EXTENSION OF THE ^{14}C CALIBRATION CURVE TO *ca.* 40,000 cal BC BY SYNCHRONIZING GREENLAND $^{18}O/^{16}O$ ICE CORE RECORDS AND NORTH ATLANTIC FORAMINIFERA PROFILES: A COMPARISON WITH U/Th CORAL DATA

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ABSTRACT. For a better understanding of pre-Holocene cultural history, archaeologists are in need of an absolute time scale that can be confirmed and duplicated by different dating methods. Proxy data available from archaeological sites do not, in themselves, allow much reflection on absolute age. Even when founded on supporting radiocarbon data, Paleolithic chronologies that are beyond the actual limits of ^{14}C calibration still remain relative ones, and thus are often quite tentative. Lacking the possibility of calibration for the Paleolithic, archaeologists often attempt to correlate their data with different time scales from different archives that are thought to be absolute or calendric. The main result of this paper is that the GISP2 and U/Th chronologies duplicate each other over their entire range of data overlap, while other time scales (*i.e.*, GRIP, most varve sites) differ significantly. The context-derived ^{14}C calibration curve provides a large potential to correlate the various climate archives as recorded in ice cores and deep ocean drillings with terrestrial sequences.

INTRODUCTION

Using tree-ring records, the radiocarbon calibration curve presently reaches back to *ca.* 9450 den BC[1] near the termination of the Younger Dryas cold stage. Although the Preboreal German Pine Master Chronology (Becker, Kromer and Trimborn 1991; Kromer and Becker 1993) may have to be shifted to older ages, disregarding that the shift[2] of the tree-ring based calibration curve is well established. A further systematic extension of the calibration curve based on tree-rings seems unlikely—at least in the near future—for the period before the Late Glacial interstadial. On a global scale there is a lack of well-preserved trees from the glacial periods. Thus, to construct a calibration curve reaching back to the present limits of the ^{14}C method at *ca.* 45,000 BP for routine measurements, additional proxy records must be utilized.

Presently, a "first-order" (Bard *et al.* 1993) data set for ^{14}C calibration is available from pairs of $^{234}U/^{230}Th$ mass spectrometric (TIMS), and conventional β-decay and accelerator mass spectrometry (AMS) ^{14}C measurements on corals (Bard *et al.* 1993; Edwards *et al.* 1993). The combined tree-ring and U/Th calibration curve (Stuiver and Reimer 1993) reaches back from the present to the end of the Last Glacial Maximum (LGM)[3] at 19,950 cal U/Th BC, with a single additional data point at 28,275 cal U/Th BC. However, the Late Glacial coral ages are systematically older than data derived from lacustrine varve counts from different regions (Hajdas *et al.* 1995), by up to 1000 cal yr at the onset of the Late Glacial interstadial. The disagreement between the U/Th-data and most varve counts still remains unresolved.

[1]In this paper, we use the following as abbreviations for the "absolute" time scales: den BC/AD for tree-ring ages, cal BC/AD for calibrated ^{14}C ages, cal U/Th BC/AD for U/Th yr converted to the cal BC/AD scale, and cal GRIP/GISP2 BC/AD for ice-core synchronizations with the cal BC/AD scale.

[2]Post-conference comment: This shift has been confirmed, *cf.* Spurk *et al.* (1998).

[3]In the nomenclature used in this paper, Last Glacial Maximum is the period between interstadials IS 3 and IS 2 (Dansgaard *et al.* 1993; Johnsen *et al.* 1992). The Late Glacial is the period from IS 2 until the onset of the Holocene. The Oldest Dryas is the period between IS 2 and IS 1, as derived from European continental records.

Proceedings of the 16th International ^{14}C Conference, edited by W. G. Mook and J. van der Plicht
RADIOCARBON, Vol. 40, No. 1, 1998, P. 495–504

First studies in calibrating Paleolithic archaeological ^{14}C data (mainly of Magdalenian and Late Paleolithic age in Central Europe) have applied the Stuiver and Reimer (1993) calibration curve (Street, Baales and Weninger 1994), but have not checked the reliability of the underlying U/Th-measurements. In an attempt to resolve the discrepancies between the different time scales, we have undertaken efforts to derive additional, independent calibration data sets.

Perhaps more reliable than annually laminated lacustrine sediments, ice core records from polar regions at present offer the largest potential to construct an additional time scale for ^{14}C calibration with a resolution of 1 yr, as with tree rings. Techniques for the direct measurement of $^{14}CO_2$ and ^{14}CO trapped in polar ice have been developed recently (*e.g.*, van Roijen, van der Borg and de Jong 1995; Wilson 1995), but problems with dissolution of carbonate dust may prevent reliable ^{14}C dates from CO_2 in Greenland ice (Wahlen, personal communication 1997).

Time Scales and Absolute Chronology in Different Climate Archives

For most terrestrial stratigraphies, including archaeological sites, absolute ages are not available. Most archaeological chronologies are based on comparative studies *e.g.*, typology or palynology, and are only roughly synchronized with Pleistocene climate oscillations recorded in other archives. In Paleolithic studies researchers have tended to transform *their* chronologies to marine records (Martinson *et al.* 1987), instead of referring to the higher resolution of the ice core records of Greenland and Antarctica (*e.g.*, Dansgaard *et al.* 1993; Johnsen *et al.* 1992; Meese *et al.* 1994; Sowers *et al.* 1993; Taylor *et al.* 1993a). Geologists focusing on terrestrial sequences often point out the insecurities of such correlations, referring to the complex relations between all the climate parameters known up to now. Worse, terrestrial sequences mostly contain stratigraphical gaps that are often difficult to identify, and archaeological deposits are well known for secondary if not primary disturbances.

On the other hand, by comparing different high-resolution archives, in recent years the relative chronology of the Last Glacial Cycle has become quite elaborate, in some details showing that climate signatures in deep-sea cores obviously match those recorded in ice cores (*e.g.*, Behl and Kennett 1996; Bond *et al.* 1993; Fronval *et al.* 1995; Keigwin *et al.* 1994; Lehman and Keigwin 1992; Sowers and Bender 1995). Convincing correlations, based on various methods, imply that most Pleistocene climatic fluctuations, even short-termed, were coherent in different regions. Most of these records lack calendric time scales, but there is wide agreement that changes in climate took place at more or less the same time (Broecker 1992). Whereas for the last 55.6 kyr (Sowers *et al.* 1993; Bender *et al.* 1994) ice-core counts (*i.e.*, Dansgaard *et al.* 1993; Johnsen *et al.* 1992; Meese *et al.* 1994; Sowers *et al.* 1993) have the highest resolution, the chronological frame for the older periods is based on deep-sea records (SPECMAP) and orbital theories (Kukla *et al.* 1981; Martinson *et al.* 1987).

The widely established global climate changes shown in marine records and ice cores should imply a transfer onto the continents. In recent years important steps have been taken in this direction using palynology (*i.e.*, Behre and van der Plicht 1992; Guiot *et al.* 1989; Mangerud, Sonstegaard and Sejrup 1979; Woillard and Mook 1982), varves (Goslar, Arnold and Pazdur 1995), stable isotopes (Lotter *et al.* 1992), and even beetle-paleotemperature reconstructions (Lowe *et al.* 1995). However, these correlations of terrestrial with marine and ice-core records cover only the most recent and the most prominent climate oscillations. As a consequence of this transfer, the dating accuracy available for Paleolithic archaeological sites is limited, at least restricted to broader correlations with other archives. While all these archives are apparently leading to identical relative chronologies, time scales still differ as outlined above, and the problem is put to the archaeologist, who has to decide (based on his background knowledge of the site) which scale to favor.

Required Data Sets and Calibration Methods

At least for the Upper Paleolithic, ^{14}C dating still remains the first-choice dating method, when applicable. Without the possibility of ^{14}C calibration, it is difficult to compare ^{14}C ages with results obtained by other dating methods, which often wrongly leads to the assumption that some data cannot be relied on. Hence, the archaeologist often rejects one or the other data set derived by the different methods, which in the Paleolithic—when approaching the limits of ^{14}C dating—are more often the ^{14}C ages, and this is often motivated simply by referring to the potential danger of sample contamination. This problem, of course, will strongly impact any correlations with other archives.

Potentially useful data to construct a glacial calibration curve must fulfill a number of criteria. If possible, the data should be from long-term, continuous and undisturbed stratigraphies with the highest possible time resolution. The required sequences have to contain ^{14}C-datable materials, uncontaminated, in large amounts, and carbon content related closely to the atmosphere, to avoid inaccurate carbon reservoir corrections. Further, the stratigraphies should have their own time scales, or be related to an independent chronology. In one way or another, all these criteria are fulfilled by peat stratigraphies and lacustrine and marine sediments, but never simultaneously and to differing degrees of reliability. Thus, to construct a calibration curve reaching back to the limits of the ^{14}C method, a combination of different proxy records seems to be necessary.

To support statistical analysis and interpretation of archaeological ^{14}C data, we are using different computer programs and methods (Weninger 1995), all written in FORTRAN-77 and with HPGL graphic output. The hardware comprises an IBM-compatible 486 processor and laser printer. The program CALKN performs Dendro- and Archaeological Wiggle Matching (Pearson 1986), and 2-D Dispersion Calibration (Weninger 1986), used to calibrate single dates as well as sets of data. CALKN has a numeric accuracy of 1 yr on the ^{14}C and the calendric scales. For convenience in updating the calibration database, in archaeological studies we employ the data sets of Stuiver and Reimer (1993), for the range AD 2000 to 18 kyr cal BC. A new program CALKN-PAL extends the time scale to maximum 200 kyr with 10-yr steps to explore relations between ^{14}C, U/Th, and TL-data. Designed as a tool for Paleolithic research, this program plots the data in context with maximum two additional graphs showing global paleoclimate data. Options are line graphs or histogram representation, scaled automatically to the time window chosen for the input data.

Marine Records

The required criteria on a calibration data set, outlined above, with emphasis both on reliable synchronisms with the ice-core records and on the time covered in the records, led us to studies by Bond *et al.* (1993) and Fronval *et al.* (1995). In brief, these studies show that sea-surface temperatures (SST), as derived from marine foraminifera abundances (Bond *et al.* 1993) and ice-rafted detritus (IRD) in the North Atlantic (Fronval *et al.* 1995), reveal series of rapid climate oscillations that match those obtained in records from Greenland ice. In detail, Bond *et al.* (1993) present high-resolution marine records of *N. pachyderma* (foraminifera living close to sea-surface) from DSDP-609 and V23-81 cores, using Heinrich events and Ash Zones (far spread in the North Atlantic) as fixed isochrones. Fronval *et al.* (1995) elaborate on inter-core correlations of the cores ODP-644 and DSDP-609/V23-81 based on IRD. These records, combined, reveal series of apparently related abrupt climate changes in the North Atlantic (Bond and Lotti 1995). As previously predicted (Broecker, Bond and Klas 1990), the terminations of Dansgaard-Oeschger Cycles (Broecker, Bond and Klas 1990) in the ice cores correlate with the marine Heinrich events (Bond *et al.* 1992). This having being established, all three cores match the GRIP $\delta^{18}O$ record.

TABLE 1. ^{14}C Data from Marine Cores V23-81, DSDP-609 and ODP-644, Transferred to cal GRIP and cal GISP2 Time Scales

Core*	Depth (cm)	Sp.†	^{14}C age BP ± 1σ	C‡	*Ca.* cal BC GRIP	*Ca.* cal BC GISP2
V23-81	154.5	*N.p.*	10,900 ± 140	(+)	10,450	10,640
V23-81	198.5	*N.p.*	12,320 ± 220	(+)	12,250	12,544
DSDP-609	74.0	*N.p.*	12,350 ± 220	(+)	12,650	12,723
DSDP-609	80.0	*G.b.*	13,250 ± 90	(+)	12,850	13,226
V23-81	210.0	*N.p.*	13,440 ± 120	(i.)	13,150	13,753
DSDP-609	84.5	*N.p.*	14,590 ± 230	(+)	13,500	14,000
V23-81	213.0	*N.p.*	13,600 ± 120	(i.)	13,550	14,067
V23-81	217.0	*N.p.*	13,610 ± 100	(i.)	13,950	14,488
V23-81	219.0	*N.p.*	13,630 ± 100	(i.)	14,050	14,898
V23-81	221.0	*N.p.*	14,150 ± 110	(i.)	14,150	14,908
V23-81	223.0	*N.p.*	14,330 ± 100	(i.)	14,250	15,118
V23-81	227.0	*N.p.*	14,770 ± 110	(+)	14,350	15,538
ODP-644	no. 1	*N.p.*	15,050 ± 85	(+)	14,450	15,833
DSDP-609	87.5	*N.p.*	15,960 ± 240	(-)	14,550	15,932
V23-81	229.0	*N.p.*	15,040 ± 110	(+)	14,700	16,228
DSDP-609	90.5	*N.p.*	16,360 ± 150	(+)	15,950	17,773
DSDP-609	98.5	*N.p.*	16,960 ± 120	(-)	16,850	18,653
ODP-644	no. 2	*N.p.*	16,215 ± 90	(+)	17,050	18,733
ODP-644	no. 3	*N.p.*	17,760 ± 100	(+)	18,450	20,372
DSDP-609	106.0	*N.p.*	18,940 ± 220	(+)	18,650	20,827
DSDP-609	110.5	*N.p.*	19,970 ± 330	(+)	19,300	21,456
V23-81	321.0	*N.p.*	20,420 ± 180	(+)	19,300	21,456
V23-81	323.0	*N.p.*	20,470 ± 160	(+)	19,525	21,578
V23-81	327.0	*N.p.*	20,570 ± 180	(+)	19,650	21,706
ODP-644	no. 4	*N.p.*	19,045 ± 130	(-)	19,700	21,825
DSDP-609	111.5	*N.p.*	20,550 ± 260	(i.)	19,725	22,124
V23-81	329.0	*N.p.*	20,990 ± 170	(+)	20,200	22,279
V23-81	331.0	*N.p.*	21,210 ± 170	(+)	20,275	22,543
V23-81	333.0	*N.p.*	21,700 ± 180	(+)	20,450	22,792
DSDP-609	112.5	*N.p.*	21,110 ± 220	(+)	20,450	22,792
DSDP-609	115.5	*N.p.*	21,370 ± 220	(+)	20,825	23,049
V23-81	337.0	*N.p.*	21,960 ± 190	(+)	20,875	23,176
ODP-644	no. 5	*N.p.*	19,875 ± 115	(-)	20,950	23,200
DSDP-609	119.0	*N.p.*	22,380 ± 340	(+)	21,425	24,122
ODP-644	no. 6	*N.p.*	23,280 ± 150	(-)	22,850	25,800
DSDP-609	140.0	*G.i.*	25,260 ± 440	(+)	23,850	26,991
V23-81	371.0	*N.p.*	24,680 ± 200	(+)	24,100	27,083
DSDP-609	148.0	*N.p.*	26,170 ± 310	(-)	25,450	28,152
V23-81	381.0	*N.p.*	26,270 ± 260	(i.)	25,650	28,487
DSDP-609	154.0	*N.p.*	29,170 ± 660	(-)	25,850	28,669
V23-81	391.0	*N.p.*	28,980 ± 320	(i.)	26,850	29,892
V23-81	393.0	*N.p.*	29,050 ± 310	(+)	27,000	30,173
DSDP-609	166.5	*N.p.*	30,080 ± 680	(-)	27,000	30,173
DSDP-609	175.0	*G.i.*	30,720 ± 730	(-)	27,250	30,505
ODP-644	no. 7	*N.p.*	30,415 ± 360	(-)	27,350	30,550
ODP-644	no. 8	*N.p.*	32,685 ± 425	(-)	33,250	36,700
ODP-644	no. 9	*N.p.*	38,985 ± 870	(-)	40,350	42,900

*References: V23-81 and DSDP-609 = Bond *et al.* (1993); ODP-644 = Fronval *et al.* (1995).

†Species: *N.p.* = *N. pachyderma; G.i.* = *G. inflata; G.b.* = *G. bulloides*

‡Correlation: (+) = good correlation; (i.) = interpolated between neighboring data/peaks; (–) = bad correlation.

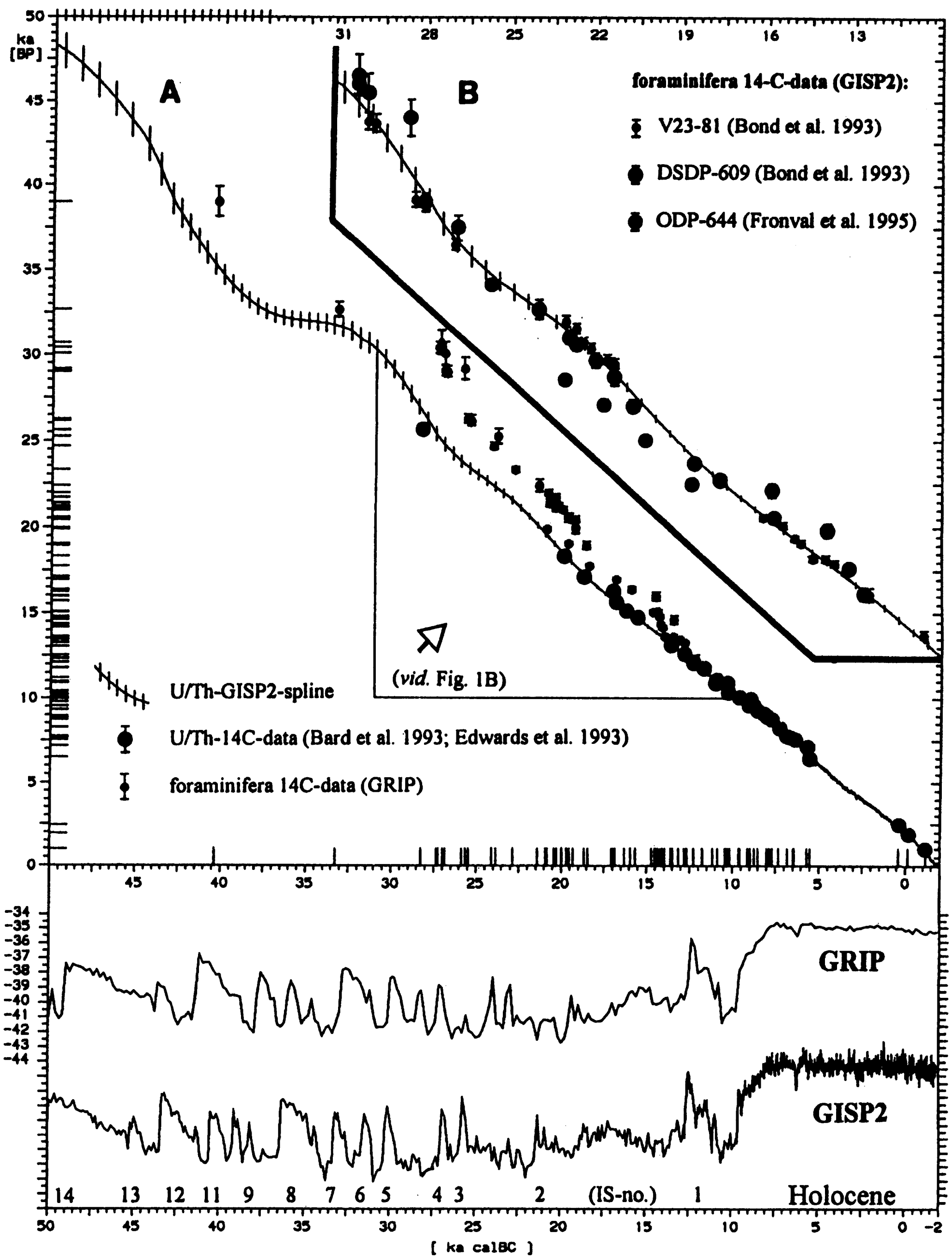

Fig. 1. A. Spline led through U/Th ^{14}C data (Bard *et al.* 1993; Edwards *et al.* 1993), SST-derived (Bond *et al.* 1993) and IRD-derived (Fronval *et al.* 1995) ^{14}C cal GISP2 data, revealing progressive deviations between the U/Th cal GISP2 and the cal GRIP time scales. $\delta^{18}O$ records of GRIP (Dansgaard *et al.* 1993; Johnsen *et al.* 1992) and GISP2 (Grootes *et al.* 1993; Meese *et al.* 1994; Sowers *et al.* 1993; Stuiver, Grootes and Braziunas 1995) are given in context. **B.** Spline as in A. with the zoomed time-window 10–31 kyr cal GISP2 BC and ^{14}C cal GISP2 data derived from marine cores (Bond *et al.* 1993; Fronval *et al.* 1995), showing agreement with the combined U/Th cal GISP2 spline.

From these marine cores, Bond *et al.* (1993) and Fronval *et al.* (1995) give a total of 47 AMS ^{14}C measurements (all with an assumed marine reservoir correction of constant 400 BP) on *N. pachyderma*, *G. inflata*, and *G. bulloides* (Table 1). Sampling of DSDP-609 and V23-81 is concentrated around Heinrich events H1–H3, giving 38 AMS ^{14}C dates (Bond *et al.* 1993). The ODP-644 core offers 9 additional AMS ^{14}C dates (Fronval *et al.* 1995).

As mentioned above, the marine core-to-core correlations are established by fixed isochrones, and also by the temporal fine-structure of SST and IRD; the authors thus synchronize these records first to the GRIP time scale (Bond *et al.* 1993; Fronval *et al.* 1995) and later to the GISP2 time scale (Bond and Lotti 1995). We use these correlations, reading peak-to-peak as close as possible, to derive GRIP-age readings for very specific samples, namely those which are ^{14}C-dated. For sample positions that are difficult to read, notably around the LGM, we have used linear depth-age interpolation between framing sample positions or Heinrich events. Having derived paired ^{14}C/GRIP ages, for comparison we transferred the data to the GISP2 time scale (Table 1), according to the established inter-ice-core correlations (Grootes *et al.* 1993; Taylor *et al.* 1993b). To check on mistakes, we repeated the study, but refrained from further data manipulation. We made use of all ^{14}C data; no measurements were discarded. The two data sets (^{14}C *vs.* cal-GRIP/cal-GISP2) are shown in Table 1 and Figure 1.

Results

Using these correlations, the time scales for both potential ^{14}C calibration data sets (^{14}C cal GRIP and ^{14}C cal GISP2) are given by the GRIP (Dansgaard *et al.* 1993; Johnsen *et al.* 1992) and GISP2 chronologies (Grootes *et al.* 1993; Meese *et al.* 1994; Sowers *et al.* 1993; Stuiver, Grootes and Braziunas 1995). Due to the complex correlations, it is difficult to quantify the inaccuracies at each point of both calibration curves. The obtained data series independently can be compared with the U/Th calibration records (Bard *et al.* 1993; Edwards *et al.* 1993), which show atmospheric ^{14}C changes smoothed by the ocean surface (Stuiver and Braziunas 1993). Each of the marine sets can be seen as a meaningful test set for checking the internal chronology of the two ice cores.

In carrying out the plan of deriving a Glacial calibration curve from the marine data of Bond *et al.* (1993) and Fronval *et al.* (1995), we ran into the difficulty that age discrepancies exist between the otherwise identical GRIP and GISP2 records. The age discrepancies between GRIP and GISP2 increase with depth and total up to *ca.* 3 ka at the time of IS 4 (Fig. 1, lower half). Of course, the offsets between GRIP and GISP2 time scales are well known, and thus would not be remarkable except that we clearly observe good agreement between the GISP2-calibrated marine ^{14}C data sets and the U/Th coral ^{14}C data, in the entire age range covered by both data sets (Fig. 1B, inlay). In comparison, when scaled to the GRIP core, the marine ^{14}C data deviate progressively from the U/Th curve (raw data and spline in Fig. 1).

As the result of the near-perfect agreement (*i.e.*, within error-limits given by the authors) between the GISP2-derived calibration curve and the U/Th-^{14}C coral data, in Figure 1 we use a spline interpolation function to smooth the combined data set. The spline data and the $\pm 1\sigma$ error estimates, derived from a separate spline, are given in Table 2. The few readily apparent outliers (Fig. 1B, inlay) all derive from the ODP-644 core, mainly from the interval 23.5–18.0 kyr cal GISP2 BC. These values may be traced back to our difficulties in identifying IRD peak-to-peak $\delta^{18}O$ correlations between ODP-644 (Fronval *et al.* 1995) and (both) GRIP and GISP2 ice cores. As mentioned above, we undertook no secondary efforts to identify "better" positions for any of these samples, to avoid non-reproducible pseudo-accuracies. The spline graph (Fig. 1A; Table 2) extrapolates the combined data set, with only two additional dates (both ODP-644) reaching back to *ca.* 43.0 kyr cal

GISP2 BC. The data base of a tentative long-term ^{14}C plateau in the splined calibration curve at 32.0 kyr BP with length *ca.* 5 kyr, is minimal to non-existent (Fig. 1A), although this potential plateau may turn out to be real when archaeologists take a closer look at available early Upper Paleolithic Aurignacian series of data from well-stratified sites.

TABLE 2. Data Set of Spline Function (Fig. 1) Led Through U/Th ^{14}C Data* and ^{14}C cal GISP2 Data†

Cal GISP2 BC	/AD 2000	^{14}C age BP ± 1σ	Cal GISP2 BC	/AD 2000	^{14}C age BP ± 1σ
9720	11,720	10,100 ± 150	18,000	20,000	16,556 ± 84
10,000	12,000	10,158 ± 136	18,500	20,500	17,006 ± 89
10,500	12,500	10,598 ± 126	19,000	21,000	17,488 ± 96
11,000	13,000	11,032 ± 117	19,500	21,500	18,000 ± 104
11,500	13,500	11,461 ± 109	20,000	22,000	18,530 ± 113
12,000	14,000	11,883 ± 101	20,500	22,500	19,070 ± 123
12,500	14,500	12,297 ± 95	21,000	23,000	19,610 ± 135
13,000	15,000	12,704 ± 89	21,500	23,500	20,139 ± 148
13,500	15,500	13,101 ± 84	22,000	24,000	20,649 ± 162
14,000	16,000	13,490 ± 80	22,500	24,500	21,128 ± 178
14,500	16,500	13,870 ± 77	23,000	25,000	21,568 ± 195
15,000	17,000	14,240 ± 75	23,500	25,500	21,963 ± 214
15,500	17,500	14,606 ± 74	24,000	26,000	22,325 ± 234
16,000	18,000	14,973 ± 74	24,500	26,500	22,672 ± 255
16,500	18,500	15,346 ± 75	25,000	27,000	23,022 ± 278
17,000	19,000	15,731 ± 77	25,500	27,500	23,394 ± 302
17,500	19,500	16,132 ± 80	26,000	28,000	23,803 ± 326
26,500	28,500	24,269 ± 352	35,000	37,000	32,015 ± 467
27,000	29,000	24,809 ± 380	35,500	37,500	32,066 ± 450
27,500	29,500	25,440 ± 407	36,000	38,000	32,131 ± 436
28,000	30,000	26,261 ± 386	36,500	38,500	32,229 ± 426
28,500	30,500	26,994 ± 416	37,000	39,000	32,373 ± 421
29,000	31,000	27,735 ± 448	37,500	39,500	32,581 ± 422
29,500	31,500	28,462 ± 479	38,000	40,000	32,864 ± 432
30,000	32,000	29,148 ± 509	38,500	40,500	33,220 ± 449
30,500	32,500	29,769 ± 538	39,000	41,000	33,647 ± 473
31,000	33,000	30,299 ± 565	39,500	41,500	34,141 ± 504
31,500	33,500	30,715 ± 591	40,000	42,000	34,697 ± 542
32,000	34,000	30,996 ± 611	40,500	42,500	35,313 ± 586
32,500	34,500	31,418 ± 531	41,000	43,000	35,985 ± 635
33,000	35,000	31,637 ± 526	41,500	43,500	36,710 ± 690
33,500	35,500	31,790 ± 515	42,000	44,000	37,482 ± 750
34,000	36,000	31,893 ± 500	42,500	44,500	38,300 ± 815
34,500	36,500	31,962 ± 484	43,000	45,000	39,160 ± 884

*Bard *et al.* (1993); Edwards *et al.* (1993)
†Bond *et al.* (1993); Fronval *et al.* (1995)

The Potential of the GISP2 "Context Calibration" in Archaeology

To summarize, the U/Th-^{14}C coral data given by Bard *et al.* (1993) and Edwards *et al.* (1993) are well replicated by the SST-derived ^{14}C data of Bond *et al.* (1993), and are in reasonable agreement with the IRD-derived ^{14}C data of Fronval *et al.* (1995), when both are synchronized with the GISP2 time scale. In consequence, due to known differences between the GRIP and GISP2 time scales (Dansgaard *et al.* 1993; Grootes *et al.* 1993; Johnsen *et al.* 1992; Meese *et al.* 1994; Sowers *et al.* 1993; Stuiver, Grootes and Braziunas 1995; Taylor *et al.* 1993a) yet to be resolved, there are discrepancies increasing with age (Fig. 1A) between the U/Th and ^{14}C GRIP data. Of course, we cannot refute the possibility that both the U/Th and GISP2 time scales are wrong, but see no reason to follow this hypothesis: annual ice layer countings of GISP2 reach back further (Meese *et al.* 1994; Sowers *et al.* 1993) than in the GRIP record. Also the GISP2 chronology is partly interpolated (and thus calibrated) with the SPECMAP-based Vostok chronology (Bender *et al.* 1994; Sowers *et al.* 1993) and in broader agreement with orbital theories (Martinson *et al.* 1987), and altogether implies higher reliability. We also conclude that varve chronologies from different regions (Hajdas et al. 1995) must contain unidentified errors, *i.e.,* gaps and/or dates of potentially reworked terrestrial macrofossils.

Conclusion

Since our research field is archaeology, our prime interest lies in the comparison of terrestrial stratigraphies (which contain documentation of human activities), with the relative sequence of Glacial climatic changes, as recorded with high resolution in marine archives and ice cores. It seems that archaeologists are best advised, presently, to base the absolute chronology for the Glacial periods on U/Th-calibrated ^{14}C data, in context with climate information that is scaled to the GISP2 ice core.

As an addendum to the Groningen Conference, we recommend further reference to the work presented by Kitagawa and van der Plicht (1998) and Voelker *et al.* (1998) in this issue. Computer programs for explorative research on calibration of ^{14}C data for the Paleolithic periods, shown with optional GISP2/GRIP/VOSTOK/SOLAR INSULATION climate context, are available from the authors. The data sets for Glacial ^{14}C calibration will be updated as new data become available.

Acknowledgments

We gratefully acknowledge the comments, recommendations and additional sources of literature provided by the reviewer.

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