Radiocarbon age of late glacial deep water from the equatorial Pacific

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Received 15 August 2006; revised 2 November 2006; accepted 6 December 2006; published 1 May 2007.

[1] Radiocarbon age differences for pairs of coexisting late glacial age benthic and planktic foraminifera shells handpicked from 10 sediment samples from a core from a depth of 2.8 km in the western equatorial Pacific are not significantly different from that of 1600 years calculated from measurements on prenuclear seawater. This places a lower limit on the depth of the interface for the hypothetical radiocarbon-depleted glacial age seawater reservoir required to explain the 190‰ drop in the $^{14}C/C$ for atmospheric CO_2, which occurred during the mystery interval (17.5 to 14.5 calendar years ago). These measurements restrict the volume of this reservoir to be no more than 35% that of the ocean. Further, ^{14}C measurements on a single Last Glacial Maximum age sample from a central equatorial Pacific core from a depth of 4.4 km water fail to reveal evidence for the required 5- to 7-kyr age difference between benthic and planktic foraminifera shells if the isolated reservoir occupied only one third of the ocean. Nor does the ^{13}C record for benthic forams from this abyssal core yield any evidence for the excess respiration CO_2 expected to be produced during thousands of years of isolation. Nor, as indicated by the presence of benthic foraminifera, was the dissolved oxygen used up in this abyssal water.

Citation: Broecker, W., E. Clark, S. Barker, I. Hajdas, G. Bonani, and E. Moreno (2007), Radiocarbon age of late glacial deep water from the equatorial Pacific, *Paleoceanography*, *22*, PA2206, doi:10.1029/2006PA001359.

1. Introduction

[2] Radiocarbon measurements on known age materials suggest that the $\Delta^{14}C$ for atmospheric CO_2 and for surface ocean $\sum CO_2$ dropped by 190‰ between about 17.5 and 14.5 kyr [*Beck et al.*, 2001; *Hughen et al.*, 2004; *Fairbanks et al.*, 2005]. Such a large drop in a relatively short period of time is very difficult to explain. Interestingly, it occurred during a time interval marking the onset of the last deglaciation, a period when a set of curious changes took place [*Denton et al.*, 2006].

[3] Before getting into the cause of the radiocarbon decline, a few words about its context are in order. The transition from the last period of glaciation to the present period of interglaciation appears to have been triggered about 17.5 kyr ago, when an armada of icebergs (Heinrich event 1) was launched into the northern Atlantic from the Hudson Bay lobe of the Laurentide ice sheet. It ended about 14.5 kyr ago when a rejuvenation of conveyor circulation ushered in the Bölling-Allerod warm. As demonstrated by *McManus et al.* [2004], export of deep water from the Atlantic appears to have shut down during this time period. Further during this time period, atmospheric CO_2 rose halfway back to its interglacial value. *Denton et al.* [2006] refer to this 3-kyr time period as the mystery interval. One aspect of the mystery concerns an apparent inconsistency in the European climate record. As was the case for Greenland and the northern Atlantic, the Mediterranean remained very cold during the mystery interval [*Cacho et al.*, 1999]. However, it was during this time interval that glaciers in the Alps retreated beyond the heads of the major valleys suggesting that warm conditions prevailed [*Schlüchter*, 1998; *Denton et al.*, 1999]. In an attempt to reconcile these two observations, *Denton et al.* [2006] call on seasonality. Summer temperatures, warmed as a result of increased atmospheric CO_2, caused the glaciers to recede. However, winter temperatures remained cold because of extensive sea ice cover in the northern Atlantic.

2. Radiocarbon Decline

[4] This paper deals with another aspect of the mystery interval puzzle. Between about 17.5 kyr and 14.5 kyr, the ^{14}C to C ratio in the atmosphere [*Beck et al.*, 2001] and in the surface ocean [*Hughen et al.*, 2004; *Fairbanks et al.*, 2005] dropped by about 190‰. As the Greenland ice core ^{10}Be record shows no evidence for a dramatic decrease in the production of cosmogenic isotopes during the mystery interval [*Muscheler et al.*, 2005], the most likely explanation for this drop is that it was caused by the mixing into the rest of the ocean of glacial age low-radiocarbon-content waters previously isolated in an abyssal reservoir. A compelling case for the existence of such a reservoir was made by *Adkins and Schrag* [2003] based on a profile of pore water salinities in a southern Atlantic deep sea drilling core.

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0883-8305/07/2006PA001359

These authors attributed the existence of this reservoir to the rain of dollops of brine released during seasonal excursions of the glacially expanded Antarctic sea ice apron.

3. Benthic-Planktic ^{14}C Age Differences

[5] If, indeed, the cause of the ^{14}C drop was the demise of this radiocarbon-deficient ocean reservoir, then its existence should stand out in age differences between coexisting benthic and planktic foraminifera shells. Were the reservoir large enough to cause the 190‰ drop in ^{14}C to C ratio, the benthic-planktic age difference would have to have been far larger than that of about 1600 years for today's Pacific Ocean. For example, if the reservoir constituted one third the volume of the world ocean, its ^{14}C to C ratio would have had to have been about half that in today's deep Pacific. For the ^{14}C to have been reduced to this extent would have required that the period of isolation was on the order of one radiocarbon half-life (5.7 kyr). Hence one might conclude that its ^{14}C signature should be easy to find.

[6] It turns out that this is not the case. Thus far our attempts have been negative [*Broecker and Barker*, 2007] or ambiguous [*Broecker et al.*, 2004a]. However, if this reservoir was stabilized by extra salt, it must have been located at the bottom of the water column. Hence the search must be extended beyond the 2-km water depth at which our published measurements were made. However, obtaining reliable benthic-planktic age differences becomes ever more difficult the deeper one goes. Because of serious biases introduced by bioturbation [see *Barker et al.*, 2007] one requirement for a suitable core is a high sedimentation rate (>15 cm/10^3 years). As open ocean sediments in the Pacific generally have accumulation rates no greater than 3 cm/10^3 years, the search for suitable cores must be concentrated along the ocean margins. However, as the incorporation of reworked (i.e., pre-aged) material is common in such environments, it is necessary to demonstrate that the ^{14}C ages of species sufficiently robust to survive retransport is not significantly older than that for fragile species which tend to be broken up during along-bottom transport [*Broecker et al.*, 2006].

[7] We report here results from a core from 2.8-km water depth in the western equatorial Pacific with a sedimentation rate of 50 cm/kyr. As only one third of the ocean lies below this water depth, we had hoped that this core would record both the existence and the demise of this isolated reservoir. To this end, we carried out radiocarbon analyses at 10 depth intervals ranging in calendar age from before 17.5 kyr to after 12.5 kyr. As summarized in Table 1, at each depth we analyzed both a fragile planktic (i.e., *G. sacculifer*) and a robust planktic (*N. dutertrei*). As the agreement between the two planktic ages was satisfactory, we are confident that the presence of reworked material has not introduced significant biases. As can be seen in Figure 1, the benthic-planktic age difference for all 10 samples lies within the measurement error (±200 years) of today's. Further, as shown in Figure 2, the age differences at this depth are not significantly greater than those obtained on western equatorial Pacific cores from about 2-km water depth.

[8] It should be noted that no correction has been made for the lag of the deep ocean radiocarbon content associated with the temporal decline in surface ocean ^{14}C to C ratio. While such a correction is necessary if the benthic-planktic age differences are to be converted to ventilation rates, as we instead are concerned with radiocarbon inventories, this correction is not appropriate.

[9] Clearly then, if we are to find evidence in support of the existence of a large radiocarbon-depleted abyssal reservoir, we must look to sediments deeper than 2.8 km. So far, we have not found any sediment core that fulfills our criteria. In desperation, we analyzed shells from a core from 4.4-km depth [*Broecker et al.*, 2001] in the central equatorial Pacific with a sedimentation rate of only 3 cm/kyr. As listed in Table 2, the ^{14}C ages for robust shells of *N. dutertrei*, of *P. obliquiloculata* and of *G. tumida* yielded ages respectively 1310, 1580, and 1940 years older than that for the fragile shells of *G. sacculifer.* While this could well signal the presence of reworked material, it might instead signal the impact of dissolution in the core top bioturbated zone [see *Barker et al.*, 2007]. The latter is quite possible because of the low sediment accumulation rate. Interestingly, the radiocarbon age of the mixed benthics was 1.6 kyr older than that for *G. sacculifer*. However, the radiocarbon ages for the three robust planktics were no different than those for the benthics. Our initial inclination was to disregard these results. However, on further consideration, while these results are certainly unsuitable for a precise determination of the radiocarbon age of glacial deep water, they appear to exclude the possibility that the benthics had a radiocarbon age of 6 kyr or so older than that for the planktics as would be required if the upper bound of the isolated reservoir lay beneath 2.8-km water depth. That this is highly unlikely can be seen from the plot of radiocarbon age versus depth in the piston core shown in Figure 3. The age for the *G. sacculifer* shells falls close to a line joining the radiocarbon ages for samples from shallower and deeper in the core. We can think of no scenario that would have led to a reduction of the benthic–*G. sacculifer* age difference from 6 or so thousand years to 1.6 kyr.

[10] Consistent with the conclusion that the water at the site of this abyssal core is not part of the sought-after low radiocarbon reservoir is the ^{13}C record for benthic foraminifera obtained by Oregon States's Alan Mix. In a separate paper [*Broecker and Barker*, 2007] we show these unpublished results with the comment that the glacial ^{13}C values are no lower than those for cores from 2.8 km and shallower. The absence of an enhanced respiratory ^{13}C signal supports the conclusion that glacial age water at 4.4 km in the equatorial Pacific was not part of the sought-after isolated reservoir.

4. Discussion

[11] As support for a 190‰ drop in the ^{14}C to C ratio for the atmosphere and surface ocean comes from three independent records [*Beck et al.*, 2001; *Hughen et al.*, 2004; *Fairbanks et al.*, 2005], its existence is difficult to put aside. As the *Fairbanks et al.* [2005] results are the most convincing, we reproduce those covering the critical age range

Table 1. Radiocarbon Results on Foraminifera Samples From MD01-2386 (1.1°N, 130°E, 2.82 km)

	Number of Shells	Weight of Shells, mg	Radiocarbon Age	Lab[a]
Depth in Core 298–302 cm				
G. sacculifer	1015	25.3	12,490 ± 105	ETH
P. obliquiloculata	2015	31.8	12,750 ± 85	ETH
N. dutertrei	1989	25.9	12,730 ± 95	ETH
N. dutertrei	–	1.8	12,550 ± 180	WHOI
Benthic	23	1.6	14,100 ± 210	WHOI
Benthic–mean planktic			14,100–12,630 = 1470 ± 250	
Depth in Core 323–327 cm				
G. sac	750	27.6	12,800 ± 80	ETH
N. dutertrei	1000	29.8	12,740 ± 90	ETH
Benthic	47	4.8	14,200 ± 75	WHOI
Benthic–mean planktic			14,200–12,770 = 1430 ± 200	
Depth in Core 348–352 cm				
G. sacculifer	750	27.6	13,470 ± 95	ETH
N. dutertrei	1000	26.6	13,490 ± 95	ETH
Benthic	44	3.3	15,100 ± 85	WHOI
Benthic–mean planktic			15,100–13,480 = 1620 ± 200	
Depth in Core 373–377 cm				
G. sacculifer	300	10.7	14,250 ± 70	WHOI
N. dutertrei	900	28.4	14,250 ± 70	WHOI
Benthic	40	2.3	15,350 ± 220	WHOI
Benthic–mean planktic			15,350–14,250 = 1100 ± 350	
Depth in Core 398–401 cm				
G. sacculifer	196	6.4	14,500 ± 75	WHOI
N. dutertrei	1145	24.4	13,920 ± 110	ETH
P. obliquiloculata	747	26.2	14,560 ± 100	ETH
Benthic	99	4.6	16,000 ± 95	WHOI
Benthic–mean planktic			16,000–14,200 = 1800 ± 200	
Depth in Core 423–427 cm				
G. sacculifer	186	6.6	15,050 ± 65	WHOI
N. dutertrei	1108	33.8	14,950 ± 75	WHOI
Benthic	178	8.4	16,450 ± 90	WHOI
Benthic–mean plantkic			16,450–15,000 = 1450 ± 150	
Depth in Core 448–452 cm				
G. sacculifer	166	5.7	14,900 ± 55	WHOI
N. dutertrei	862	24.7	15,300 ± 60	WHOI
Benthic	65	4.5	16,900 ± 80	WHOI
Benthic–mean plantkic			16,900–15,100 = 1800 ± 150	
Depth in Core 473–477 cm				
G. sacculifer	60	2.0	15,350 ± 250	WHOI
N. dutertrei	511	15.6	15,900 ± 80	WHOI
Benthic	118	5.6	17,550 ± 90	WHOI
Benthic–mean plantkic			17,550–15,750 = 1800 ± 150	
Depth in Core 498–502 cm				
G. sacculifer	172	6.0	16,100 ± 65	WHOI
P. obliquiloculata	810	26.5	16,340 ± 120	ETH
N. dutertrei	790	26.1	16,590 ± 130	ETH
Benthic	165	9.1	17,850 ± 60	WHOI
Benthic–mean plantkic			17,850–16,340 = 1510 ± 150	
Depth in Core 523–527 cm				
G. sacculifer	276	9.9	17,150 ± 60	WHOI
P. obliquiloculata	720	23.3	16,340 ± 150	ETH
N. dutertrei	750	21.5	16,840 ± 160	ETH
Benthic	122	7.6	18,550 ± 65	WHOI
Benthic–mean plantkic			18,550–16,775 = 1775 ± 250	

[a] ETH, Eidgenossische Technische Hochschule; WHOI, Woods Hole Oceanographic Institution.

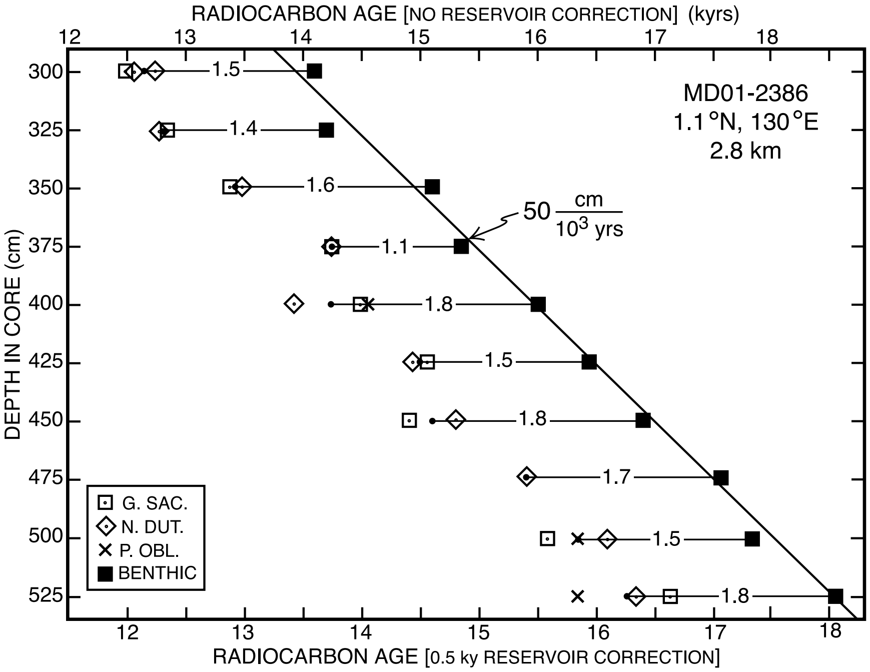

Figure 1. Radiocarbon age for foraminifera shells from a west equatorial Pacific core taken at a water depth of 2.8 km. The age difference between mixed benthics and the average for the planktonics is given in kiloyears.

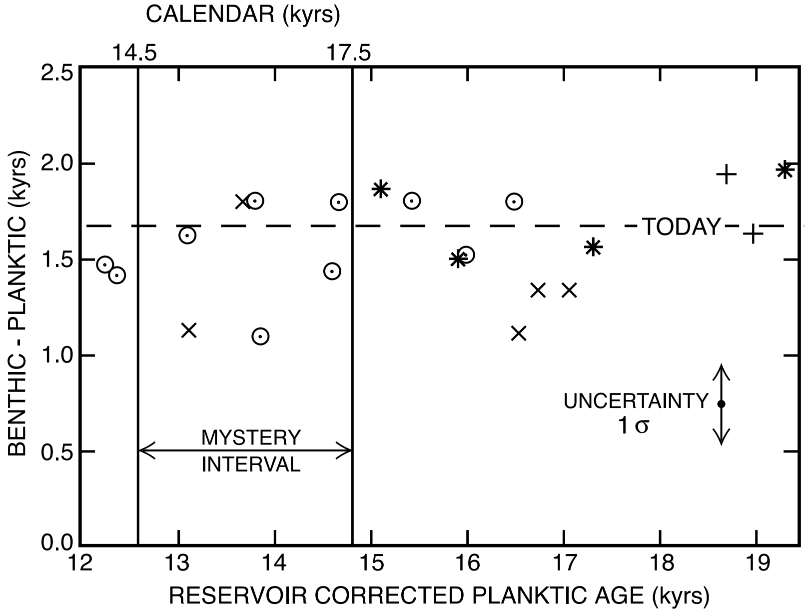

Figure 2. Summary of benthic-planktic age differences obtained on samples from three western equatorial Pacific cores and one South China Sea core. The circles are for samples from MD01-2386 (1°N, 130°E, 2.8 km, this paper); the crosses are for samples from Morotai Basin core MD98-2181 (6°N, 126°E, 2.1 km [*Broecker et al.*, 2004b, 2006]); the plus signs are for samples from Admiralty Island core MD97-2138 (1°S, 146°E, 1.9 km [*Broecker et al.*, 2004a]); and the asterisks are for a core from the South China Sea (sill depth 2 km [*Broecker et al.*, 1990]). The dashed line is today's value.

Table 2. Results From Two Equatorial Pacific Cores Taken at 2°S and 140°W

Depth in Core, cm	Material	^{14}C Age, years	Error, years
	TT13-19 Multicore 4.38 km		
1–2	bulk $CaCO_3$	4,045	51
12–14	bulk $CaCO_3$	6,685	58
22–24	bulk $CaCO_3$	11,510	84
	TT13-18 Piston Core 4.35 km		
12–14	bulk $CaCO_3$	6,080	61
22–25	bulk $CaCO_3$	10,095	77
29–30	bulk $CaCO_3$	12,296	99
53–56	*G. sacculifer*	21,020	150
53–56	*N. dutertrei*	22,330	150
53–56	*P. obliquiloculata*	22,600	160
53–56	*G. tumida*	22,960	160
53–56	benthic	22,610	180
79–80	bulk $CaCO_3$	28,655	385

in Figure 4. In a separate paper [*Broecker and Barker*, 2007], on the basis of the ^{10}Be record in Greenland ice [*Muscheler et al.*, 2005], we discount the possibility that this decrease was produced by a major drop in ^{14}C production during the mystery interval. If the oxidation of fossil organics were called upon, the 5000 or so gigatons of ^{14}C-free fossil carbon required to create the observed 190‰ decrease would lead to a huge drop in ^{13}C in foraminifera. Such a drop is not seen. Were it a methane burp, it would surely show up in the ice core record. It does not. Were this carbon added as volcanic CO_2, it would have caused a very large increase in atmosphere CO_2 content. Again, such an increase is not seen in the ice core record. It was this absence of other acceptable candidates that forced us to conclude that the villain must be a large radiocarbon-depleted ocean reservoir.

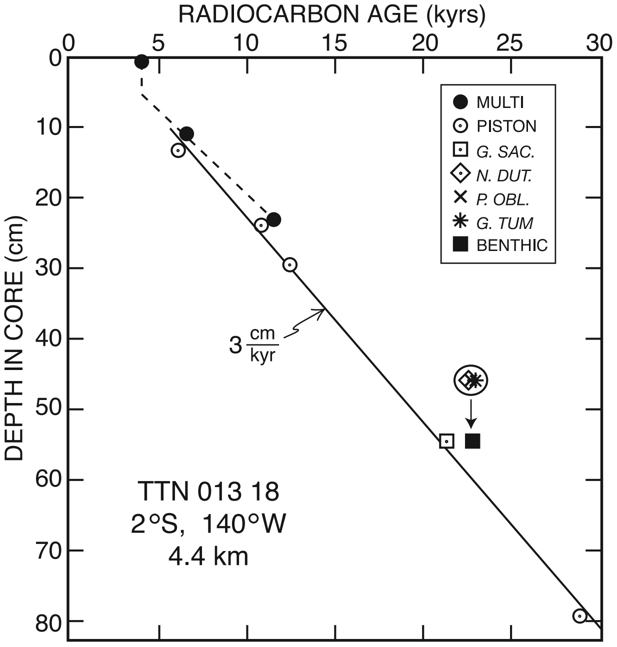

Figure 3. Radiocarbon results as a function of depth in a pair of deep-sea cores from a water depth of 4.4 km in the central equatorial Pacific (see Table 2 for listing).

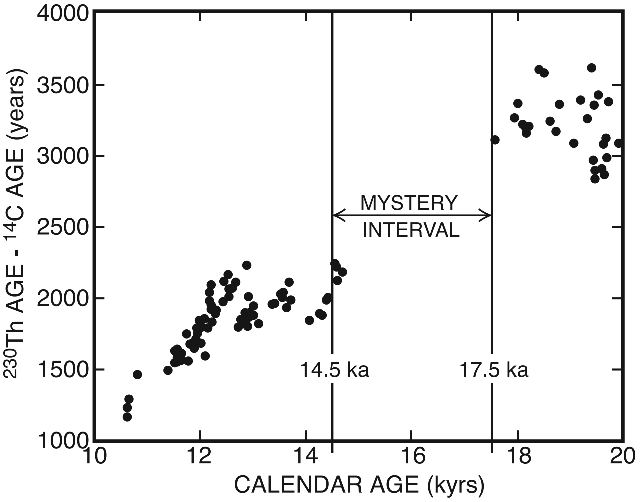

Figure 4. Difference between ^{230}Th age and ^{14}C age for corals from Barbados and Christmas Island as a function of calendar age [*Fairbanks et al.*, 2005]. Note that for some reason, no corals formed within the mystery interval were dated.

[12] The problem is that, if ocean waters at 4.4 km and shallower than 2.8 km are excluded, it appears to be impossible to designate a volume of ocean water large enough to do the job. In this regard it should be noted that as the *Adkins et al.* [2002] pore water salinity profile at 3290 m in the South Pacific shows no evidence of the presence of the hypersaline reservoir. If the idea that the isolated reservoir consists of hypersaline water is put aside, we could perhaps call on a reservoir located in the depth range lying between 2.8 and 4.4 km. To do the job, the water in this limited reservoir would have to have a radiocarbon age relative to that for warm surface water of at least 10 kyr! It should also have had a large ^{13}C deficiency and have been oxygen free.

[13] This leaves us in an awkward position. If the explanation for the drop in the ^{14}C to C ratio does not lie in an isolated ocean reservoir (or for that matter, in any other source of ^{14}C-deficient carbon), then the answer is perhaps that the production rate of ^{14}C plunged during the mystery interval. As unlikely as this appears, until a detailed record of ^{10}Be from an Antarctic ice core is published, it cannot be discarded.

[14] **Acknowledgments.** Discussions with Lloyd Keigwin and Bob Anderson proved very helpful. Financial support was provided by the National Science Foundation under grant OCE-0435703. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. This is Lamont-Doherty Earth Observatory contribution 6984.

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