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Evaluation of an Apparent Late Pleistocene (25–40 ka BP) Sea Level High Stand: An Artifact of a Greatly Enhanced Cosmic Ray Flux of ~60 ka BP

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ABSTRACT

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Certain marine deposits found along the Atlantic coast of the southeastern United States and dated by the radiocarbon method from 25 ka to 40 ka BP may have actually been deposited at 60±2 ka BP. The radiocarbon dates on these deposits as a population are not greatly affected by contamination as is commonly thought. Instead, their apparent juvenile nature may have resulted from the earth being subjected to a greatly enhanced cosmic ray flux which produced greater than normal amounts of ^{10}Be and ^{14}C. ^{10}Be concentration anomalies are present in polar ice cores whereas ^{14}C enhancement is reflected by comparing published radiocarbon apparent ages to corresponding ages determined by amino acid racemization, thermoluminescence, or uranium disequilibrium series methods. Numerical modeling of the ^{14}C budget suggests a cosmic ray flux enhancement beginning about 60 ka BP, lasting for 200 to 400 years and having an intensity of 150 to 250 times that of the modern flux. This discovery could resolve a long-standing debate on the chronology of sea level changes during the mid- to late Wisconsin.

ADDITIONAL INDEX WORDS: *Radiocarbon dating, U.S. southeast Atlantic coastal plain.*

INTRODUCTION

Along the Atlantic coast of the United States are found several strandline deposits at or near the elevation of modern mean sea level which date by the radiocarbon method from 25 to 40 ka BP (Table 1). In addition to these, dredge haul samples from shelf areas have produced samples suggesting an apparent high stand from 25 to 40 ka BP (MACINTYRE *et al.*, 1975, 1978; SCHRODER and SHULTZ, 1993). The existence of these 'younger' than expected deposits have been discussed and debated for a number of years (CURRAY, 1960; BROECKER, 1965; FAIRBRIDGE, 1971; EMERY and MILLIMAN, 1971; EMERY and UCHUPI, 1972; THOM, 1973; BELKNAP and KRAFT, 1977; FIELD *et al.*, 1979; BLOOM, 1983; COLMAN *et al.*, 1989; TOSCANO, 1989; FINKELSTEIN and KEARNEY, 1988, 1989). The chief problem is that the above noted sites and samples indicate sea level standing at a higher elevation than is indicated by the oxygen isotope based sea level curve (Figure 1).

The general explanation for the apparent juvenile nature of these dates is that the samples were contaminated with young carbon by various means prior to laboratory analysis. Contamination could have occurred by *in situ* cementation with calcite or calcitization of aragonite in association with ground water, growth of roots of younger plants within the sediment, growth of fungus upon recently collected peat samples, or the accidental mixing of collected material with some younger carbon source. The contamination problem is well discussed in the literature (GEYH and SCHLEICHER, 1990; GROOTES, 1983). The general theme of the contamination hypothesis is that if material from the last widely accepted high stand of approximately 125 ka BP were to have rendered an apparent radiocarbon age of 25 to 40 ka BP, this could have resulted from contamination by as little as one to four percent modern carbon. Modern carbon refers here to carbon that has been in isotopic equilibrium with the atmospheric carbon reservoir sometime in the last 200 years, and thus has a mean apparent radiocarbon age of <200 yr BP. For the radiocarbon method to provide accurate age determinations, the sample must remain in a system that is closed to carbon from the time it is formed until the time it is assayed. Should the system be open to carbon, then the

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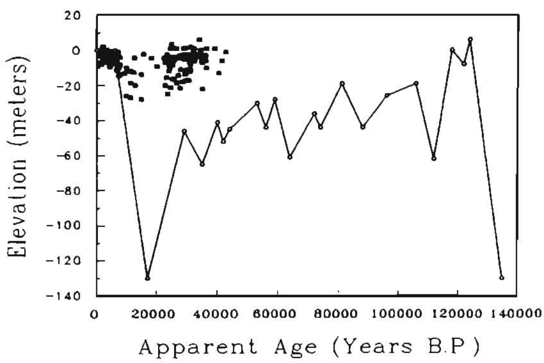

Figure 1. Elevation relative to modern mean sea level of published radiocarbon-dated marine deposits from onshore areas of the Atlantic coast of the United States. Only a partial posting has been made for dates younger than 4,000 years BP. Reference curve (solid line) is the oxygen isotope-based sea-level curve extracted from CHAPPELL and SHACKLETON (1986).

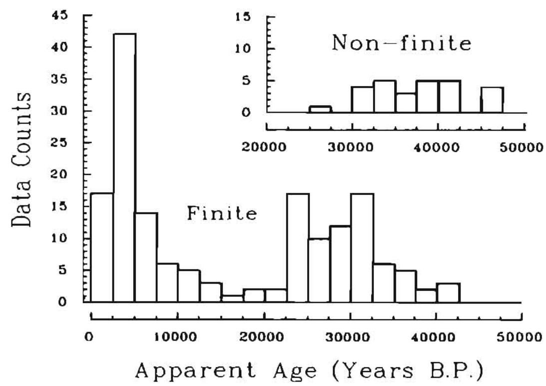

Figure 2. Distribution of finite and non-finite radiocarbon dates from marine deposits of the Atlantic coastal plain of the southeastern United States. Finite dates posted at their median age; non-finite dates posted at their minimum age. Incomplete posting of dates less than 2 ka BP.

prospective samples may become contaminated with modern or younger carbon to varying degrees. A suite of samples taken from this open system will exhibit apparent ages ranging from the youngest, which is the most contaminated, to the oldest or least contaminated. The frequency distribution of apparent ages from an open situation should be characterized by a smooth exponential decrease toward the date of the contaminating carbon and with the maximal or modal value still being the true but uncalibrated radiocarbon date.

The distribution of apparent radiocarbon ages from the deposits of the southeastern United States (Figure 2) does not follow this predicted pattern for the contamination hypothesis. If the absolute age of these deposits is in the range of 100 to 125 ka BP, as is suggested by the isotope-based sea level curves, and if contamination is the sole or dominant process affecting these dates, then the number of finite apparent dates in the range of 22 to 40 ka BP should be much less than the number of nonfinite dates, where the nonfinite dates represent those samples with less contamination or no contamination at all, but of an age beyond the range of the dating method employed. The population of dates in Figure 2 suggests that the bulk of the samples actually date from this approximate period, 25 to 40 ka BP, and are not significantly contaminated by younger carbon. A further argument against the contamination hypothesis is that in the case of the majority of the samples noted in Table 1, they were collected via coring below modern salt marsh sediments. These samples were buried by anywhere from 4 to 10 meters of saltmarsh-estuarine-marine sediments which date from 4 ka BP to in some cases at least 15 ka BP and thus were not in contact with a younger atmosphere for a span of time equal to one to three radiocarbon half lives. If these samples were truly from 125 ka BP, then the required contamination levels would be two, three, or four times that noted above for contamination by strictly modern carbon. Contamination of such a degree would be rather easy to recognize, suggesting that few of these samples were significantly contaminated. This still does not preclude the possibility that one or more of the samples in the population are actually contaminated. The conclusion that one must draw is that contamination did not significantly affect the sample population as a whole and that if the oxygen isotope based sea level curve is accurate and representative of the area in which the samples were collected, then some other process besides contamination has affected the apparent ages of the samples.

The only other inference that may rectify the conflict between the apparent ages of these samples and the sea level curve is that the rate of ^{14}C production in the past has not been constant as was assumed by Libby when the method was con-

Table 1. *Sites within the Southeastern Coastal Plain of the U.S. where radiocarbon dates indicate a sea level high stand near Modern Mean Sea Level (MMSL) at 24 ka to 40 ka.*

General Location	Elevation Relative to Modern Mean Sea Level	Number of Dates in the Range 22,000 to 40,000 yr BP*	References
Southeastern Delaware 38.5N, 75.1W	+5 to −1 m	2 (4)	JORDAN (1974)
Assateague Is., Maryland 38.0N, 75.3W	−1 to −2 m	2 (1)	OWENS and DENNY (1979)
Delmarva Peninsula, Virginia 37.2N, 75.9W	−2.5 to −4.55 m	10 (2)	FINKELSTEIN and KEARNEY (1988)
Roanoke Is., North Carolina 35.9N, 75.6W	−6 to −7 m	2 (?)	RIGGS and O'CONNOR (1974)
Cape Lookout North Carolina 35.3N, 76.5W	−3.5 to −21.9 m	16 (11)	SUSMAN and HERON (1979), BERELSON (1979), HERBERT (1978), MIXON and PILKEY (1976), MOSLOW (1977), STEELE (1980)
Permuda Is., North Carolina 34.5N, 77.6W	−3 to −4 m	2 (0)	CLARK *et al.* (1986)
Cape Fear North Carolina 33.9N, 77.9W	+1 to −4.5 m	9 (2)	DOCKAL (1992, 1993), WHITEHEAD and DOYLE (1969), ZULLO (*personal communication*), CLEARY (*personal communication*)
Myrtle Beach, South Carolina 33.8N, 78.9W	+1 m	2 (4)	DUBAR *et al.* (1974)
Cape Roman, South Carolina 33.0N, 79.4W	−4.65 to 4.75 m	1 (0)	ECKARD *et al.* (1986)
Charleston, South Carolina 32.5N, 80.0W	−3.2 to −11.9 m	5 (1)	MOSLOW (1980)
Sapelo Is., Georgia 31.5N, 81.2W	−1 to −10 m	7 (6)	HAILS and HOYT (1968), HOYT *et al.* (1965), HOYT *et al.* (1966)
Cape Canaveral, Florida 28.4N, 80.6W	−8.3 to −25 m	2 (0)	FIELD (1974)
Apalachicola, Florida 29.8N, 85.0W	−4 to −10 m	11 (4)	SCHNABLE and GOODELL (1968)

*Number of non-finite dates in parentheses

ceived (LIBBY, 1955). Variations in ^{14}C production rate have been noted in conjunction with solar processes and variations in the magnetic field of the earth (DAMON *et al.*, 1978; GROOTES, 1983; BARBETTI, 1986). However, the magnitude of these variations is not sufficient to resolve the problem of apparent ages being too young by as much as 20 to 70 ka.

Analysis of ^{10}Be content of ice cores from Greenland and Antarctica may have shed some light on this problem. ^{14}C and ^{10}Be share a common origin; namely both are formed by the interaction of cosmic rays with elements of the upper atmosphere. Analysis of the published ice core data revealed one or more spikes in the concentration of ^{10}Be corresponding to dates of approximately 60 ka BP and 35 ka BP based on their relative position in the ice cores (BEER *et al.*, 1988, 1992; RAISBECK *et al.*, 1987; REEH *et al.*, 1991; YIOU *et al.*, 1985). These ^{10}Be spikes may indicate periods of time when the earth's atmosphere was subjected to an enhanced cosmic ray flux due to the passage of the solar system through a shock wave of a supernova (KOCHAROV, 1990; 1991a; 1991b; SONETT *et al.*, 1987; SONETT, 1991). If such an event could produce elevated amounts of ^{10}Be, then one must also presume that the enhanced cosmic ray flux could generate greater than normal amounts of ^{14}C. This implies that carbon samples accumulated during the event, and for a time thereafter, would have presented future apparent ages at the time of their formation and would today give apparent ages younger than their absolute age. The objective of the remainder of this paper is to explore the possibility and ramifications of this phenomena as it relates to late Wisconsin sea level changes. Throughout this paper all radiocarbon ages will be reported as conventional radiocarbon ages based on the Libby half-life of 5568 years for ^{14}C.

MODEL AND SUPPORTING DATA

The process begins with the collapse of a large star (*i.e.*, > 3 solar masses) and the resulting explosion or supernova. This produces a shock wave or disturbance which propagates at great velocity away from the site of the explosion (TRIMBLE, 1983; WEILER and SRAMEK, 1988). With time, the velocity and intensity of the shock or supernova remnant diminishes. The disturbance caused by the shock wave is thought to produce cosmic rays (TRIMBLE, 1983). COX and ANDERSON (1982) suggested that the solar system was now within a supernova remnant formed by an event $\sim 10^6$ years BP. GEHRELS and CHEN (1993) report that the solar system lies at the edge of the remnant from the Geminga supernova dating from again $\sim 10^5$ years BP. When the solar system passes through such a shock, it is subjected to an enhanced cosmic ray flux. The cosmic rays interact in the atmosphere of the earth to produce a suite of cosmogenic radionuclides including ^{14}C and ^{10}Be. Changes in the cosmic ray flux should produce proportional changes in production rates of both nuclides. The production and distribution of ^{10}Be has been reviewed by MCHARGUE and DAMON (1991) and that of ^{14}C by DAMON *et al.*, (1978). ^{10}Be, once produced, is brought down to the surface by precipitation. ^{10}Be has a residence time of less than 2 years in the atmosphere (GEYH and SCHLEICHER, 1990). At the surface it is mixed within the soils, joins the glacial ice column, or enters the oceans where it may have a residence time of 750 years (MCHARGUE and DAMON, 1991) before entering the sediment column.

^{14}C, once formed, reacts quickly with oxygen to produce carbon dioxide, which remains within the atmosphere until it is incorporated within some living tissue or enters the oceans as dissolved carbon dioxide or dissolved bicarbonate. Unlike ^{10}Be, ^{14}C remains as an active component of the atmosphere, biosphere, and hydrosphere with only small amounts entering the sediment column. If the cosmic ray flux is constant for a long period of time, *e.g.*, more than several half lives of ^{14}C, then the concentrations in the atmosphere, biosphere, and oceans should also be constant, predictable, but not necessarily equal. Variations in concentration among these three reservoirs results from the fact that ^{14}C forms in the atmosphere and then later enters the biosphere or oceans. The carbon in these other reservoirs is older appearing than the coeval atmosphere carbon. The degree of oldness in appearance or 'reservoir effect' is related to the rate of exchange between each reservoir. During periods of changing cosmic ray flux the reservoir effect is magnified. As the solar system enters a supernova shock wave the cosmic ray flux increases rapidly, thereby increasing the production rate of ^{14}C. The concentrations of ^{14}C in the reservoirs change with the atmosphere experiencing the greatest increase; the biosphere has a similar but slightly less increase than the atmosphere and the oceans an even smaller increase.

This can be simulated numerically by using a two-box carbon system where the atmosphere and biosphere reservoirs form one subsystem of the carbon system and the oceans the other subsystem. The amount of carbon in the oceans is approximately 17 times that of the combined atmosphere and biosphere (see LIBBY, 1955 or BERNER and BERNER, 1987). The apparent radiocarbon age of modern ocean water is about 900 to 1000 years BP (see BRADLEY, Figure 3.6, p. 58, 1985). This, coupled with the decay rate of ^{14}C and the assumptions that the amount of loss of ^{14}C to the sediment column is not significant, the ventilation rate of the oceans is constant, and that the amount of carbon in both subsystems is constant, allows for an approximation of the exchange rate of carbon between the two subsystems. With these assumptions, it is then a simple matter of keeping account of how much ^{14}C enters the system and how it distributed between the two subsystems while at the same time allowing for decay. One can then track the variations in ^{14}C concentration during periods of enhanced ^{14}C production rate. Since the apparent age is proportional to concentration of ^{14}C in a sample, it is possible to model the effect of a cosmic ray enhancement on the apparent ages of carbon samples (Figure 3). A brief period of cosmic ray flux enhancement creates a spike in the apparent age versus absolute age curve. If the time of initiation of the flux enhancement is known as well as its intensity relative to the normal or modern flux and the duration, then it is a simple matter to predict the calibration needed to correct apparent ages to their absolute value. However, these values

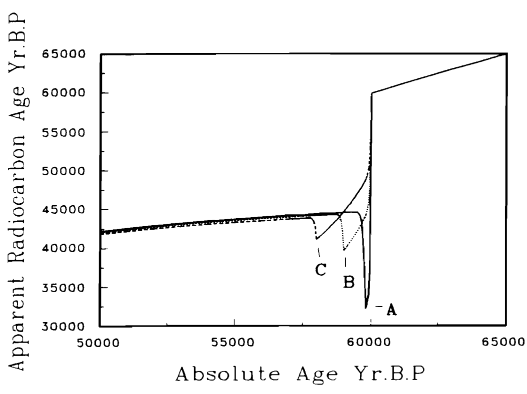

Figure 3. Model prediction of the variation in apparent radiocarbon age and absolute age due to cosmic ray enhancement. For all three model predictions carbon mass of the ocean subsystem was 17 times that of the combined atmosphere and biosphere; mean ocean age was 900 years, and enhancement began at 60 ka BP. Curve (A) the enhancement had an intensity of 250 times the modern flux and lasted for 200 years. Curve (B) is for an intensity of 50 times and a duration of 1000 years. Curve (C) is for an intensity of 25 times and a duration of 2000 years.

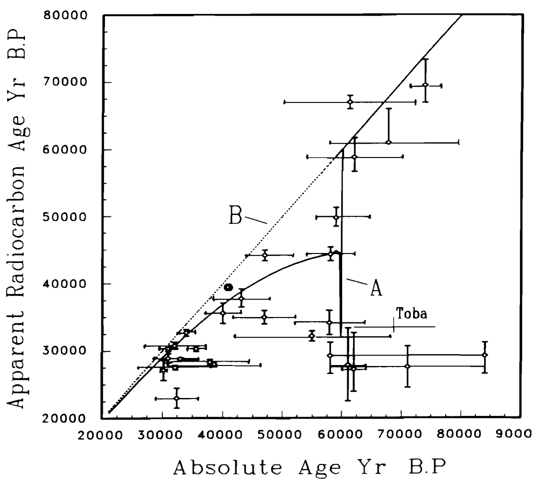

Figure 4. Plot of published radiocarbon dates versus corresponding or absolute dates. Curve (A) represents the model predicted date deviations assuming a cosmic ray flux enhancement initiated at 60 ka BP which lasted for 200 years and had a mean intensity of 250 times the modern cosmic ray flux (curve 'A' of Figure 3). For curve (B) apparent radiocarbon age equals the absolute age. Error bars are posted as published for single dates. For multiple corresponding dates a weighted mean was calculated and for multiple radiocarbon dates the entire range was posted. Situations with corresponding ages less than 30 ka BP are not posted. Sources listed in Table 2.

are not directly ascertainable since neither ice cores nor deep sea sediments retain a complete and uniform record of the cosmogenic nuclide flux. To evaluate these values one must turn to the scant published record where radiocarbon dating has been accompanied by some other dating method such as uranium disequilibrium series, thermoluminescence, amino acid racemization, or correlation to the oxygen isotope curve, (Table 2 and Figure 4). The results of the other methods, referred to hereafter as corresponding dates, will be assumed to reflect absolute time.

DISCUSSION

Radiocarbon dates beyond 60 ka are rare largely due to the difficulty of the measurement process and the few laboratories that are able to conduct such measurements. Of the three dates found from an extensive literature search, all had a reasonable correlation to their corresponding date (Figure 4). Dates between 35 and 60 ka have widely varying corresponding dates. Those between 25 and 35 ka have corresponding dates close to that of the radiocarbon date or a corresponding date in the range of 55 to 70 ka. Dual-dated material younger than 25 ka has not been evaluated here but has been evaluated by Bard *et al.*, (1993).

It would appear from the cited apparent and corresponding dates that an enhancement in the cosmic ray flux occurred at 60±2 ka BP. Prior to this time, there is reasonable agreement between the apparent ^{14}C ages and their corresponding or "absolute" ages; afterwards there is sizable disagreement. This is in agreement with the ^{10}Be concentrations of the Vostok ice core. Direct evaluation of the duration of the event from the ^{14}C record is more speculative. Samples with the greatest deviation between their apparent ^{14}C ages and the corresponding ages cluster around 60 ka. The mutual overlap of the error bars of the corresponding dates suggesting a duration time of 2 to 3 ka. The duration and the average intensity increase relative to modern cosmic ray flux intensity can be estimated indirectly by examining the difference between the ^{14}C apparent dates and corresponding dates for the time period after the expected enhancement event. That difference is proportional to the excess amount of ^{14}C in the carbon system of the earth where the excess ^{14}C is equal to the product of the duration of the event

Table 2. *Radiocarbon dates with corresponding dates determined by some other method for the time period 24 ka to 75 ka.*

No.	Location	Sample Relationship*	^{14}C Apparent Age (yr BP)**	Corresponding Age (yr BP)	Method***	References
1	Grand Pile, France	6	69,500 + 3,800 − 2,600	73,910 ± 2,590	Oxygen isotope curve	WOLILLARD and MOOK (1982), MARTINSON *et al.* (1987)
		6	49,800 + 1,500 − 1,300	58,960 ± 5,560		
2	Pierrevill, Saint Lawrence Lowlands, Canada	3	65,300 ± 1,400 67,000 ± 2,000 74,700 + 2,700 − 2,000	61.2 ± 11 ka 61.1 ± 9.2 ka	TL	OCCHIETTI (1989), LAMOTHE *et al.* (1992)
3	Nelson River, Banks Island, Canadian Arctic	1	>61,000	67,700 + 11,700 − 9,900	$^{230}Th/^{234}U$	VINCENT (1992)
4	British Columbia, Canada	2b	58.8 + 2.9 − 2.1 ka	62 ± 8 ka 62 ± 12 ka	TL	BERGER (1988), CLAGUE (1980)
5	Snows Cut, Cape Fear, North Carolina	2a	24,390 ± 420 26,380 ± 500 29,000 ± 700 32,150 ± 550	57,000 ± 3,000 57,000 ± 4,000 62,000 ± 4,000 65,000 ± 3,000 65,000 ± 4,000 68,000 ± 5,000 73,000 ± 7,000 weighted mean: 62,000 ± 2,000	U-series	DOCKAL (1992, 1993), PROSSER (1993)
6	Delmarva Peninsula, Virginia	5	23,340 ± 770 23,550 ± 370 25,700 ± 650 26,960 ± 320 27,980 ± 1,510 28,930 ± 580 29,390 ± 490 30,540 ± 520 30,870 ± 470 33,940 ± 530	61,000 ± 3,000	U-series	FINKELSTEIN and KEARNEY (1988), MIXON (1985), MIXON *et al.* (1982)
7	Cape Henry and Roanoak Island, Northeastern North Carolina and Southeastern Virginia	5?	non specified number of dates 24,560 to 30,660	9 dates, 62 ± 4 ka to 79 ± 5 ka weighted mean: 71 ± 5 ka	$^{230}Th/^{234}U$	SZABO (1985), RIGGS and O'CONNOR (1974)
				3 dates, 69 ± 11 ka to 73 ± 13 ka	^{231}Pa	
				3 dates on sediments enclosing above: 76 ± 28 ka	U-series	

Table 2. *Continued.*

No.	Location	Sample Relation-ship*	^{14}C Apparent Age (yr BP)**	Corresponding Age (yr BP)	Method***	References
8	Shackleford Banks, North Carolina	2b	29,280 + 2,000 − 2,680	Greater than 62 ± 4 ka; but less than 79 ± 5 ka	AAR & U-series	Susman and Heron (1979), Wehmiller *et al.* (1988), Szabo (1985)
9	Nepean River, New South Wales, Australia (Basal Clay)	2a	34,200 ± 1,800	57,880 ± 5,800	TL	Nanson and Young (1987)
	(Basal Gravels)	3	33,590 ± 510 37,100 ± 1,600	47,000 ± 5,200	TL	
	(Upper Gravels)	3	37,750 + 1,500 − 1,250	43,100 ± 4,700	TL	
10	Baffin Island, Canadian Arctic	1	44,400 ± 1,000	58,000 ± 4,000	^{230}Th	Szabo *et al.* (1981)
11	Clear Lake, California	2b		55,000 ± 13,000	AAR	Blunt *et al.* (1981), Adam *et al.* (1981)
	core depth = 7,955 cm		32,200 ± 750			
	core depth = 8,010 cm					
12	Camp Breton Island, Bay of St. Lawrence, Nova Scotia	2a	44,200 ± 800	47 + 4.7 − 4.3 ka	$^{230}Th/^{234}U$	Mott (1989), Causse and Hillaire-Marcel (1986)
13	Reef III, Huon Peninsula, New Guinea	2a	35.4 ± 1.4 35.8 ± 1.6	35 ± 3 ka 42 ± 3 ka 42 ± 3 ka 42 ± 3 ka weighted mean: 40 ± 3 ka	$^{230}Th/^{234}U$	Barbetti (1986), Bloom *et al.* (1974), Chappell (1974), Chappell and Veeh (1978)
14	Worth Point, Banks Island, Canadian Arctic		>35,000 41,090 ± 770	40,900 + 300 − 500	TL	Vincent (1992)
15	Reef II, Huon Peninsula, New Guinea	2a	28.5 ± 0.6 ka 29.3 ± 0.8 ka	31.0 ± 2.5 ka	TL	Barbetti (1986), Chappell (1974), Chappell and Veeh (1978)
16	Dolni Vestonice, Czechoslovakia	2a	28,300 ± 300 29,000 ± 200	33,000 ± 3,000	TL	Barbetti (1986), Barbetti and Flude (1979)
17	Lake Mungo, Australia (several different fire pits)	1	30,780 ± 520	29,500 ± 4,100 31,300 ± 5,600 35,300 ± 5,600	TL	Barbetti (1986), Barbetti and Polach (1973), Barbetti and Flude (1979)
		1	28,310 ± 410	37,900 ± 6,400		
		1	27,530 ± 340	32,000 ± 5,700 32,300 ± 5,800		
		1	28,000 ± 410	38,600 ± 7,700		

Table 2. *Continued.*

No.	Location	Sample Relation-ship*	^{14}C Apparent Age (yr BP)**	Corresponding Age (yr BP)	Method***	References
18	Barbados	1	27,120 ± 1,500	30,040 ± 210 30,470 ± 240	$^{230}Th/^{234}U$	Bard *et al.* (1990)
19	Searles Lake California (alternating beds of salt and mud)	2b			^{231}Th	Peng *et al.* (1978)
			28,600 ± 400			
	(M4 top)		30,200 ± 400			
	(M4 bottom)			31,000 ± 1,500		
	(S3)		30,500 ± 400			
	(M3 top)		30,300 ± 500			
	(M3 bottom)			35,600 ± 1,500		
	(S2)		30,300 ± 300			
	(M2 top)		32,600 ± 500			
	(M2 bottom)			34,000 ± 1,500		
	(S1)		32,800 ± 600			
	(M1 top)					
20	Zhaitang, China	3	23 ± 1.5 ka	32.4 ± 3.5 ka	TL	Lu *et al.* (1987)

*Sample relationships: 1—same sample for both methods; 2a—same site, same bed or feature, but different sample; 2b—same site, different beds or features, 3—same bed or lithologic unit, different but spatially close sites; 4—same lithologic unit but different and removed sites; 5—probably same lithologic unit but different and removed sites; 6—correlation to oxygen isotope curve

**Conventional ages using the Libby half life

***AAR = amino acid racimization; TL = thermoluminescence

Table 3. *^{10}Be concentrations from Vostok, Antarctic Ice Core.*

Sample Designation	Nominal Depth (m)	Sample Length (cm)	Estimated Deposition Interval (yr)	^{10}Be Conc. ($\times 10^{3}$ atoms g^{-1})	Mean ^{10}Be for Level ($\times 10^{3}$ atoms g^{-1})
36?*	900*	25*	21*	162*	
37a**	925	25	21	266 ± 19	269 ± 20
37b(1)**	925	7	6	212 ± 17	
37b(2)**	925	6	5	231 ± 21	
37b(3)**	925	7	6	302 ± 21	
37b(4)**	925	6	5	342 ± 27	
38e(1)**	950	7	6	136 ± 10	139 ± 10
38e(2)**	950	7	6	141 ± 11	
38e(3)**	950	9	8	141 ± 11	

*Extracted from Figure 1 of YIOU *et al.* (1985)
**Copied from Table 1 of RAISBECK *et al.* (1987)

and the average intensity normalized to the modern flux intensity during the event with allowances made for decay. Duration and average intensity enhancement can therefore can be found through iterative solutions of the numerical model where the enhancement is initiated at 60 ka BP, where excess ^{14}C corresponds to those indicated for the absolute age period of 35 to 45 ka and where the enhancement produces a maximum deviation of about 28 to 30 ka at the end of the enhancement. The best solution to the numerical model indicates a duration of 200 to 400 years with a corresponding average intensity enhancement of 250 to 150 times modern cosmic ray flux respectively. That solution is in good agreement with 22 (80%) of the 28 situations noted in Table 2. Two situations, both with thermoluminescence dates, fall well outside the model and four others are close to agreement.

Initiation of the enhancement at 60±2 ka is in agreement with the age of an anomalous ^{10}Be concentration in the Vostok ice core as evaluated by RAISBECK *et al.*, (1987). The duration of the enhancement of 2 to 4 ka, as indicated by the overlap of the corresponding date error bars, is in reasonable agreement with the RAISBECK *et al.*, (1987) interpretation from the ice core data. A duration of 200 to 400 years as derived from iterative solutions of the numerical model does not compare favorably with the RAISBECK *et al.*, (1987) interpretation. However, this may be due to the sampling interval of the Vostok ice core, where a 7 to 25 cm long sample was taken approximately every 25 meters. Individual Vostok samples represent accumulation times of 10 to 30 years while the interval between samples represents a time span of 2000 or more years. Thus the sampling interval could not evaluate an event duration as short as 200 to 400 years. The specific samples of interest from the Vostok core are listed in Table 3. Samples 36? and 38e(1,2,3) are at background levels and indicate that the event is constrained entirely within the interval between them, a time interval of about 5,000 years. Samples 37b(1,2,3,4), if they are reported in objective order as they occurred in the core, indicate an interval of rapidly increasing ^{10}Be concentration. However, it is not clear from RAISBECK *et al.*, (1987) if this is the situation. If not, then they simply represent an interval 25 cm in length with a variable concentration. In either case, Sample 37 does not constrain the apex of the ^{10}Be concentration enhancement; hence, the magnitude of any of the samples in the 37 group or their mean value is in no way proportional to the average enhancement. The enhancement proposed in this study and the elevation above background of Sample 37 of RAISBECK *et al.*, (1987), a value of about 2 to 3 times the modern level are therefore not comparable items.

^{10}Be measurements from a deep ocean core taken in Fram Strait, Greenland Sea (EISENHAUER *et al.*, 1990) may also support the existence of this event. Samples from core depth between 120 and 160 cm provide slightly higher concentrations than the adjacent samples. EISENHAUER *et al.* (1990) gave this segment an approximate age of 50 to 55 ka BP based upon the $^{230}Th_{excess}$ method. Deep ocean sediment data, however, cannot provide any clues to the quantitative nature of this event since they represent a very discontinuous and garbled record of the ^{10}Be flux from the atmosphere due to variable marine flux rates, additional input from melting glaciers, lateral sediment input from turbidity currents, post deposition sediment remobilization, and biologic reworking.

The excess ^{14}C introduced by the cosmic ray enhancement was conservatively estimated based on the age deviations in the time range 35 ka to 55 ka BP. A more liberal estimate would allow for a longer duration of the event. The 200 year duration suggested here should therefore be taken as the minimum possible duration of the event and the 250 times modern cosmic ray flux as the maximum possible enhancement. Variations within reasonable limits of the other factors in the numerical model such as the relative sizes of the two carbon reservoirs or the mean ocean age do not significantly effect the duration and intensities reported here.

Radiocarbon apparent dates in the range of 25 to 40 ka BP present a serious dilemma in their interpretation, for any one such date could represent: (a) an actual date of approximately that time period which has a small error of less than +2 ka, (b) a sample of very old carbon which has been contaminated by a small amount of modern carbon, or (c) a sample dating from ~60 ka which has a greatly enhanced ^{14}C concentration. Any one of the shallow marine samples discussed earlier with apparent ages of 25 to 40 ka BP could represent any one of these. What is suggested by this study is that the group of dates as a whole indicate deposition at ~60 ka BP during a period of elevated sea level; some individual dates of the group could be contaminated older material, and there is still the remote possibility that some actually are close to their indicated age. Part of this dilemma could be resolved if multiple samples were assayed. Those that are of the approximate indicated age should be situated in an objective sequence without violation of the principle of superposition with oldest on bottom and youngest on top. Those groups of samples which may be affected by contamination with younger material should be dominated by the older ages or nonfinite ages and when in an objective or sequential stratigraphic section, should exhibit violation of the principle of superposition. Objective sequences of samples from ~60 ka BP should ideally have the lowest sample ages be >60 ka or with nonfinite dates, followed up-section by samples that are variable in age and not necessarily following the principle of superposition. These, in turn, should be overlain by older-appearing samples, >40 ka or nonfinite ages. Unfortunately there is not a single suite of samples from any location reported in the literature that allows for a definitive resolution of this situation. Based upon the oxygen isotope sea level curves, it is probably unlikely that any of the sample sites, with reported apparent ages of 25 to 40 ka BP along the Atlantic coast of the southeastern United States, represent deposition at the indicated time. Furthermore, contamination may be a factor in one or more of the reported sites of the apparent 25 to 40 ka BP high stand; but it could not be the factor at all the sites.

Giving the sites along the Atlantic coast of the United States which have radiocarbon dates of 25 to 40 ka BP an actual date of 60 ka BP provides a better agreement with the oxygen isotope based sea level curve. However even at this time, the areas of these sites should have been above sea level based upon their current elevations. At ~60 ka BP sea level should have stood 28 meters below its current position (CHAPPELL and SHACKLETON, 1986). The current elevations of the affected sites may not have been the same as their elevation at the time of deposition. There is a north to south decrease in the elevation of the sites with these affected dates (Figure 5). This general trend probably represents the remains of the forebulge of the last glacial advance. The entire set of sites should also be uniformly uplifted due to postglacial additions of water to the ocean basin and subsequent displacement of material from the asthenosphere, thus forming a coastal zone bulge which is somewhat like the glacial forebulge. In a similar manner, 60 ka BP represents a point in time just after a rapid growth of ice sheet mass. Thus the coastal areas at this time would have been situated at a lower absolute elevation, a position opposite that of the coastal zone bulge. The approximate 20 to 30 meter difference between the modern elevation of the 60 ka BP sites and the oxygen isotope sea level curve elevation of sea level is, therefore, probably the sum of these three glacial-isostatic responses to changes in crustal load distribution. Deviations in the general trend may be due to local tectonic movements such as that in the area of the Cape Fear, an area where

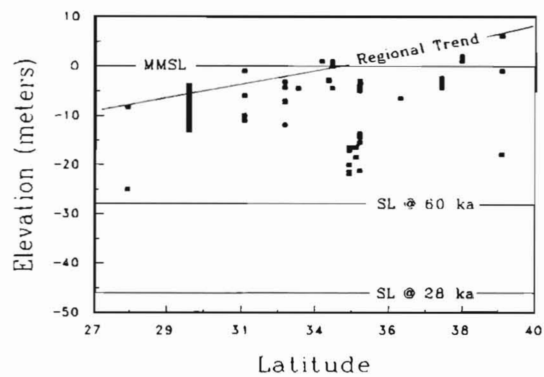

Figure 5. Elevation with respect to modern mean sea level (MMSL) of radiocarbon dated marine material of apparent age 23 to 40 ka BP from sites along the Atlantic Coastal Plain of the United States. Data set is the same as used in Figures 1 and 2, refer to Table 1 for sources.

Plio-Pleistocene crustal warping has been described by ZULLO and HARRIS (1979).

An age of ~60 ka BP for this apparent high stand is further supported from the glacial record where there is argument for a deglaciation of Scandinavia at this time (LUNDQVIST, 1986) and reduction in the mass of the Lurentide ice sheet (ANDREWS *et al.,* 1986) and the Cordilleran ice sheet (FULTON, 1986). When this high stand began, when it ended, and to what elevation it rose is not ascertainable from the sites listed earlier. The samples with the problem radiocarbon dates represent carbon accumulation during a brief (few hundred years) period of time. Their wide distribution along the Atlantic coast would suggest that sea level was falling or fell immediately after the accumulation period. Some speculation points to climatic changes induced by the eruption of Toba in Indonesia at this time as the cause of the sea level fall. An ash deposit attributed to the eruption of Toba but found in Malaysia, overlies a ^{14}C dated wood which has apparent ages of 33,250±1800 yr. BP and 36,500±2500 yr. BP (STAUFFER, 1973). The ash gives an isothermal plateau fission-track age of 68±7 ka (CHESNER *et al.,* 1991). If the eruption initiated the Late Wisconsin ice advance and was coeval with the cosmic ray enhancement, then the 60±2 ka BP date would represent the apex of the high stand.

CONCLUSIONS

The sea level high stand indicated by apparent radiocarbon dates of 25 to 40 ka BP actually dates from 60±2 ka BP. The radiocarbon dates are in error due to the presence of excess amounts ^{14}C which resulted from an enhancement of the cosmic ray flux. The flux enhancement had a duration of 200 or more years and a maximum enhancement of 250 times the present flux. The indicated age of the high stand fits better with the oxygen isotope-based sea level curve. There are, however, still uncalibrated differences in elevation due to the continued presence of the late Wisconsin glacial forebulge and effects of isostatic adjustments along the continental margins due to mass transfers between the oceans and the ice sheets.

Radiocarbon apparent ages which fall in the range of ~25 ka to ~40 ka need additional scrutiny; they could represent two possible points in time, one corresponding to the indicated apparent age plus a few thousand years and the other equal to 60±2 ka. Such an age could also be simply due to contamination. However, contamination cannot be the source of the problem for all the dates reported in the literature. Resolution of the actual meaning of such apparent radiocarbon ages requires either additional dating on the same material by some other method or multiple ^{14}C dates taken from an objective stratigraphic sequence at the problem site.

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