A NEW ^{14}C CALIBRATION DATA SET FOR THE LAST DEGLACIATION BASED ON MARINE VARVES

KONRAD A. HUGHEN,[1,2] JONATHAN T. OVERPECK,[1,3] SCOTT J. LEHMAN[1]
MICHAELE KASHGARIAN,[4] JOHN R. SOUTHON[4] and LARRY C. PETERSON[5]

ABSTRACT. Varved sediments of the tropical Cariaco Basin provide a new ^{14}C calibration data set for the period of deglaciation (10,000 to 14,500 years before present: 10–14.5 cal ka BP). Independent evaluations of the Cariaco Basin calendar and ^{14}C chronologies were based on the agreement of varve ages with the GISP2 ice core layer chronology for similar high-resolution paleoclimate records, in addition to ^{14}C age agreement with terrestrial ^{14}C dates, even during large climatic changes. These assessments indicate that the Cariaco Basin ^{14}C reservoir age remained stable throughout the Younger Dryas and late Allerød climatic events and that the varve and ^{14}C chronologies provide an accurate alternative to existing calibrations based on coral U/Th dates. The Cariaco Basin calibration generally agrees with coral-derived calibrations but is more continuous and resolves century-scale details of ^{14}C change not seen in the coral records. ^{14}C plateaus can be identified at 9.6, 11.4, and 11.7 ^{14}C ka BP, in addition to a large, sloping "plateau" during the Younger Dryas (~10 to 11 ^{14}C ka BP). Accounting for features such as these is crucial to determining the relative timing and rates of change during abrupt global climate changes of the last deglaciation.

INTRODUCTION

Radiocarbon dating is an important tool for studying the natural variability of the global climate system. High-resolution paleoclimate records show that many large, abrupt changes occurred during the last deglaciation, and there is increasing evidence that some of these may have been global in scope (Bender *et al.* 1994; Lowell *et al.* 1995; Denton and Hendy 1994; Behl and Kennett 1996). ^{14}C dating is necessary for determining the relative timing of these changes and their propagation through the climate system, but its utility is limited by the fact that the ^{14}C "clock" runs at different speeds depending on the atmospheric ^{14}C inventory. Studies have shown that atmospheric ^{14}C concentration (Δ^{14}C) has varied significantly through time (Stuiver 1970; Linick *et al.* 1986; Stuiver *et al.* 1986; Bard *et al.* 1990; Stuiver *et al.* 1991; Becker 1993; Goslar *et al.* 1995), as a result of changes in ^{14}C production rate (a function of variability in the Earth's geomagnetic field strength and solar activity), and redistribution of ^{14}C between reservoirs (primarily a function of oceanic thermohaline circulation). Because of Δ^{14}C changes, the ^{14}C time scale departs from true calendar ages in a nonlinear fashion by as much as 3000 yr (Bard *et al.* 1990).

The highest-resolution ^{14}C calibration data set, based on tree-ring chronologies from German oaks and pines (Becker, Kromer and Trimborn 1991; Kromer and Becker 1993; B. Kromer, personal communication), currently begins *ca.* 12 calendar ka BP, just prior to the abrupt termination of the Younger Dryas cold period, a dramatic climatic oscillation lasting from *ca.* 13 to 11.7 cal ka BP (Alley *et al.* 1993). Tree rings thus do not provide calibration during several of the other large and abrupt climate changes of the last deglaciation. Previous attempts to extend ^{14}C calibration prior to the interval covered by tree rings have used paired ^{14}C-U/Th dates on corals (Bard *et al.* 1990; Edwards *et al.* 1993; Bard *et al.* 1993; Bard *et al.* 1996) as well as annually laminated sediment (varve) chronologies with ^{14}C-dated macrofossils from European lakes (Hajdas *et al.* 1993; Hajdas *et al.* 1995; Goslar *et al.* 1995) and the Baltic Sea (Wohlfarth 1996). Each of these data sets agrees with the tree-ring calibration for the period later than *ca.* 12 cal ka BP. Prior to 12 cal ka BP, however,

[1] INSTAAR and Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309 USA
[2] Present address: Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachussets 02138 USA
[3] NOAA Paleoclimatology Program, National Geophysical Data Center, Boulder, Colorado 80303 USA
[4] Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, California 94551 USA
[5] Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida 33149 USA

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the coral results disagree with the longer chronologies from Lakes Soppensee (Hajdas *et al.* 1993) and Holzmaar (Hajdas *et al.* 1995), as well as the Swedish varve chronology (Wohlfarth 1996). The lack of agreement between coral and varve data sets, together with the discontinuous or low-resolution nature of these time series, introduces substantial uncertainty to ^{14}C calibration prior to 12 ka BP.

In this paper, we present a new ^{14}C calibration data set from varved marine sediments of the Cariaco Basin that spans most of the last deglaciation. Several independent lines of evidence are used to demonstrate the accuracy of both Cariaco Basin calendar (varve) and ^{14}C chronologies. These data extend a continuous ^{14}C calibration an additional 3000 yr before the tree-ring record to the Glacial/Bølling event boundary and resolve short-lived changes in ^{14}C during the early Younger Dryas and Bølling/Allerød periods that are not resolved by data sets based on corals (Bard *et al.* 1990; Edwards *et al.* 1993; Bard *et al.* 1993; Stuiver and Reimer 1993; Bard *et al.* 1996).

VARVE CHRONOLOGY

Laminated Sediments

The Cariaco Basin is an anoxic marine basin off the coast of Venezuela (Fig. 1), separated from the open Caribbean Sea by shallow sills (<146 m), that possesses varved sediments with the potential for continuous, high-resolution AMS ^{14}C dating due to high concentrations of planktonic foraminifera (Overpeck *et al.* 1989; Peterson *et al.* 1991; Hughen *et al.* 1996a, 1996b, 1998). The climate cycle in the Cariaco Basin region consists of a dry season with strong trade winds and coastal

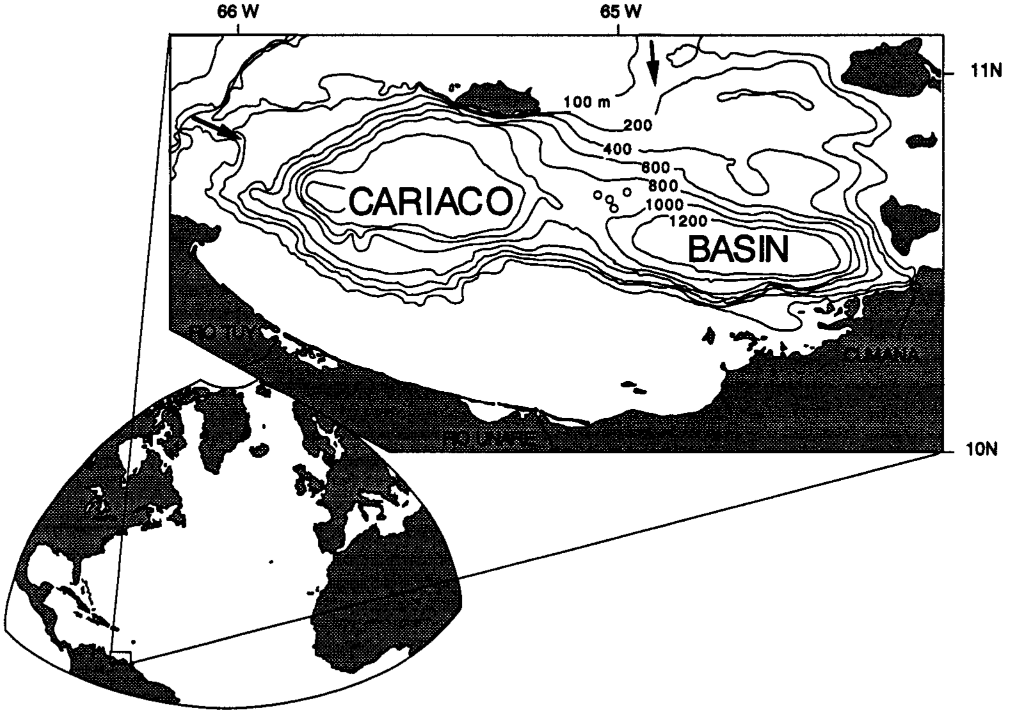

Fig. 1. Location and bathymetry of the Cariaco Basin, off the coast of Venezuela in the southern Caribbean Sea. Shallow sills (arrows mark two channels to the west and east, 146 and 120 m deep, respectively) isolate deep waters, which are presently anoxic below 300 m, allowing preservation of finely laminated sediments. o = locations of piston cores PL07-39PC, -56PC, -57PC and -58PC. Contour interval is 200 m.

upwelling, alternating with a rainy season with weaker winds and no upwelling. This climatic regime results in the annual deposition of laminae couplets of light-colored, plankton-rich and dark-colored, terrigenous mineral grain-rich layers (Overpeck *et al.* 1989; Peterson *et al.* 1991; Hughen *et al.* 1996a). The annual nature of the laminae couplets was investigated in well-laminated surface sediments containing two distinct turbidites, using ^{210}Pb dating and historical records of earthquakes (which would be expected to result in turbidity currents) in the neighboring region. The independent dating methods yielded ages of 58 ± 4 and 89 ± 5 yr (^{210}Pb), *vs.* 61 and 90 yr (historical) for the two turbidites, in good agreement with paired-laminae counts of 60 and 90 yr, respectively. This agreement using multiple dating methods demonstrates that the laminae couplets are annually deposited varves (Hughen *et al.* 1996a).

The Cariaco Basin has distinct, thick laminae at depths corresponding to ages of 12.7–9.0 ^{14}C ka BP, after which they become thinner and less pronounced toward the surface. Four sediment cores were cross-correlated on the basis of distinct, millimeter-scale "marker laminae", and laminae couplets were counted to create a floating annual chronology 5500 varve-years long, covering the period of deglaciation from *ca.* 8.0 to 12.7 ^{14}C ka BP (Hughen *et al.* 1996b, 1998). AMS ^{14}C dates were obtained on 60 samples of the planktonic foraminifer *Globigerina bulloides*, hand-picked from 1.5 to 2 cm thick samples, each corresponding to 10–15 varve years. The samples were taken from cores PL07-56PC and PL07-39PC (Fig. 2; Table 1), over the same sediment interval in which the varves were counted. The floating varve chronology was anchored to absolute calendar age by "wiggle-matching" ^{14}C *vs.* calendar age variations to those measured in the German pine dendrochronology (Kromer and Becker 1993; B. Kromer, personal communication; Hughen *et al.* 1998). Recently, the

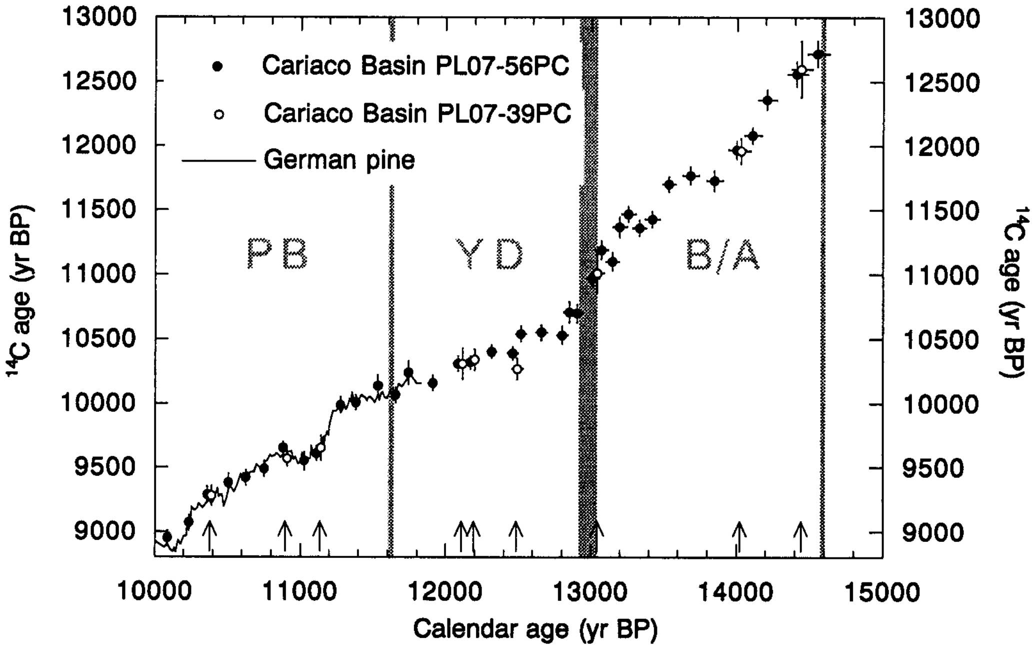

Fig. 2. ^{14}C *vs.* calendar ages for two different Cariaco Basin sediment cores, PL07-56PC and PL07-39PC, and German pines (B. Kromer, personal communication; Kromer and Becker 1993). Vertical shaded lines delineate boundaries between Preboreal (PB), Younger Dryas (YD), and Bølling/Allerød (B/A) climatic events. Width of lines indicates duration of these transitions based on Cariaco Basin gray scale and varve chronology. Small arrows indicate locations of ^{14}C dates from core PL07-39PC, shown here to evaluate the reproducibility of Cariaco Basin ^{14}C dating. All ^{14}C errors are reported at 1σ.

TABLE 1. Radiocarbon and Varve Ages for Cariaco Basin Sediment Samples

Sample ID	Depth (cm)	Varve age (yr BP)	^{14}C age (yr BP ±1σ)	Δ^{14}C (‰ ±1σ)	Lab code (CAMS-)*
PC56-269	268–269.5	9966 (+20 −20)	8920 (±70)	99.8 (+9.7 −9.7)	29390
PC56-279	278–279.5	10,087 (+20 −20)	8950 (±60)	111.8 (+8.5 −8.5)	29389
PC56-283	283–284.5	10,234 (+20 −20)	9070 (±60)	115.0 (+8.6 −8.6)	27097
PC56-290	289–290.5	10,360 (+20 −20)	9290 (±60)	101.5 (+8.5 −8.5)	27096
PC56-295	294–295.5	10,505 (+20 −20)	9380 (±70)	108.5 (+9.8 −9.8)	27095
PC56-299	298–299.5	10,624 (+20 −20)	9420 (±60)	119.0 (+8.6 −8.6)	27094
PC56-304	303–304.5	10,751 (+20 −20)	9490 (±60)	126.5 (+8.6 −8.6)	27093
PC56-306	306–307.5	10,880 (+20 −20)	9650 (±50)	121.6 (+7.3 −7.3)	27092
PC56-311	310–311.5	11,026 (+20 −20)	9550 (±70)	155.9 (+10.2 −10.2)	27091
PC56-319	318–319.5	11,112 (+20 −20)	9610 (±60)	159.3 (+8.9 −8.9)	23406
PC56-334†	333–335	11,218 (+20 −20)	8260 (±60)	389.2 (+10.7 −10.7)	29388
PC56-346	345–347	11,277 (+20 −20)	9990 (±60)	128.0 (+8.7 −8.7)	29387
PC56-355	354–355.5	11,381 (+20 −20)	10,010 (±60)	139.5 (+8.7 −8.7)	23405
PC56-368	367–369	11,533 (+20 −20)	10,140 (±80)	142.0 (+11.4 −11.4)	29386
PC56-384	383–384.5	11,655 (+24 −24)	10,070 (±60)	169.1 (+9.2 −9.2)	23404
PC56-401	401–402.5	11,742 (+27 −29)	10,240 (±90)	156.7 (+13.2 −13.3)	22517
PC56-426	425–426.5	11,911 (+28 −31)	10,160 (±60)	192.4 (+9.6 −9.8)	23403
PC56-447	446–447.5	12,085 (+32 −32)	10,310 (±60)	195.3 (+9.9 −9.9)	23402
PC56-464	463.5–465	12,170 (+32 −32)	10,320 (±50)	206.1 (+8.7 −8.7)	23401
PC56-487	486–487.5	12,318 (+34 −34)	10,400 (±50)	215.7 (+9.0 −9.0)	23400
PC56-521	520–521.5	12,463 (+38 −36)	10,390 (±50)	238.8 (+9.5 −9.3)	23399
PC56-538	537.5–539	12,520 (+38 −36)	10,540 (±60)	224.3 (+10.6 −10.4)	23398
PC56-552	551–552.5	12,658 (+41 −38)	10,550 (±60)	243.4 (+11.0 −10.8)	23397
PC56-560	559–561	12,802 (+41 −38)	10,530 (±70)	268.4 (+12.5 −12.3)	27090
PC56-569	568–570	12,850 (+41 −38)	10,710 (±80)	247.5 (+13.6 −13.4)	27089
PC56-575	574–575.5	12,904 (+43 −39)	10,700 (±70)	257.2 (+12.6 −12.3)	23396
PC56-596	596–597.5	13,014 (+46 −41)	10,970 (±70)	231.9 (+12.6 −12.2)	20515
PC56-607	606–608	13,071 (+46 −41)	11,190 (±70)	207.0 (+12.3 −11.9)	27088
PC56-616	615–617	13,146 (+51 −45)	11,100 (±70)	231.7 (+13.0 −12.5)	27087
PC56-623	622–623.5	13,196 (+53 −47)	11,370 (±80)	198.2 (+14.0 −13.5)	23395
PC56-639	639–640.5	13,256 (+53 −47)	11,470 (±60)	192.0 (+11.7 −11.1)	23394
PC56-644	643–645	13,332 (+53 −47)	11,360 (±60)	219.6 (+12.0 −11.4)	30902
PC56-655	654–656	13,421 (+53 −47)	11,430 (±60)	222.1 (+12.0 −11.4)	30901
PC56-662	661–662.5	13,536 (+53 −47)	11,700 (±60)	198.2 (+11.8 −11.2)	22515
PC56-672	671.5–674	13,683 (+61 −52)	11,770 (±70)	209.2 (+13.8 −12.9)	27086
PC56-685	684–685.5	13,844 (+61 −52)	11,730 (±80)	239.1 (+15.2 −14.4)	22514
PC56-697	696–697.5	13,998 (+66 −56)	11,970 (±70)	225.2 (+14.5 −13.4)	20516
PC56-711	710–711.5	14,108 (+66 −56)	12,080 (±60)	224.8 (+13.4 −12.3)	22513
PC56-725	724–725.5	14,206 (+71 −60)	12,360 (±80)	196.9 (+15.7 −14.6)	20517
PC56-737	736–737.5	14,410 (+78 −65)	12,560 (±100)	196.6 (+18.6 −17.4)	20518
PC56-744	743–745.5	14,553 (+81 −70)	12,720 (±100)	193.5 (+18.8 −17.8)	28687
PC39-293	293–295	10,390 (+20 −20)	9280 (±80)	106.9 (+11.1 −11.1)	1737
PC39-305	305–309	10,910 (+20 −20)	9570 (±60)	137.0 (+8.7 −8.7)	2954
PC39-334	334–336	11,142 (+20 −20)	9650 (±100)	157.7 (+14.3 −14.3)	1738
PC39-401	401–404	12,115 (+32 −32)	10,310 (±120)	199.6 (+18.1 −18.1)	1739
PC39-441	441–444	12,200 (+32 −32)	10,340 (±80)	207.5 (+12.6 −12.6)	2955
PC39-462	462–465	12,493 (+38 −36)	10,270 (±80)	262.0 (+13.6 −13.5)	1740
PC39-521	521–524	13,044 (+46 −41)	11,010 (±150)	230.3 (+23.4 −23.2)	1741
PC39-573	573–576	14,028 (+66 −56)	11,960 (±100)	231.2 (+18.0 −17.2)	1742
PC39-621	621–622.5	14,440 (+78 −65)	12,600 (±220)	195.0 (+33.9 −33.2)	1748

11,770
420
12,190
500
11,690

13683
1950
11733

*All ^{14}C analyses were made at CAMS, Lawrence Livermore National Laboratory. ^{14}C measurements are AMS dates using conventional half-life of 5568 yr and reservoir correction of 420 yr. ^{14}C and Δ^{14}C errors are reported at 1σ.

†^{14}C age of this sample is anomalously young—we have no explanation as to the cause.

German pines themselves have been securely anchored to German oaks (B. Kromer, personal communication) and thus now constitute an absolute and continuous calendar time scale. The Cariaco Basin and German pine ^{14}C variations were matched by incrementally adjusting the calendar-age offset until the correlation between the data sets was maximized ($r = 0.99$), anchoring the varve chronology in absolute calendar time (Hughen *et al.* 1998). The uncertainty of the wiggle-match was determined by the amount of offset between the data sets that still yielded a correlation coefficient of at least $r = 0.99$. This resulted in an uncertainty of ±20 cal yr during the period covered by the match itself. Cumulative errors in varve counting were constrained to accrue only within the 3000 yr older than tree rings and provide an additional 1–2% uncertainty during that period (Table 1).

Paleoclimate Verification of Varve Chronology

Records of relative reflectance, or gray scale, have been measured on fresh surfaces of split Cariaco Basin sediment cores. Gray scale values correlate well with records of light laminae thickness, which correspond to annual upwelling intensity, and therefore trade wind strength (Hughen *et al.* 1996b). Gray scale and light laminae thickness both record large and abrupt changes during deglaciation, including decade-to-century–scale variability during the Bølling/Allerød, Younger Dryas and Preboreal periods that correlates well with high-resolution terrestrial and marine paleoclimate records from the high-latitude North Atlantic region (Hughen *et al.* 1996b). In particular, annually dated records of light laminae thickness from the Cariaco Basin and δ^{18}O in the GRIP ice core from Greenland (Johnsen *et al.* 1992) both show strikingly similar patterns and durations of abrupt events at the scale of a single decade. The brevity of these decade-scale events occurring in two widely separated sites suggests that they were essentially synchronous (*i.e.*, occurring within 10 yr) and caused by the same mechanism (Hughen *et al.* 1996b). Atmospheric and coupled ocean-atmosphere general circulation model (GCM) results (Rind *et al.* 1986; Schiller, Mikolajewicz and Voss 1997) show that cooling in the high-latitude North Atlantic region produces an increase in trade wind intensity over the tropical North Atlantic, thus explaining the synchronous climate linkage between North Atlantic sea surface and air temperatures, and trade wind–driven upwelling in the tropical Cariaco Basin (Hughen *et al.* 1996b).

The tight linkage between Cariaco Basin and Greenland ice core paleoclimate records was used to assess independently the accuracy of the anchored varve chronology. Cariaco Basin gray scale and accumulation from the GISP2 ice core (Alley *et al.* 1993) are plotted during the period of deglaciation, each versus its individual annual chronology (Fig. 3). In addition to the large changes at the Glacial/Bølling boundary and the beginning and end of the Younger Dryas (14.7, 13 and 11.7 cal ka BP, respectively), the two records show similar events and patterns of change at decade to century scales. A least-squares procedure (Paillard 1996) allowing manual identification of similar, large climate events as constraints (dashed lines, Fig. 3) was used to align the GISP2 accumulation and Cariaco Basin gray scale records along their entire lengths. The resulting correlation between the two records is good ($r = 0.69$) and was used to assign the GISP2 layer-age chronology to the Cariaco Basin gray scale record. In this way, the two independently derived chronologies could be compared directly and differences between them quantified (Fig. 3). The two chronologies consistently agree within <0.7%. The pattern of increasing disagreement with age may reflect errors in either chronology compounding downcore, the direction in which the varves and annual ice layers were counted. For most of the period from 10–14.7 cal ka BP, the difference is <20 yr, and reaches 100 yr only in the oldest part of the chronology (*i.e.*, the Glacial/Bølling boundary, Fig. 3). The Cariaco Basin ages meander randomly about the GISP2 ages, rather than remaining consistently offset, and always agree well within the combined independent errors (~1–2%) of the two chronologies. This assessment of Cariaco Basin varve ages, independent of ^{14}C considerations, provides strong evidence for the accuracy of the Cariaco Basin calendar chronology.

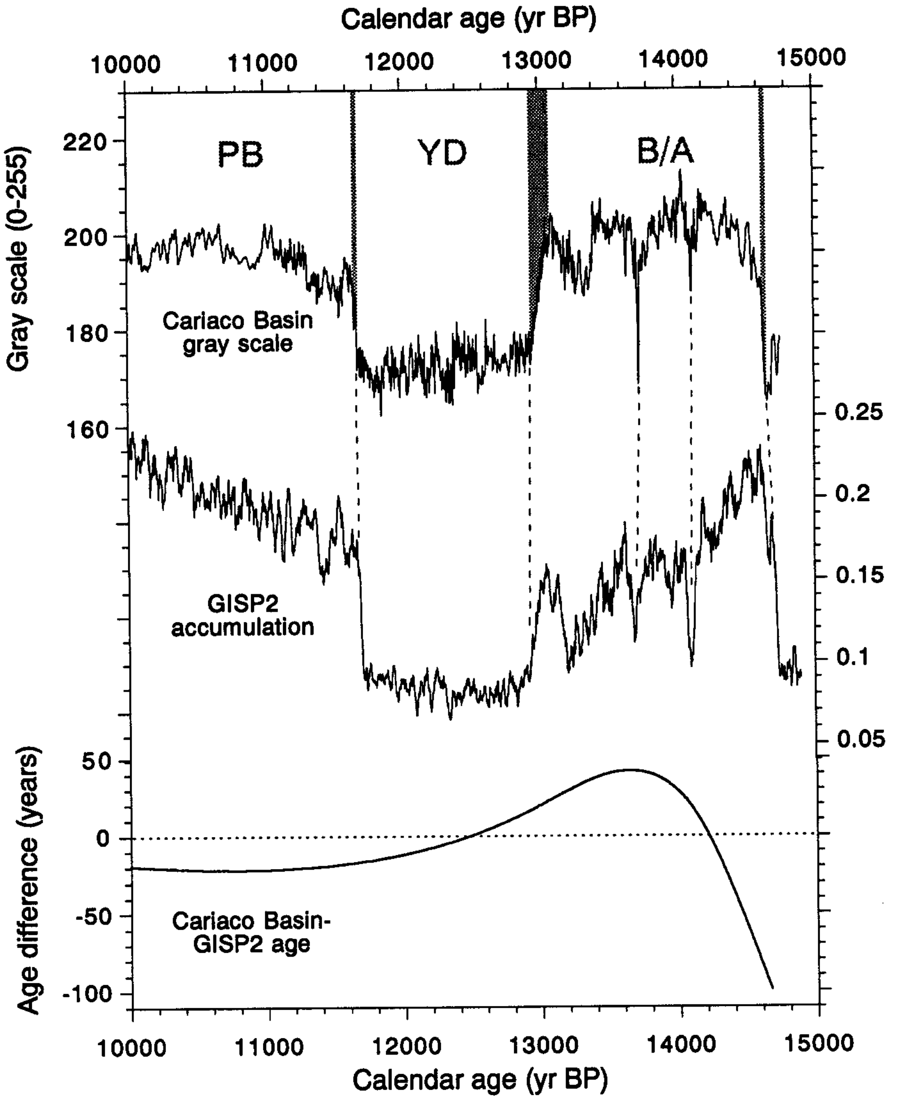

Fig. 3. Comparison of high-resolution paleoclimate records from Cariaco Basin and GISP2 Greenland ice core. Upper curve is Cariaco Basin gray scale. Shaded lines drawn from gray scale record indicate timing and durations of paleoclimate event transitions. PB, YD, B/A as in Figure 2. Center curve is GISP2 annual ice accumulation (Alley *et al.* 1993). Dashed lines from GISP2 to Cariaco Basin record indicate major climatic events used to constrain correlation of the two records. This correlation was used to quantitatively compare the two independent chronologies. Lower curve shows the age difference as a function of time. The chronologies mostly agree within 20 yr, and only differ by as much as 100 yr toward the beginning of deglaciation.

^{14}C CHRONOLOGY

Sample Reproducibility

In addition to possessing an accurate annual varve chronology, the Cariaco Basin sediments are also well suited for reliable ^{14}C dating. The high sediment deposition rate and concentration of foraminifera provide high-resolution ^{14}C sampling (10–15 varve years per ^{14}C date, with no mixing artifacts from bioturbation), at closely spaced intervals (one ^{14}C date every ~100 varve years). To test whether ^{14}C dates thus obtained could be reproduced, ^{14}C ages from cores PL07-56PC and -39PC are plotted together in Figure 2. Calendar ages for the two cores were assigned using detailed cross-correlations with individual millimeter-scale "marker" laminae and high-resolution gray scale records. The ^{14}C dates for both cores show close agreement, demonstrating that Cariaco Basin ^{14}C dates are reproducible and that ^{14}C and calendar ages from one core can be readily applied to other cores from the basin.

Reservoir Age

The ocean reservoir stores vastly more carbon than the atmosphere, particularly in deep waters. Depending on the rate of mixing from below, the surface ocean typically has ^{14}C ages 400–1600 yr older than the atmosphere, reflecting the marine reservoir age (Broecker and Peng 1982; Stuiver *et al.* 1986; Ingram and Southon 1996). In any ^{14}C-dated marine sediment record, the magnitude and stability of reservoir age with time is an important issue. The present-day Cariaco Basin reservoir age has been measured on two sediment samples of known recent age and averages 420 yr (Hughen *et al.* 1996a). This age is close to the open-ocean surface Atlantic value, despite the fact that the basin experiences variable seasonal upwelling. The good agreement with the open-ocean reservoir age is probably related to basin bathymetry. Shallow sills surrounding the basin limit entry to waters less than 146 m deep that are well equilibrated with the atmosphere. Furthermore, tritium profiles (Holman and Rooth 1990) as well as δ^{13}C and ΣCO_2 profiles (Deuser 1973) within the Cariaco Basin indicate the presence of continual mid-depth ventilation with Caribbean Sea thermocline water and an estimated residence time of *ca.* 100 yr. Thus, only "young" water is ultimately available within the basin to replace surface water advected offshore during Ekman drift-induced upwelling.

The reliability of Cariaco Basin ^{14}C dates also depends on the stability of the reservoir age through time. Bard *et al.* (1994) used the Vedde volcanic ash layer (~10.3 ^{14}C ka BP on land) to identify terrestrial and North Atlantic marine sediments deposited at the same time, and showed that, on average, high-latitude ^{14}C reservoir age increased during the Younger Dryas relative to the present value by *ca.* 300–400 yr. This was due to reduced northward advection of young, well-equilibrated surface waters into the high-latitude North Atlantic, together with increased sea ice, which isolated surface waters from the atmosphere and allowed a greater proportion of upward mixing of old, deep waters. However, this effect was probably limited to high latitudes and would not have affected the Cariaco Basin. At low latitudes, reservoir ages are less variable, due to a well-ventilated thermocline (Slowey and Curry 1992) and the lack of sea ice to act as a barrier to the atmosphere.

Direct evidence for a stable Cariaco Basin reservoir age through time is seen in the close match between tree-ring and Cariaco Basin ^{14}C ages from 10.0 to 11.8 cal ka BP (Fig. 4). The reservoir age remains the same, within errors, during a period of almost 2000 yr. More importantly, the reservoir age remains constant across the large change in upwelling at the Younger Dryas termination. This climate shift, representing one of the largest transitions in the Cariaco Basin record between periods of intense and reduced upwelling, occurred in less than a decade (Hughen *et al.* 1996b). Cariaco Basin ^{14}C dates overlap with the tree-ring ^{14}C record immediately prior to the Younger Dryas–Preboreal transition (Figs. 2 and 4). If variable upwelling had influenced reservoir age, we would expect to see it here. However, there is no discernible shift to older ^{14}C ages in Cariaco Basin dates during the Younger Dryas. In addition, high-resolution series of ^{14}C dates from terrestrial macrofossils have been measured from Lake Krakenes, Norway (H. Birks, personal communication) and Lake Madtjärn, Sweden (S. Björck, personal communication). The Lake Krakenes and Lake Madtjärn records can be correlated to the Cariaco Basin at sediment transitions bracketing the Younger Dryas, clearly discernible in both records. The Cariaco Basin ^{14}C ages show no offset from the ter-

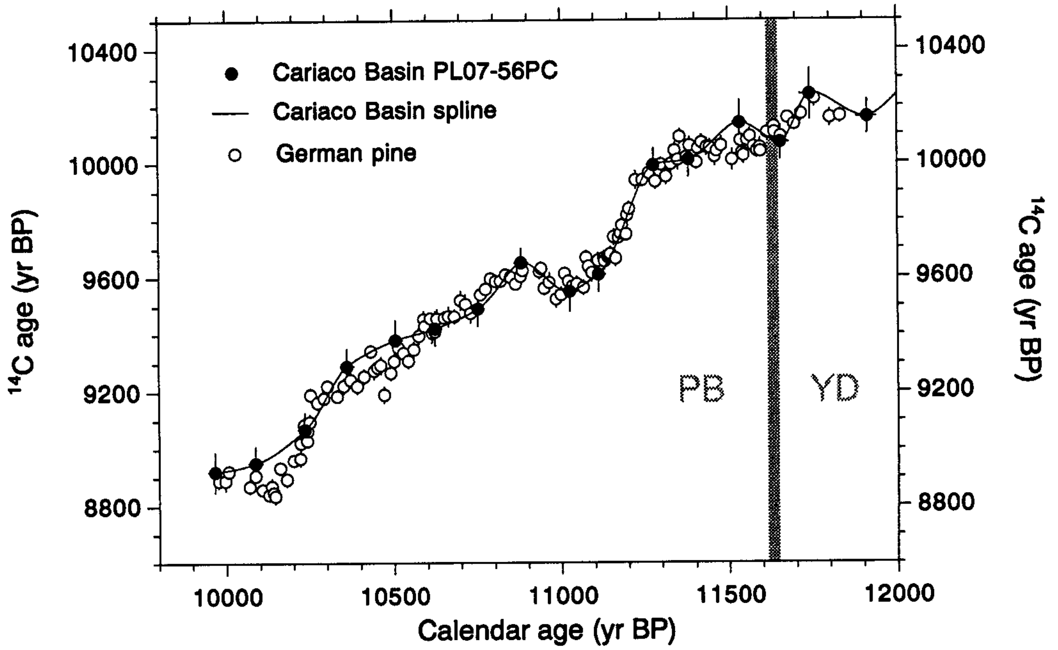

Fig. 4. Interpolation spline (Stineman 1980) used to provide continuous calibration curve from Cariaco Basin core PL07-56PC data set, compared to data from German pines (B. Kromer, personal communication); PB, YD and shaded line as in Figures 2 and 3. Correlation between spline and German pine data is excellent ($r = 0.99$). Cariaco Basin dates that overlap with tree rings and bracket the abrupt shift from intense to reduced upwelling at the Younger Dryas termination show no systematic increase in ^{14}C ages during the Younger Dryas. All ^{14}C errors are reported at 1σ.

restrial ^{14}C dates throughout the Younger Dryas and during the late Allerød period. The weight of evidence clearly supports the conclusion that the Cariaco Basin reservoir age reflects open Atlantic values, and has not changed significantly through time due to variations in local upwelling.

CALIBRATION

Fitted Spline

The evaluation of both Cariaco Basin varve and ^{14}C chronologies provides independent evidence that the chronologies are accurate and can be used as an alternative data set for ^{14}C calibration during the period of deglaciation. In order to provide continuous calibration coverage, an interpolation spline (Stineman 1980) was fitted to the Cariaco Basin data set (Figs. 4 and 5). This spline was chosen over other possibilities (for instance, cubic spline, linear interpolation) for several reasons. First, the spline approximates a linear interpolation between points, which is a simple interpretation and avoids the risk common to cubic splines of creating structure beyond the resolution of the data. Second, the spline has the advantage over a linear interpolation of providing a continuous curve which passes smoothly through the data points. The interpolation spline shows excellent agreement with the German pine data ($r = 0.99$) and preserves detailed century-scale variability, for example during the Preboreal period, *ca.* 9.6 ^{14}C ka BP (Fig. 4).

The interpolation spline was used to create a curve through the entire Cariaco Basin data set to extend continuous ^{14}C calibration from 9.0 to 12.7 ^{14}C ka BP. This represents an objective treatment of the calibration in that no Cariaco Basin data points are excluded, and the same interpolation procedure used to match the curve to tree rings is used to extend the curve further back in time. The full

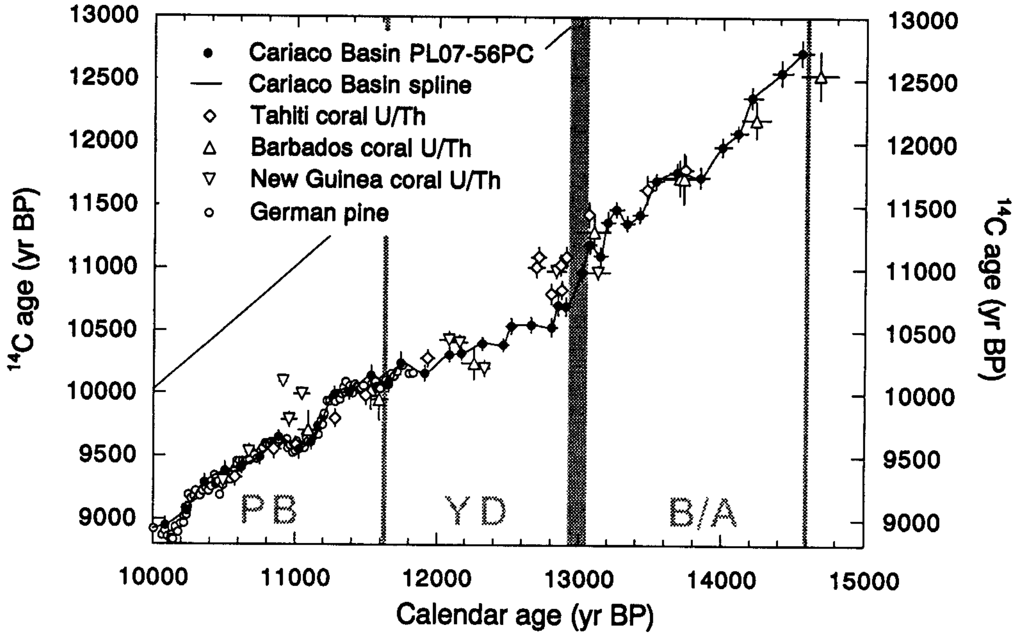

Fig. 5. Interpolation spline extended through all of the Cariaco Basin data set and compared to coral ^{14}C-U/Th data from Tahiti (Bard *et al.* 1996), Barbados (Bard *et al.* 1993) and New Guinea (Edwards *et al.* 1993). PB, YD, B/A and shaded lines as in Figures 2 and 3. Cariaco Basin curve shows close agreement with German pine data from 10–12 cal ka BP, and general agreement with coral data older than 12 cal ka BP. Cariaco Basin data set resolves considerable detail that is not resolved by the coral data, including plateaus at 11.7 and 11.4 ^{14}C ka BP, and century-scale structure imposed on a gradually-sloping "plateau" during the Younger Dryas. All ^{14}C errors reported at 1σ.

Cariaco Basin calibration spline is plotted together with paired ^{14}C-U/Th dates from Atlantic (Bard *et al.* 1990) and Pacific corals (Edwards *et al.* 1993; Bard *et al.* 1996), and agrees in general with corals throughout most of the record (Fig. 5). However, the data sets do show some large differences, particularly during the Preboreal and Younger Dryas periods. The Cariaco Basin data set shows less scatter around the tree-ring data than corals (Fig. 5), suggesting greater reliability during the earlier period as well. The Cariaco Basin data also provide greater resolution and bridge the numerous gaps in the coral data. The new Cariaco curve resolves detailed changes prior to the 9.6 ^{14}C ka BP plateau, including the precise timing of the beginning and end of a long sloping "plateau" with superimposed century-scale structure during the Younger Dryas. In addition, there are plateaus at 11.7 and 11.4 ^{14}C ka BP, and the possibility of a brief plateau or reversal immediately preceding the Younger Dryas at 11.1 ^{14}C ka BP.

Identifying features such as plateaus in the ^{14}C calibration curve, and determining their relationships to abrupt climatic events occurring at the same time, is crucial for a wide range of paleoenvironmental studies. Calculating rates of change or sedimentation rates in ^{14}C-dated sediment cores depends greatly on whether, and how, the ^{14}C dates are calibrated. For example, a sediment age-depth curve based on uncalibrated ^{14}C dates will introduce error into rate-of-change and proxy flux calculations. A linear age-depth model that uses uncalibrated ^{14}C ages (upper curve, Fig. 6a) will change significantly when those ^{14}C ages are calibrated (lower curve, Fig. 6a). Using uncalibrated ^{14}C ages to calculate sedimentation rates creates large anomalies, artificially increasing values during plateaus when the ^{14}C "clock" is running more slowly than calendar time, and decreasing values when ^{14}C is running faster (Fig. 6b). Uncalibrated ^{14}C chronologies can result in substantial, abrupt changes in sedimentation rate (and rate of change) calculations that coincide with, but do not necessarily relate

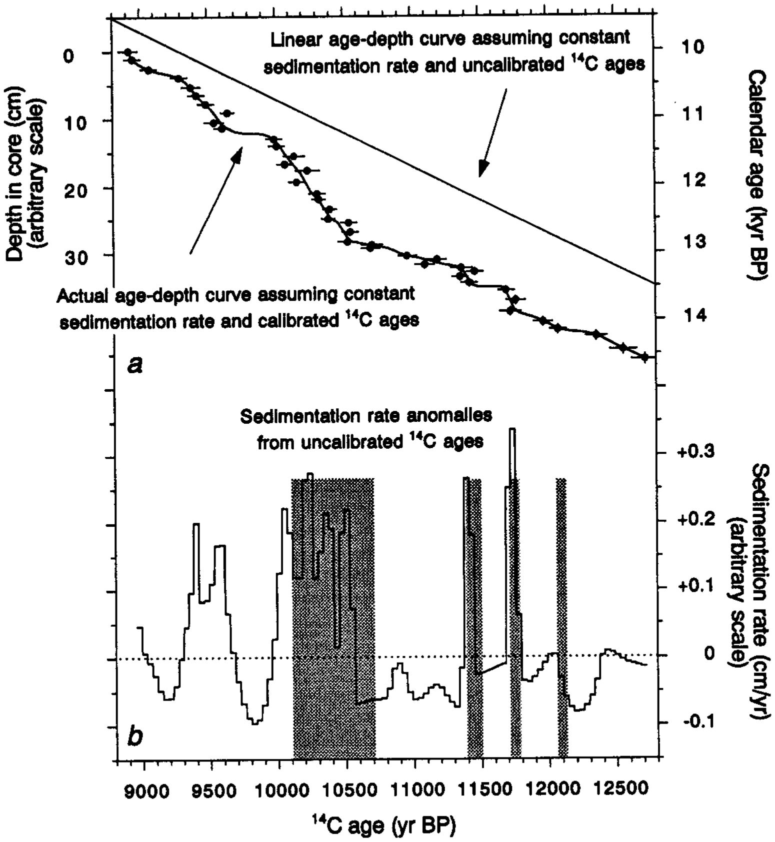

Fig. 6. Modeled age-depth curves and sedimentation rate calculations (for a hypothetical core) resulting from calibrated *vs.* uncalibrated ^{14}C ages. *(a)* Upper curve, linear age-depth curve based on constant sedimentation rate and using uncalibrated ^{14}C ages (assumed to equal calendar age). Lower curve, age-depth curve based on constant sedimentation rate and using calibrated ^{14}C ages. Detailed structure and large divergences from linear age-depth model result from using calibrated ^{14}C age-depth model. *(b)* Sedimentation rate anomalies resulting from differences between upper and lower curves in a above. Periods when ^{14}C age changes slower than calendar age (^{14}C plateaus) result in significant positive anomalies in sedimentation rate. Conversely, periods of rapid ^{14}C change result in negative anomalies. Dashed line indicates "background" sedimentation rate resulting from linear age-depth curve. Timing of Younger Dryas and century-scale climatic events during the Bølling/Allerød intervals (defined using Cariaco Basin gray scale) are indicated by shaded rectangles. The timing of sedimentation rate anomalies resulting solely from lack of ^{14}C calibration is very similar to the timing of true paleoclimatic events. All ^{14}C errors reported at 1σ.

to, paleoclimate change. For example, the large, sloping ^{14}C "plateau" from 10 to 10.6 ^{14}C ka BP and smaller plateaus at 11.4 and 11.7 ^{14}C ka BP defined by the Cariaco Basin data occur close to the timing of the climatic Younger Dryas and century-scale cold events during the Bølling/Allerød, respectively (Fig. 6b). Several previous studies have investigated rates of environmental change during the last deglaciation, and show increased rates of change occurring *ca.* 10–11 ^{14}C ka BP, as well as smaller events before this time (Jacobson, Webb and Grimm 1987; Overpeck 1987; Overpeck, Bartlein and Webb 1991). As suggested here, however, at least a part of these signals may be artifacts resulting from the lack of accurate ^{14}C calibration. Ironically, this problem appears to be compounded by high-resolution sampling for ^{14}C dating, as a limited number of ^{14}C dates will tend to smooth over the sharp bends in the calibration curve and thus produce a smaller, smoothed anomaly during the Younger Dryas.

CALIBRATION PROGRAM

The new ^{14}C calibration data set from the Cariaco Basin is available online for use as an alternative deglacial calibration beyond tree-ring based calibrations. The data are available in a look-up table and program for converting files of ^{14}C dates to calendar dates at http://www.ngdc.noaa.gov/paleo/paleo.html. Details of the program and its use are available at this site as well. The Cariaco Basin spline data are presented at decade resolution for ease of calculation on the part of the user, because ^{14}C dates are typically reported to the nearest decade. However, it should be noted that the resolution of the actual calibration data is *ca.* one date per 100 yr and does not resolve decade-scale changes in Δ^{14}C that may have occurred. The Cariaco Basin calibration is intended to serve as a higher-resolution alternative to curves based on coral ^{14}C–U/Th dates during deglaciation (11.5–14.5 cal ka BP), and as a complement to longer curves based on corals that extend back to 30 cal ka BP.

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