 | 37.20±0.68 | GifA100554 | 43.16 |
| 11 | 14.83 | 43.51 | 41.70±1.1 | GifA100555 | 46.47 |
| 12 | 15.48 | 46.77 | 46.40±1.8 | GifA100556 | 48.01 |

[a] Reservoir correction of 500 years applied.

The most accurate approach to the age calibration of the older part of the GRIP record is to use the records from radiometrically dated speleothems. Our assumption is that the more closely the speleothem record resembles the Greenland record, the more precisely the events are synchronized. The most complete record is from Hulu Cave (Wang et al., 2001), where the record can be correlated to Greenland providing plausible age controls at the base of several interstadials. At Vilars (Genty et al., 2003), there is a record that does not resemble the Greenland records so closely, but the base of GIS 17 (base of MIS 3) appears to be reliably dated at about 60 ka. A record has been described from Socotra where the climate sequence closely resembles the GIS 9 to GIS 13 interval (Burns et al., 2003). Finally, Spötl and Mangini (2002) have provided a very detailed and closely dated sequence from a cave in the Austrian Alps that exactly matches the GIS 14 to GIS 16 interval. Apart from the Socotra record, these chronologies are all approximately concordant (re-dating of the Socotra record yields dates in agreement with the other sites used here; personal communications from Augusto Mangini 2003 and from Steve Burns, 2004). We use a date of 59 ka for the base of GIS 17 as a control at the lower end of MIS 3 that is consistent with the available data.

We modified the GRIP SS09sea time scale of Johnsen et al. (2001) by inserting an age of 29.0 for the base of GIS 3, and an age of 59.0 for the base of GIS 17, and interpolating linearly on modelled age between these points. Table 2 gives the ages for the base of each interstadial based on this interpolation. For the convenience of users we give the ages of the same points on the three previously published scales. Above GIS 3 we fixed the base of GIS 1 (at 14.66 ka) at the same age. We assigned an age of 74.5 ka to the base of GIS 20 on the basis of the dating of this event in Hulu Cave (Wang et al., 2001). The GRIP data are shown on this new scale in Fig. 2A.

An independent test of the validity of simply interpolating the Greenland time scale for MIS 3 between two calibration points, is to examine the relative positions of warm events A1–A4 (which are almost exactly the temporal equivalents of the bases of GIS 8, GIS 12, GIS 14 and GIS 17; Blunier and Brook, 2001) in the Antarctic records. We have examined the position of each of these events in Vostok (Petit et al., 1999), Dome Fuji (DF) (Watanabe et al., 2003) and Dome C (DC) (EPICA Community Members, 2004). At these three sites, the time interval of interest is in the upper half of the ice sheet so that the effect of layer thinning is small. However, in order to virtually eliminate this effect, we compared our estimates to a published age on a glaciological scale for each of these events, rather than plotting them against depth. In order to consistently locate the events, we carefully evaluated the relationship between each ice core isotope record and that of the Byrd ice core, having converted the age

Table 2
Ages for GIS bases (mid-point of the isotopic transition)

| GIS no. | This work | GISP2 | GRIP SS09 | GRIPSS09sea |
|---|---|---|---|---|
| 3 | 29.00 | 27.84 | 25.59 | 27.40 |
| 4 | 30.06 | 29.03 | 26.61 | 28.56 |
| 5 | 33.44 | 32.37 | 30.01 | 32.26 |
| 6 | 34.64 | 33.59 | 31.25 | 33.58 |
| 7 | 36.29 | 35.32 | 32.95 | 35.38 |
| 8 | 39.00 | 38.43 | 35.75 | 38.34 |
| 9 | 40.83 | 40.25 | 37.71 | 40.34 |
| 10 | 42.10 | 41.17 | 39.12 | 41.74 |
| 11 | 43.87 | 42.58 | 41.07 | 43.68 |
| 12 | 47.24 | 45.46 | 44.36 | 47.36 |
| 13 | 49.45 | 47.25 | 46.72 | 49.78 |
| 14 | 54.29 | 52.14 | 51.99 | 55.08 |
| 15 | 55.66 | 53.78 | 53.52 | 56.58 |
| 17 | 59.00 | 58.24 | 57.23 | 60.24 |
| 20 | 74.50 | 73.02 | 74.00 | 77.12 |

Greenland interstadial ages are also used to convert the data from the Byrd Ice core (Blunier and Brook, 2001) and the Cariaco Trench (Hughen et al., 2004) to the age scale of this paper.

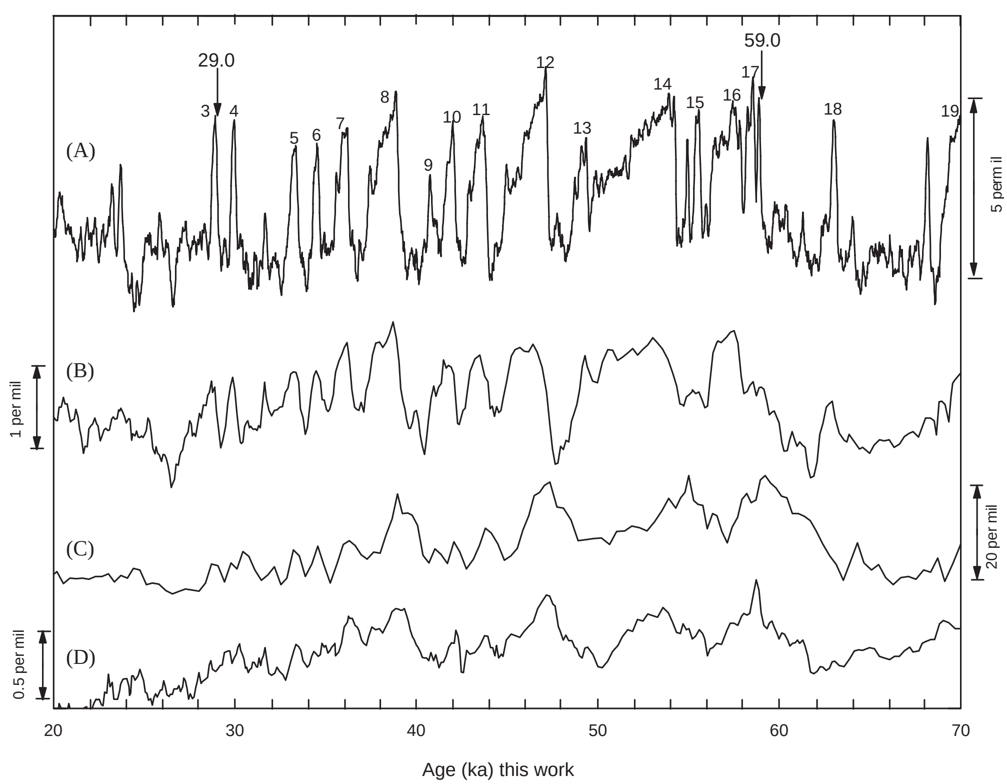


Fig. 2. (A) $\delta^{18}O$ in GRIP ice core (Johnsen et al., 2001), time scale of this paper; arrows show the two age controls used to create this age scale. (B) $\delta^{18}O$ in *Globigerina bulloides* (3-point running mean), core MD95-2042, time scale of this paper by correlation to (A). (C) $\delta^{18}O$ in benthic species (3-point running mean), core MD95-2042 (Shackleton et al., 2000), time scale of this paper. (D) $\delta^{18}O$ in DC ice core (EPICA Community Members, 2004), time scale of this paper.

scale for that core given by Blunier and Brook (2001) to our new Greenland scale. To achieve this, we first transferred their methane record (which was tied to the GISP2 age scale) using the age pairs in Table 2. We made the adjustments by placing controls at the base of each methane peak, since it is established that each methane rise was synchronous with a Greenland warming (Severinghaus et al., 1998). This comment is particularly relevant at the base of GIS 15 where the methane record from Greenland is less detailed and we correlate the well-constrained methane rise in Byrd directly to the base of the GRIP isotopic interstadial. We then made the identical adjustments to the Byrd ice $\delta^{18}O$ data set.

At the base of MIS 3, we estimate an age of 59 ka for A4. There is a significant uncertainty at this point because in Greenland there are three very short interstadial peaks at the base of GIS 17 that are only recorded in very high-resolution records. We assigned an age of 59.0 ka to the base of the first of these interstadial peaks. The methane records are not of sufficiently high resolution to record this detail, either in Greenland or at Byrd. However, the data shown by Blunier and Brook (2001) suggest that the A4 peak does indeed coincide with the very first rise in methane concentration in MIS 3. Fig. 3 shows our age for each event versus the published age for DF, DC and Vostok. The estimates for DF and DC are remarkably linear with respect to those for Greenland, implying that the glaciological models give a linear representation of true age over this interval.

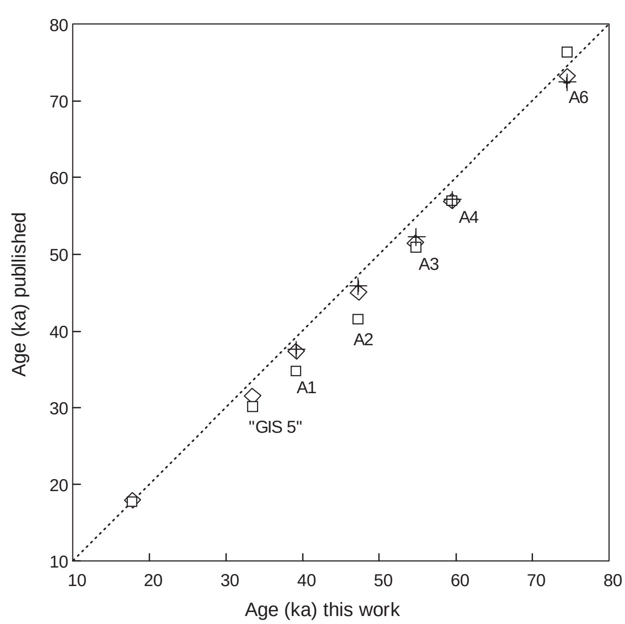


Fig. 3. Relationship between glaciological age estimates of events in central Antarctic ice cores, and estimates in Byrd (Blunier and Brook, 2001), revised to the age scale of this paper. Squares: Vostok (ages from Petit et al., 1999); diamonds: DF (Watanabe et al., 2003); crosses: DC (EPICA Community Members, 2004); dotted: 1:1 line.

In order to evaluate our scale, we estimated the age of events A1–A3 in the Antarctic cores by interpolating over the entire MIS 3 interval. Near the top of MIS 3, not all Antarctic cores can be confidently correlated to Byrd and hence to Greenland on the basis of the ice isotope records but the temporal equivalent of GIS 5 (33.4 ka) can be clearly identified, so we interpolated between this event and A4 (59.0 ka). The interpolated ages of A1 are 38.86 ka (DC) and 39.20 ka (DF) compared with 38.99 ka in Greenland. For A2 we find 47.41 ka (DC) and 47.00 ka (DF) compared with 47.24 ka in Greenland. For A3 the ages of 53.11 ka (DC) and 53.45 ka (DF) are significantly lower than that in Greenland (54.29 ka), which we attribute to difficulties in properly reconciling the Byrd record with the others. On the other hand, the figures for Vostok are markedly different, most likely implying that the GT4 age model for Vostok does not correctly represent variations in the thinning function for ice accumulated during the last glacial period. This observation is obvious if the depths of the events in Vostok versus one of the other Antarctic ice cores are plotted; it is not a conclusion deriving only from the comparison with Greenland.

We considered the option of refining the age scale by using the Antarctic cores in order to obtain independent interpolated ages for events between 29 and 59 ka, but the departures from linearity are so small that the disagreements between interpolated ages given above are well within the uncertainties in the south-to-north correlation via Byrd. Hence, we chose to retain the figures derived from GRIP where the events are more precisely determined than in Antarctica.

In order to place a stalagmite record on an age scale, it is usual to define an age–depth relationship that takes account of the ages together with their uncertainties. In Fig. 4, we take a different approach; we plot the data for the Hulu Cave stalagmites by correlating each transition in the stalagmite record with its presumed equivalent in the GRIP ice core on our new time scale. We then obtain interpolated ages for each dated sample and plot the deviation between measured age and our estimate, for each dated sample. We carried out the same operation for the SPA49 stalagmite (Spötl and Mangini, 2002). Fig. 4 shows that the ages that we derive by this method are in remarkably good agreement with the radiometric age estimates from Hulu and Spa Caves. It is important to note the good agreement at the base of GIS 11 because this is only a few hundred years prior to the onset of the Laschamp event and to the base of the $^{10}Be$ peak in Greenland ice (Yiou et al., 1997). The largest disagreement is at the base of GIS 8 where radiometric ages are 1 ka younger than ours. Dating of smaller size samples in the Hulu stalagmites may enable us to obtain a sufficiently accurate age for this transition to warrant inserting a distortion in the glaciological age

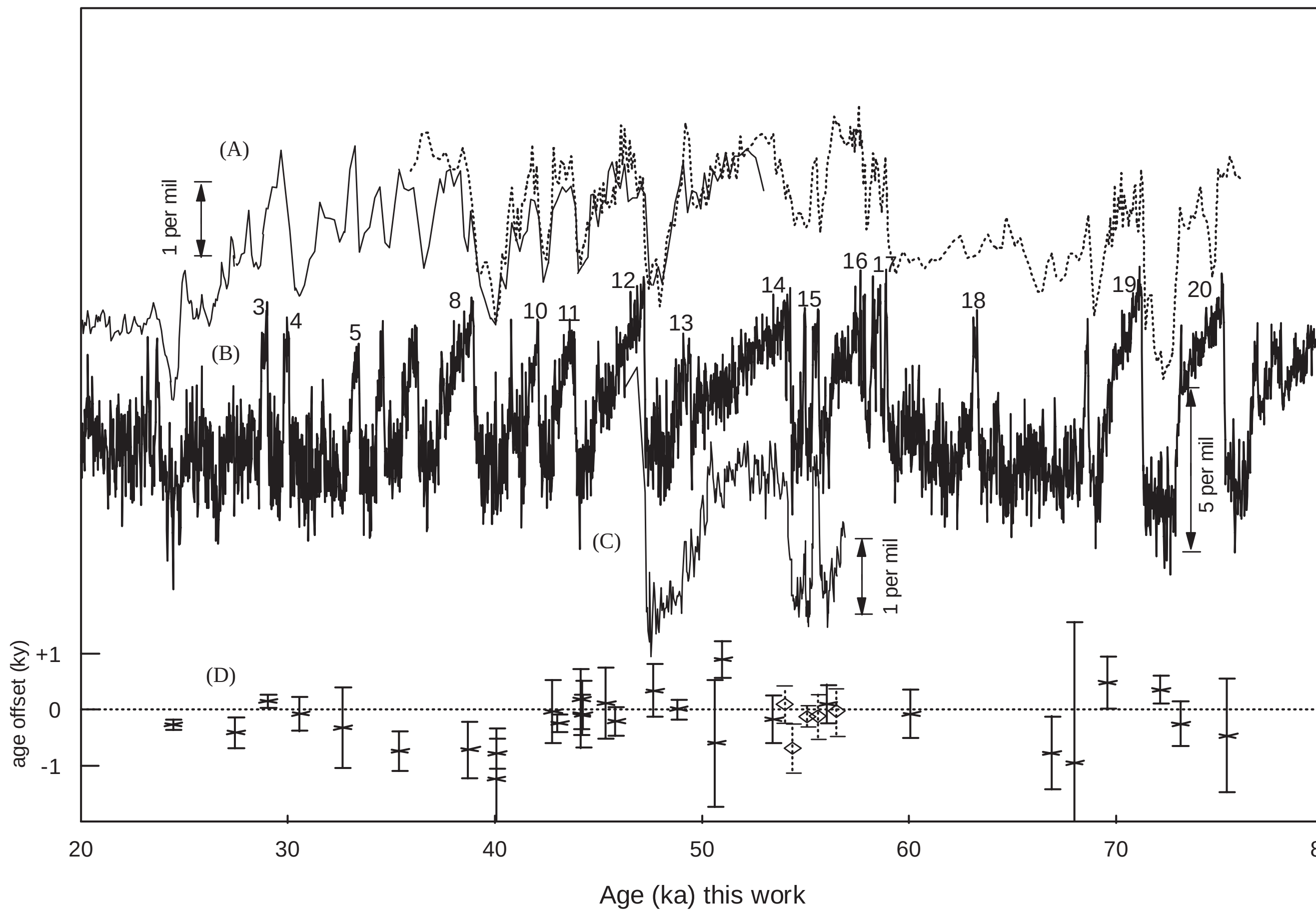


Fig. 4. (A) Oxygen isotope records for the two Hulu Cave stalagmites (solid, MSL; dotted, MSD; Wang et al., 2001) plotted on an age scale derived by correlating isotopic transitions in these data to assumed equivalents in the GRIP data on our time scale. (B): GRIP data on our time scale. (C) Spa Cave stalagmite SPA49 (Spötl and Mangini, 2002) plotted as (A). (D) deviations between each radiometric date, and the age shown on this plot, together with analytical uncertainty (1–$\sigma$). Open symbols: SPA 49, remainder: Hulu Cave.

model, but at present the linearity between GRIP DF and DC argues against this (in fact, the interpolated DF and DC estimates are only 200 years either side of our 38.99 ka GRIP estimate). In the vicinity of GIS 3 and GIS 4, the MSD stalagmite in Hulu Cave depicts a single event with an apparent duration that would encompass both these interstadials; making this interpretation the age estimates (Wang et al., 2001) are consistent with our age scale. Note that the uncertainties plotted in Fig. 4 only reflect the radiometric uncertainty; the divergent age plotted at about 51 ka is at a point almost 3 ka from the nearest calibration and the divergence almost certainly reflects the lack of features that permit correlation to Greenland over that part of the record.

## 3. Discussion

We constructed a modified GRIP age scale GRIP.SFP04 by linearly interpolating SS09sea between base GIS 3 (29.0 ka) and base GIS 17 (59 ka). Fig. 2 shows the GRIP $\delta^{18}O$ data on this new age scale, together with the MD95-2042 oxygen isotope records correlated to it and also the DC record (EPICA Community Members, 2004) on an age scale that uses our estimates for the ages of A1–A5. Fig. 5 shows $\Delta^{14}C$ reconstruction calculated for our MD95-2042 foraminifera using this new age scale. Fig. 5 compares our $\Delta^{14}C$ compared to that derived from the data of Hughen et al. (2004) for ODP Site 1002 in the Cariaco Trench, after converting their data from the GISP2 age scale to our new age scale. We do not reproduce the very high $\Delta^{14}C$ values obtained by Voelker et al. (1998, 2000) or by Beck et al. (2001). Regarding the data presented by Voelker et al. (2000) the problem appears to be that the stratigraphic link to the GISP2 scale is not fully transparent. While the density of samples is not so high as is shown by Voelker et al. (2000) and by Beck et al. (2001), it seems extremely unlikely, in the light of our understanding of the controls on $\Delta^{14}C$ (Laj et al., 2002), that their higher values could be accommodated at intermediate points between our data.

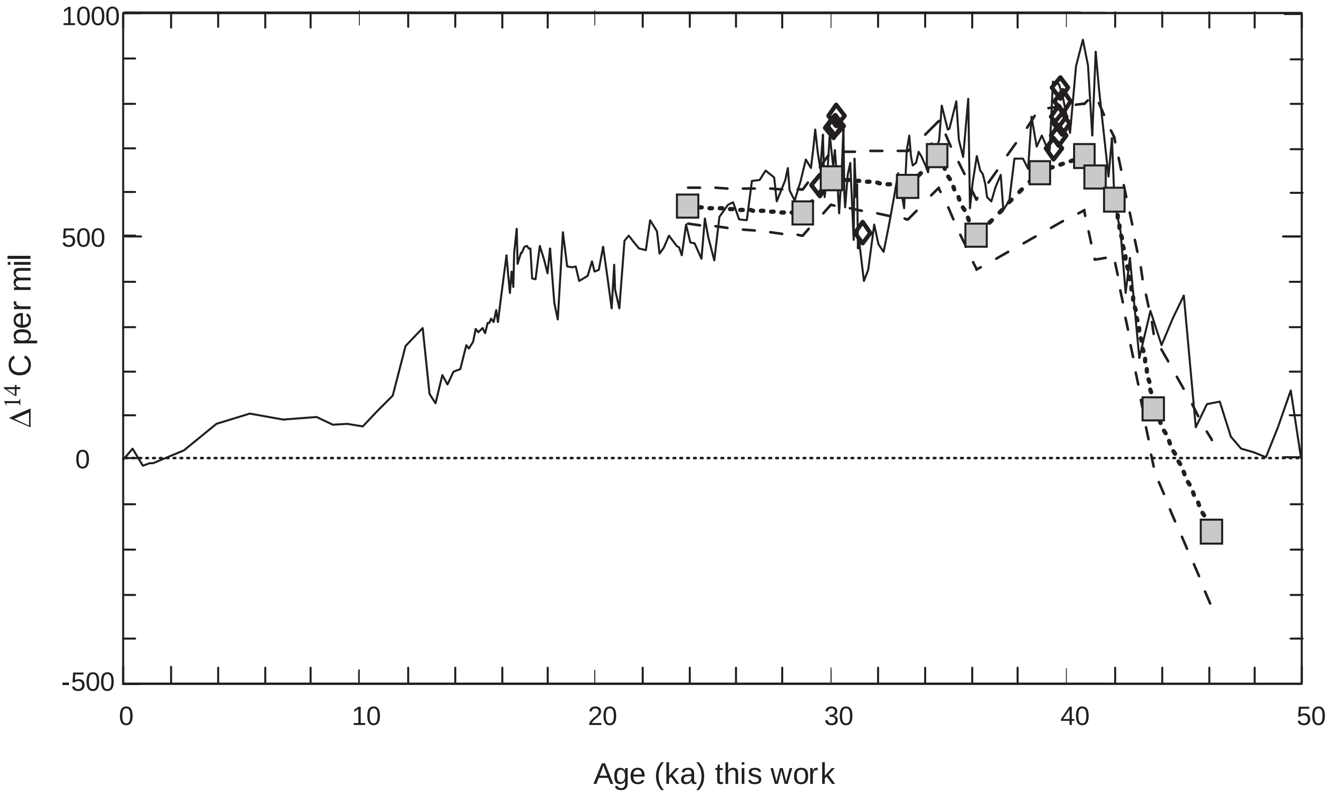


Fig. 5. Line: $\Delta^{14}C$ recalculated for the data of Hughen et al. (2004) after converting to our age scale (for the uncertainties, which are significantly smaller than ours, see Hughen et al., 2004). Filled squares: $\Delta^{14}C$ calculated from $^{14}C$ measurements in core MD95-2042 (Table 1), with uncertainty range (dashed line) taking account only of the $^{14}C$ measurement errors. Open diamonds: $\Delta^{14}C$ calculated for selected (see text) paired $^{14}C$ and $^{230}Th$ measurements on corals.

Also shown in Fig. 5 (grey boxes) are two selected intervals from the Fairbanks et al. (2003) and (Fairbanks, unpublished) data set. First, note that at 32 to 31 ka a rise in $\Delta^{14}C$ is reconstructed in both data sets. Here the Fairbanks et al. (2003) data are from drilling off Barbados and the quality of the material is particularly good. Not only does this tightly constrain the timing of this $\Delta^{14}C$ event by direct dating, but also the agreement in the absolute $\Delta^{14}C$ values would degrade if the Greenland age scale were changed (reconstructed $\Delta^{14}C$ changes by about 120 per mil for each 1000-year change in age). The Fairbanks et al. value for $\Delta^{14}C$ is 744‰, well outside the Hughen et al. estimate on the GISP2 age scale but consistent with their measurements when these are moved older by about 1000 years to our age scale. Second, note that at about 39 ka there are six independent estimates of $\Delta^{14}C$ in the complete Fairbanks et al. data set. Agreement between this combined estimate, and the adjusted Hughen et al. (2004) record again indicates that the uncertainty in our age scale is small.

Fig. 5 also shows $\Delta^{14}C$ estimates for MD95-2042; these appear to be slightly lower than those derived from the Hughen et al. (2004) data set. The difference is due to slightly higher $^{14}C$ ages in MD95-2042 than in ODP1002 at the base of each interstadial; in each case the difference is within the measurement uncertainty but it appears to be systematic. Bard et al. (2004) have also made $^{14}C$ measurements in MD95-2042 but it is hard to discern any systematic difference with respect to either data set. It is possible that the difference, if real, reflects a difference in the approach that is made to the $^{14}C$ background correction in the different AMS facilities.

We show that within the limits of present-day pole-to-pole and marine-to-ice core correlations, a time scale for the Antarctic ice cores can be constructed that is accurate in terms of calendar age. Fig. 2 shows the isotope data for DC (EPICA, 2004) on this age scale, compared with the benthic $\delta^{18}O$ data for core MD95-2042. This confirms the phase relationship that was demonstrated by Shackleton et al. (2000).

There are three directions to be pursued for further improving the MIS 3 time scale. First, additional highly resolved and precisely dated speleothem records will reduce the uncertainties in the absolute ages. Here it is particularly important to bracket rapid cold-to-warm transitions by precise age determinations. We recommend inter-laboratory comparison particularly for samples close to the bases of GIS 3 and 4, GIS 8, GIS 11, GIS 12 and GIS 15 since these are points where very precise ties to Greenland can be established. Second, the next generation of glaciological models will be fitted to more accurate constraints, and this may lead to slight changes in the record derived by interpolation between control points (for example, the relative durations of warm and cool intervals may be affected by the necessity to account for a longer duration for MIS 2 than was given by previous models). Finally, a new generation of layer-counting efforts will get under way. Here it is worth noting that already the accuracy of our age control at GIS 15 is under 0.5% of the age and it may be that layer counting the whole of the last glacial cycle will not improve upon this figure. On the other hand, the accurate counting of discrete interstadials (which have thicker annual layers), combined with a radiometric control on absolute ages, may again lead to an improvement in the glaciological models.

One way to check the accuracy of the marine $^{14}$C ages would be to compare them with $^{14}$C ages for continental interstadial deposits. The classic area for describing the interstadials of the last glacial is the Netherlands, where van der Hammen (1995) most recently reviewed the available data. He constructed a histogram of $^{14}$C ages, based on the compilation of van Huissteden (1990), for interstadial deposits in the Dinkel Valley. Ages comparable to those of Hughen et al. (2004) for GIS6 and GIS7 correspond to the subdivisions of the Danekamp while those for GIS8 match the Huneborg II interstadial. These correlations were not one of the two alternatives suggested by van der Hammen (1995), underlining the importance of establishing a chronology that permits a consistent comparison to be made between $^{14}$C and ice core "years". The mean of the uncalibrated $^{14}$C ages for the Huneborg II interstadial is $32.57 \pm 0.62$ ($n=8$), which may be compared with $32.67 \pm 0.46$ ($n=8$) for GIS8 in the data set of Hughen et al. (2004). While the similarity of the two estimates is very encouraging, it should be noted that van Huissteden (1990) was obliged to reject a number of age estimates on the basis of contamination by modern carbon; in order to make a rigorous comparison of terrestrial and marine ages it would be desirable to obtain a new set of ages from the Dinkel Valley using the most rigorous methods for eliminating contamination. It would not be realistic to use a blank correction based on $^{14}$C dating of interglacial peat, since it cannot be argued that every peat sample has experienced the same contamination, whereas this can reasonably be argued for every sample in a particular deep-sea sediment core. It should also be remarked that while it now becomes possible to assign an interstadial deposit younger than about 34 ka (uncalibrated $^{14}$C years) to the correct GIS on the basis of a single good $^{14}$C date, considerable care would be required to establish whether a deposit in another area of the globe should be assigned to an interstadial or to a stadial on the basis of a $^{14}$C date. Only the interval between GIS4 and GIS5 is long enough that a single $^{14}$C date could reliably assign a deposit to stadial time, and here it is important to note that a large proportion of the wood dates from Eastern Europe compiled by Willis and van Andel (2004) indeed fall in this interval as does the spectacular palaeolithic site from Arctic Siberia described by Pitulko et al. (2004).

It is only when we have ice core records whose age uncertainties are properly evaluated, that we can properly investigate the relationship between dated marine high-stands from MIS 3 (e.g. Chappell et al., 1996; Yokoyama et al., 2001) and the marine and ice-core records of millennial-scale climatic variability. In order to demonstrate the potential importance of this question, we examined the suite of paired $^{14}$C and $^{230}$Th dates for terraces in New Guinea published by Yokoyama et al. (2000) and made the assumption that if the calculated $\Delta^{14}$C disagrees markedly with the reconstruction in our Fig. 5 then one or both of the age estimates for that sample must be in error. Using this approach to screening we obtain $^{230}$Th ages of $31.9 \pm 0.4$ ($n=3$) for terrace IIc and $37.2 \pm 0.20$ ($n=3$) for terrace IIa; neither of these estimates supports the assumption that peaks in the benthic $\delta^{18}$O record shown in Fig. 2 correspond to ice volume minima.

## 4. Conclusions

Our new time scale for the last glacial period provides calendar ages for the Greenland interstadial–stadial sequence that are accurate to within a few hundred years. We also provide radiocarbon ages for those interstadials that are within the range of this method. Finally, our record of $\Delta^{14}$C provides an accurate depiction of the values that are associated with the Laschamp collapse and brief reversal of the Earth magnetic field. Recalculating the data published by Hughen et al. (2004) provides a reliable $\Delta^{14}$C record for the past 50 ka.

By utilizing the geologist's approach of precise stratigraphic correlation, it is possible to modify glaciological age models for ice cores collected from Greenland and Antarctica in such a manner that they are mutually consistent to within a very few hundred years. This is essential if the data from these cores are to be integrated in efforts to understand abrupt climatic change. It is already apparent that this approach is leading to more accurate glaciological age scales, and we hope that this interaction will continue as the geochronological controls are improved. The data shown in this paper are available at: http://www-pop.esc.cam.ac.uk/popdata/2004sfcp/2004sfcpindex.html.

## Acknowledgements

This work was supported by the EC through EVK2-CT-2000-00089 POP (NJS, F) and the NSF. We thank Sigfus Johnsen, Okitsugu Watanabe and Jean Jouzel for making ice core data available as well as Konrad Hughen and colleagues whose cited data are freely available. Larry Edwards, Augusto Mangini and Steve Burns were generous in their discussion of the dating of speleothems. We are specially grateful to Thomas Blunier as well as other members of the POP ice core community, and to John Chappell and his colleagues in Canberra, for stimulating discussion, and to Simon Crowhurst for preparing the figures. We are especially grateful to Martine Paterne and Piet Grootes for $^{14}C$ dates and discussion of these.

## References

Bard, E., Arnold, M., Maurice, P., Duprat, J., Moyes, J., Duplessy, J.-C., 1987. Retreat velocity of the North Atlantic polar front during the last deglaciation determined by $^{14}C$ accelerator mass spectrometry. Nature 328, 791–794.

Bard, E., Rostek, F., Ménot-Combes, G., 2004. Radiocarbon calibration beyond 20,000 $^{14}C$ year B.P. by means of planktonic foraminifera of the Iberian Margin. Quaternary Research, 61, 201–214.

Beck, J.W., Richards, D.A., Edwards, R.L., Silverman, B.W., Smart, P.L., Donahue, D.J., Hererra-Osterheld, S., Burr, G.S., Calsoyas, L., Jull, A.J.T., Biddulph, D., 2001. Extremely large variations of atmospheric $^{14}C$ concentration during the last glacial period. Science 292, 2453–2458.

Blunier, T., Brook, E.J., 2001. Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. Science 291, 109–112.

Burns, S.J., Fleitmann, D., Matter, A., Kramers, J., Al-Subbary, A.A., 2003. Indian Ocean climate and an absolute chronology over Dansgaard/Oeschger events 9 to 13. Science 301, 1365–1367.

Chappell, J., Omura, A., Esat, T., McCulloch, M., Pandolfi, J., Ota, Y., Pillans, B., 1996. Reconcilation of late quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. Earth and Planetary Science Letters 141, 227–236.

EPICA Community Members (2004). Eight glacial cycles from an Antarctic core. Nature, submitted for publication.

Fairbanks, R.G., Mortlock, R.A., Chiu, T.-C., Guilderson, T.P., Cao, L., Kaplan, A., Bloom, A.L. (2003). Marine radiocarbon calibration curve spanning 10,000 to 50,000 years B.P. based on paired $^{230}Th/^{234}U/^{238}U$ and $^{14}C$ dates on Pristine Corals. Geological Society of America Bulletin, submitted for publication.

Genty, D., Blamart, D., Ouahdi, R., Gilmour, M., Baker, A., Jouzel, J., Van-Exter, S., 2003. Precise dating of Dansgaard–Oeschger climate oscillations in Western Europe from stalagmite data. Nature 42, 833–837.

Hammer, C., Mayewski, P.A., Peel, D., Stuiver, M., 1997. Preface. Journal of Geophysical Research 102, 26315–26316.

Hughen, K., Lehman, S., Southon, J., Overpeck, J., Marchal, O., Herring, C., Turnbull, J., 2004. $^{14}C$ activity and global carbon cycle changes over the past 50,000 years. Science 303, 202–207.

Johnsen, S.J., Dalh-Jensen, D., Dansgaard, W., Gundestrup, N., 1995. Greenland palaeotemperatures derived from GRIP bore hole temperature and ice core isotope profiles. Tellus 47B, 624–629.

Johnsen, S.J., Dahl-Jensen, D., Gundestrup, N., Steffensen, J.P., Clausen, H.B., Miller, H., Masson-Delmotte, V., Sveinbjornsdottir, 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.

Laj, C., Kissel, C., Mazaud, A., Michel, E., Muscheler, R., Beer, J., 2002. Geomagnetic field intensity, North Atlantic deep water circulation and atmospheric $\Delta^{14}C$ during the last 50 kyr. Earth and Planetary Science Letters 200, 177–190.

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.

Monges Soares, A.M., 1993. The $^{14}C$ content of marine shells: evidence for variability in coast upwelling off Portugal during the Holocene. In: Isotope Techniques in the Study of Past and Current Environmental Changes in the Hydrosphere and Atmosphere (Proceedings), IAEA-SM-329/49, Vienna, pp. 471–485.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., Stievenard, M., 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399, 429–436.

Pitulko, V.V., Nikolsky, P.A., Girya, E.Yu., Basilyan, A.E., Tumoskoy, V.E., Koulakov, S.A., Astakov, S.N., Pavolva, E.Yu., Anisimov, M.A., 2004. The Yana RHS site: humans in the Arctic before the last glacial maximum. Science 303, 52–56.

Severinghaus, J.P., Sowers, T., Brook, E.J., Alley, R.B., Bender, M.L., 1998. Timing of abrupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice. Nature 391, 141–146.

Shackleton, N.J., Hall, M.A., Vincent, E., 2000. Phase relationships between millennial-scale events 64,000–24,000 years ago. Paleoceanography 15, 565–569.

Spötl, C., Mangini, A., 2002. Stalagmite from the Austrian Alps reveals Dansgaard–Oeschger events during isotope stage 3: implications for the absolute chronology of Greenland ice cores. Earth and Planetary Science Letters 203, 507–518.

van der Hammen, Th., 1995. The Dinkel valley revisited: pleniglacial stratigraphy of the eastern Netherlands and global climatic change. Mededelingen Rijks Geologische Dienst 52, 344–355.

van Huissteden, J., 1990. Tundra Rivers of the last glacial: sedimentation and geomorphological processes during the middle pleniglacial in Twente, Eastern Netherlands. Mededelingen Rijks Geologische Dienst 44-3, 3–138.

Voelker, A.H.L., Workshop participants, 2002. Global distribution of centennial-scale records for Marine Isotope Stage (MIS) 3: a database. Quaternary Science Reviews 21, 1185–1212.

Voelker, A.H.L., Sarnthein, M., Grootes, P.M., Erlenkeuser, H., Laj, C., Mazaud, A., Nadeau, M.-J., Schleicher, M., 1998. Correlation of marine $^{14}C$ ages from the Nordic Seas with the GISP2 isotope record: implications for $^{14}C$ calibration beyond 25 ka BP. In: Mook, W.G., van der Plicht, J. (Eds.), Proceedings of the 16th International $^{14}C$ Conference. Radiocarbon 40, 517–534.

Voelker, A.H.L., Grootes, P.M., Nadeau, M.-J., Sarnthein, M., 2000. Radiocarbon levels in the Iceland Sea from 25–53 kyr and their link to the Earth's magnetic field intensity. Radiocarbon 42, 437–452.

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.

Watanabe, O., Jouzel, J., Johnson, S., Parrenin, F., Shoji, H., Yoshida, N., 2003. Homogeneous climate variability across East Antarctic over the past three glacial cycles. Nature 422, 509–512.

Willis, K.J., van Andel, T.H., 2004. Trees or no trees? The full-glacial environments of central and eastern Europe. Quaternary Science Reviews, submitted for publication.

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. Berillium 10 in the Greenland Ice Core Project ice core at Summit, Greenland (Paper 97JC01265). Journal of Geophysical Research 10 (C12), 26783–26794.

Yokoyama, Y., Esat, T.M., Lambeck, K., Fifield, L.K., 2000. Last ice age millennial scale climate changes recorded in Huon Peninsula Corals. Radiocarbon 42, 383–401.

Yokoyama, Y., Esat, T.M., Lambeck, K., 2001. Coupled climate and sea-level changes deduced from Huon peninsula coral terraces of the last ice age. Earth and Planetary Science Letters 193, 579–587.