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ACCELERATOR MASS SPECTROMETRIC RADIOCARBON MEASUREMENTS ON FORAMINIFERA SHELLS FROM DEEP-SEA CORES

SAMPLE PREPARATION

WALLACE S BROECKER, MIECZYSLAWA KLAS and ELIZABETH CLARK
Lamont-Doherty Geological Observatory, Palisades, New York 10964

MASS SPECTROMETRY

SUSAN TRUMBORE[1], GEORGES BONANI, WILLY WÖLFLI and SUSAN IVY
ETH Honggerberg, CH-8093 Zurich, Switzerland

ABSTRACT. Radiocarbon ages determined by the AMS method on hand-picked foraminifera shells are reported. The results allow estimates of the ventilation rate of the deep Atlantic and Pacific Oceans during glacial time. They also extend our knowledge of the chronology of events associated with the transition from full glacial conditions ca 15,000 years ago to full interglacial conditions ca 8000 years ago. This and the previous lists (Broecker *et al* 1988c) contain all the results obtained as part of this program through the fall of 1989.

INTRODUCTION

In this paper we present radiocarbon ages obtained by accelerator mass spectrometry (AMS) (Suter *et al* 1984) on hand-picked foraminifera shells from deep-sea cores. All the ages obtained as part of this program up to the fall of 1989 are included in either this or the previous list (Broecker *et al* 1988c). In the sections that follow, we comment on the results from particular cores or groups of cores. Note that none of the ages given here have been corrected for the reservoir age. Four hundred years should be subtracted from the planktonics if they are to be compared with ages for terrestrial plants.

CEARA RISE

We studied a series of three cores taken at 2.8, 3.5 and 4.0km depths on the Ceara Rise in cooperation with Bill Curry of Woods Hole Oceanographic Institute (WHOI) in order to determine the surface-to-deep-water ^{14}C age difference for the glacial Atlantic. Broecker *et al* (1988a,b) published an interpretation of the results on one of these cores. We dated several species of planktonic forams as well as mixed benthics. Tables 1-3 list the abundance data and the ^{14}C ages.

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[1] Currently at Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratories, Livermore, CA 94550

TABLE 1
KNORR 110-82GC Equatorial Atlantic Ceara Rise
Location (4°20.2′N, 43°29.2′W) Depth 2816m

ETH no.	Depth (cm)	Coarse fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No. tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
2128	25-28	14.5	G sacc	557	30.8	222	12.3	Jun 86	14,150±160
2652	"	"	G ruber	1010	22.8	500	11.3	Jan 87	13,870±260
2129	"	"	P obliq	38	2.0	254	13.2	Jun 86	12,610±140
2241	"	"	N duter	143	8.8	213	13.0	Jul 86	13,860±190
2130	"	"	M benth	5.8	0.24	233	9.5	Jun 86	14,930±200
2018	30-33	6.8	G sacc	215	14.9	194	13.5	Apr 86	15,100±250
4436	"	"	G sacc	215	14.9	167	7.6	Dec 88	15,080±120
2019	"	"	G ruber	526	10.1	453	8.7	Apr 88	15,450±260
4438	"	"	G ruber	526	10.1	938	8.4	Dec 88	15,130±120
	"	"	P obliq	5.7	0.36	-	-	-	-
2020	"	"	N duter	62	3.7	186	11.1	Apr 86	15,170±260
4437	"	"	N duter	62	3.7	212	8.8	Dec 88	14,820±120
2021	"	"	M benth	6.7	0.21	298	9.3	Apr 88	16,350±280
2651	35-38	7.4	G sacc	216	16.3	163	12.3	Jan 87	16,090±320
2650	"	"	G ruber	496	8.7	400	7.0	Jan 87	15,870±290
	"	"	P obliq	1.6	0.08	-	-	-	-
2244	"	"	N duter	58	3.5	229	13.7	Jul 86	16,060±220
2246	"	"	M benth	4.7	0.11	187	4.4	Jul. 86	16,130±240
2131	40-43	8.9	G sacc	220	15.5	183	13.0	Jun 86	16,710±250
2132	"	"	G ruber	458	13.2	548	15.8	Jun 86	17,040±250
	"	"	P obliq	1.4	0.07	-	-	-	-
2133	"	"	N duter	87	6.3	181	13.2	Jun 86	17,610±280
2134	"	"	M benth	4.5	0.23	193	10.2	Jun 86	17,870±370
2653	45-48	8.6	G sacc	186	22.8	86	9.5	Jan 87	17,780±360
2654	"	"	G ruber	766	14.0	500	12.7	Jan 87	17,430±340
	"	"	P obliq	4.2	0.22	-	-	-	-
2248	"	"	N duter	53	3.4	199	12.9	Jul 86	17,660±260
2249	"	"	M benth	4.5	0.23	155	5.8	Jul 86	17,900±640

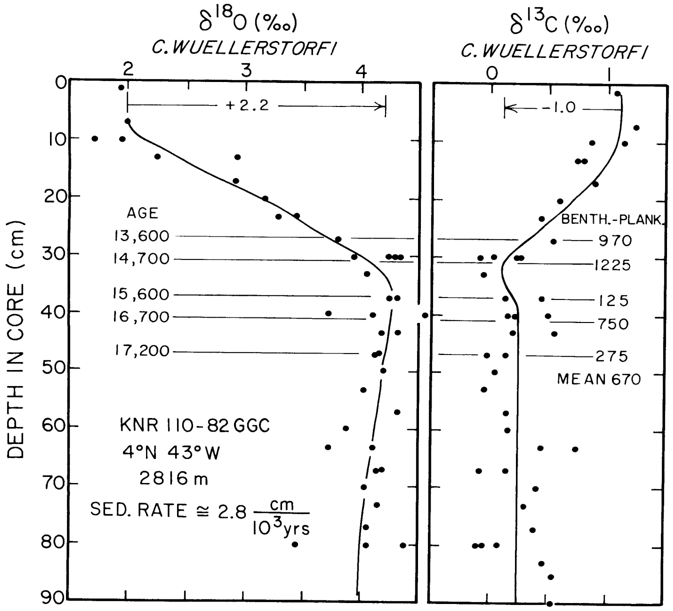

Fig 1. Oxygen and carbon isotope results for benthic foraminifera from Ceara Rise core KNR 110-82GGC (Curry *et al* 1988). This core comes from a depth of 2.8km. Shown on the left are mean ^{14}C ages for planktonic foraminifera (corrected for a 400-yr age of surface-water carbon). Shown on the right are the benthic-planktonic age differences obtained for these same samples. The mean difference for five depth horizons is 670 yr. Note that glacial water at this site is depleted by ca 1.0‰ in ^{13}C relative to that for the late Holocene.

TABLE 2
KNORR 110-66GGC Equatorial Atlantic Ceara Rise
Location (4°33.8′N, 43°22.9′W) Depth 3547m

ETH no.	Depth (cm)	Coarse fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
5070	45-50	6.4	G sacc	262	16	157	9.6	Jun 89	16,450±150
5071	"	"	N duter	57	3.9	143	9.7	Jun 89	16,660±150
5072	"	"	M benth	4.7	0.08	496	8.9	Jun 89	17,030±150
5074	49-53	6.6	G sacc	297	20	131	8.8	Jun 89	16,800±150
5075	"	"	N duter	64	4.0	156	9.6	Jun 89	17,030±150
5073	"	"	M benth	5.2	0.11	348	7.6	Jun 89	17,690±150
5076	53-58	6.9	G sacc	250	15	148	8.9	Jun 89	18,130±160
5077	"	"	N duter	78	4.5	139	8.1	Jun 89	18,060±180
5078	"	"	M benth	4.2	0.08	351	6.9	Jun 89	18,630±180
5285	56-61	6.2	G sacc	232	13.4	156	9.0	Jul 89	18,860±190
5286	"	"	N duter	79	4.2	162	8.7	Jul 89	18,980±190
5284	"	"	M benth	3.6	0.06	336	8.0	Jul 89	19,540±220

Figures 1-3 give a summary of the benthic-planktonic age differences. The mean deep-water age obtained for all three cores is 650 years (based on 14 pairs). No significant difference exists in the age obtained for the three depths, *ie*, 670 yr at 2.8km, 520 yr at 3.5km and 720 yr at 4.0km.

As shown in the tables, the abundance of *G sacculifer* is three times lower in the deep core than in the shallower ones, whereas that of *N dutertrei* is somewhat higher. As the cores are from nearly the same location, we would logically attribute this deficiency of *G sacculifer* to preferential dissolution and shell breakup. Coupled with bioturbation, this should lead to a younger age for *G sacculifer* than for *N dutertrei*. However, we see only small age differences at all depths (average of 45 yr at 2.8km, 122 yr at 3.5km and 120 yr at 4.0km). In particular, we see no increase in this age difference at 4.0km where the abundance of *G sacculifer* relative to that of *N dutertrei* is much lower.

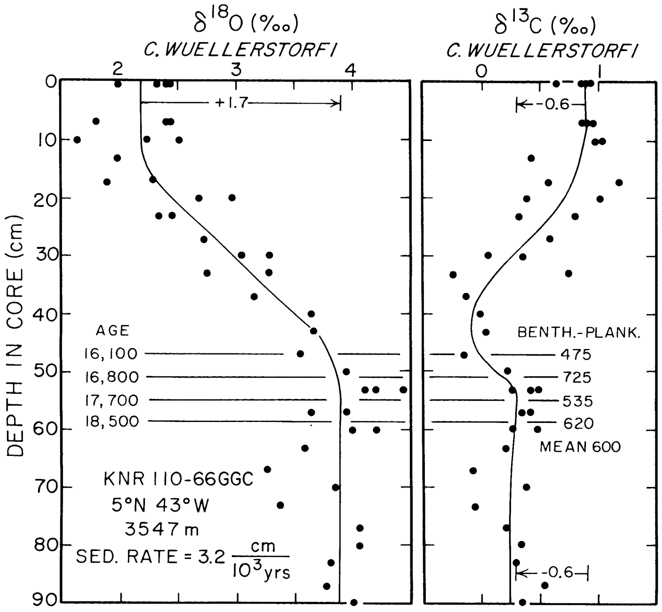

Fig 2. Oxygen and carbon isotope results for benthic foraminifera from Ceara Rise core KNR 110-66GGC (Curry *et al* 1988). The depth of this core is 3.5km. Shown on the left are mean ^{14}C ages for planktonic foraminifera (corrected for a 400-yr age of surface-water carbon). Shown on the right are the benthic-planktonic age differences obtained on these same samples. The mean difference for four levels is 520 yr. Note that glacial water at this site is depleted by a ca 0.6‰ in ^{13}C relative to that for the late Holocene.

TABLE 3
KNORR 110-50GGC Equatorial Atlantic Ceara Rise
Location (4°51.9′N, 43°12.3′W) Depth 3995m

ETH no.	Depth (cm)	Coarse fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
4786	17-20	5.9	G sacc	134	8.4	133	8.3	Apr 89	13,580±140
5219	"	"	N duter	128	7.1	178	9.9	Apr 89	14,710±140
4787	"	"	M benth	10.5	0.16	453	7.0	Apr 89	15,040±140
4783	20-23	4.8	G sacc	62	2.7	169	7.3	Apr 89	13,850±130
4784	"	"	N duter	64	3.3	152	7.8	Apr 89	14,500±200
4785	"	"	M benth	7.3	0.13	417	7.3	Apr 89	14,760±140
4772	22-27	4.5	G sacc	98	5.0	169	8.6	Apr 89	16,900±170
4773	"	"	N duter	95	5.1	162	8.7	Apr 89	16,740±210
4774	"	"	M benth	4.9	0.08	361	5.7	Apr 89	17,110±190
4777	27-32	5.5	G sacc	117	5.5	169	7.9	Apr 89	17,350±170
4778	"	"	N duter	120	5.1	166	7.1	Apr 89	17,540±160
4779	"	"	M benth	5.6	0.08	532	8.0	Apr 89	18,360±200
4780	31-36	5.5	G sacc	119	6.5	138	7.5	Apr 89	18,210±190
4781	"	"	N duter	128	7.1	142	7.9	Apr 89	18,620±200
4782	"	"	M benth	6.1	0.08	605	8.3	Apr 89	19,110±190
5067	35-40	4.4	G sacc	127	6.6	168	8.7	Apr 89	19,470±180
5068	"	"	N duter	78	4.1	159	8.3	Apr 89	18,980±160
5069	"	"	M benth	4.0	0.06	358	5.1	Apr 89	20,360±220
	"	"							

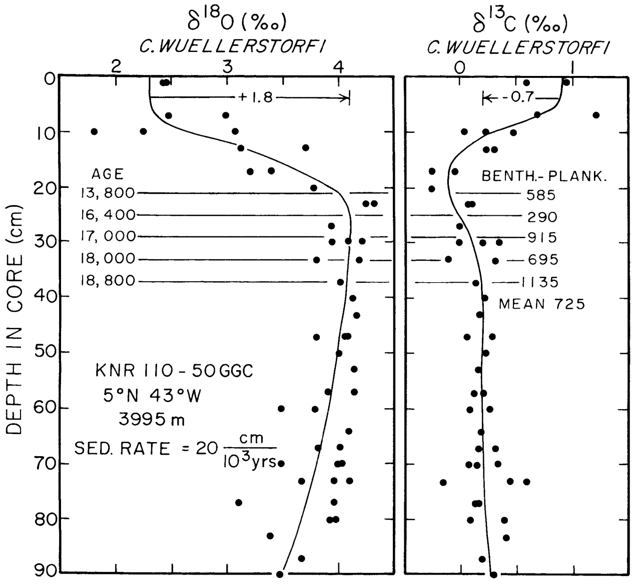

Fig 3. Oxygen and carbon isotope results for benthic foraminifera from Ceara Rise core KNR110-50GGC (Curry *et al* 1988). The depth of this core is 4.0km. Shown on the left are mean ^{14}C ages for planktonic foraminifera (corrected for a 400-yr age for surface-water carbon). Shown on the right are the benthic-planktonic age differences obtained on these same samples. The mean difference for five pairs is 725 yr. Note that glacial water at this site is depleted by ca 0.7‰ in ^{13}C relative to that for the late Holocene.

CARIBBEAN SEA

We selected Core V28-122 as representative of the low nutrient and high $^{13}C/^{12}C$ water of the intermediate depth Atlantic during glacial time (Oppo & Fairbanks 1987). As Figure 4 shows, the $\delta^{13}C$ value for benthic forams was higher during glacial time than during the Holocene in contrast to the lower glacial values for the three Ceara Rise cores (see previous section). Although V28-122 comes from 3.6km depth, it is representative of water at ca 1.8km depth in the open Atlantic, *ie*, the sill depth for the Caribbean.

As Table 4 and Figure 4 show, the three glacial-age samples yield an average benthic-planktonic age difference of 180 years, as opposed to ca 650 years for the open Atlantic. Hence, as would be expected, the low nutrient-upper water of glacial time has a lower ^{14}C age than the high nutrient-deep water of glacial time.

TABLE 4
V28-122 Caribbean Sea Columbia Basin
Location (11°56'N, 78°41'W) Depth 3623m

ETH no.	Depth (cm)	Coarse Fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
5058	106-114	5.9	G sacc	24	1.48	150	9.2	May 89	14,140±110
5059	"	"	G ruber	513	5.07	758	7.5	May 89	15,480±140
5060	"	"	M benthic	13	0.32	331	8.1	May 89	16,750±130
5063	115-123	7.4	G sacc	44	2.12	163	7.8	May 89	17,120±150
5061	"	"	G ruber	407	5.62	601	8.3	May 89	16,980±140
5062	"	"	M benthic	20	0.47	417	9.9	May 89	17,300±150
5227	125-128	6.0	G sacc	46	2.70	165	9.7	Jul 89	17,390±160
5226	"	"	G ruber	523	15.2	340	9.9	Jul 89	17,680±170
5225	"	"	M benthic	36	0.67	570	10.5	Jul 89	17,610±180
5454	127-139	-	Cibicides	-	-	229	5.5	Aug 89	18,370±200
5455	"	-	Miliolids	-	-	270	8.6	Aug 89	17,980±170
5453	"	-	Other benthics	-	-	267	10.2	Aug 89	18,730±190

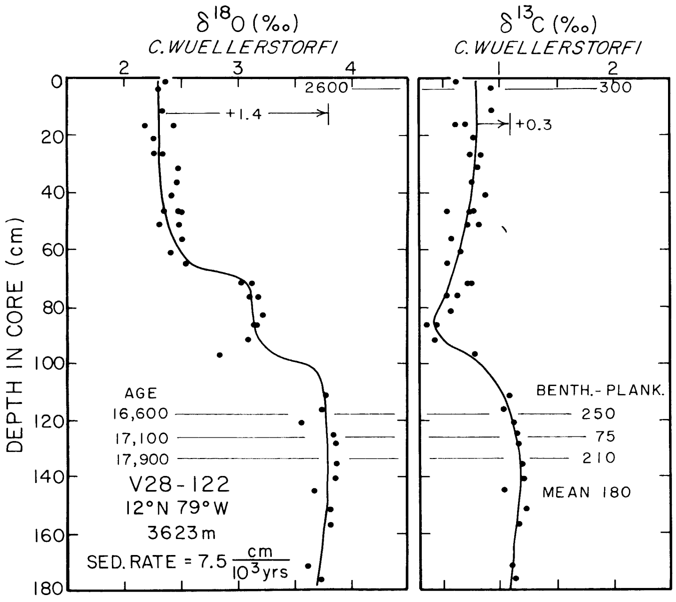

Fig 4. Oxygen and carbon isotope records for benthic forams from Caribbean core V28-122 (Oppo & Fairbanks 1987). Shown on the left are the average ^{14}C ages for planktonic foraminifera (corrected for an assumed 400-yr age for surface water) and to the right are the differences between the benthic and planktonic age. Some of the ages are from this list (Table 4). The rest are from our previous list (Broecker *et al* 1988c). Note that the glacial water at this site is enriched by ca 0.3‰ in ^{13}C relative to that for Holocene time indicating that the site of this core was bathed in low nutrient waters.

Two samples from the period of transition between full glacial and full interglacial time yield highly anomalous results. The age for *G sacculifer* is in both cases much younger than that for *G ruber* and the benthic-planktonic age difference is very large (Fig 5). We suspect that these anomalies relate to the abundance minimum for both planktonic species centered at 100cm depth (Fig 6). Both the ages of *G sacculifer* and of *G ruber* are influenced by the downward mixing of younger foraminiferal tests from shallower levels in the core.

We have another problem with this core. One of the original samples we analyzed came from 123-124cm depth (Broecker *et al* 1988c). It yielded nearly concordant planktonic ages averaging 15,700 years. As we found too few benthics in this sample, we had to pick more from slightly deeper levels. Two more problems exist. First, the benthic-planktonic age difference was larger (~700 yr) than that obtained for the three samples shown in Figure 5. Second, the ages were all ca 1500 years younger than those for the sample from 125-128cm. Hence, we exclude this result from Figure 4.

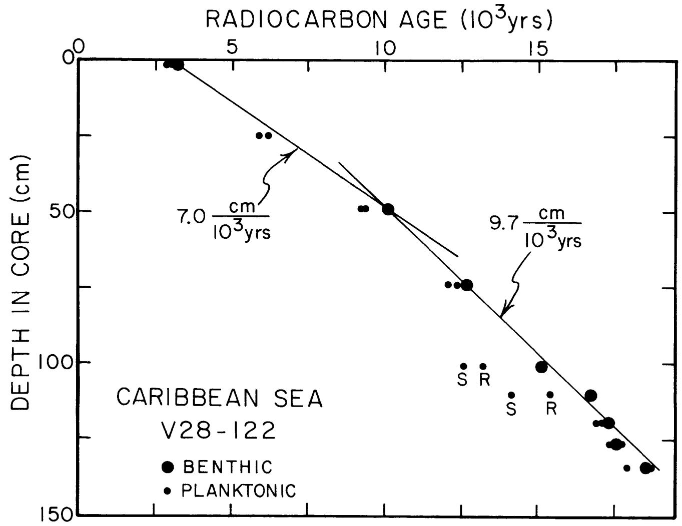

Fig 5. ^{14}C age *vs* depth in Caribbean Sea core V28-122. The *G sacculifer* (S) and the *G ruber* (R) for two levels are anomalously young. These samples come from a horizon where the abundances are very low and therefore may be strongly influenced by the downward mixing of younger specimens (Fig 6).

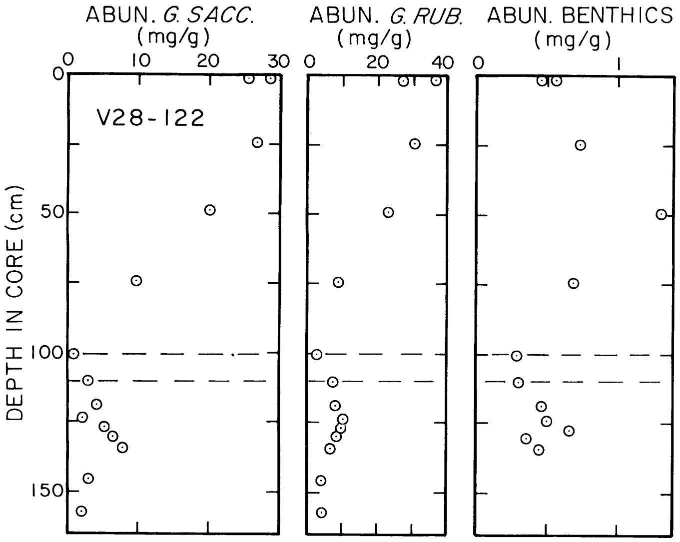

Fig 6. Abundance *vs* depth for the two planktonic and mixed benthic samples from Caribbean Sea core V28-122. The dashed lines represent the two levels yielding anomalously low planktonic ages (see Fig 5).

In an attempt to assess whether differences exist among the ages for individual species of benthic foraminifera, we divided one sample into three parts, one consisting of only *C wuellerstorfi*, one consisting of only miliolids and one consisting of the remainder of the benthics. As we see in Table 4, the three results spread by ca 2σ with the miliolids giving an 800 ± 300 year younger age than the non-miliolid-cibicides fraction. The age for the cibicides falls in between that for the other two fractions.

ORCA BASIN

We determined radiocarbon ages on two cores from the Orca Basin in the Gulf of Mexico (Table 5, Fig 7). The purpose was to define the chronology of meltwater discharge from the Mississippi River. The results from EN32-PC4 suggest that meltwater discharge was greatly reduced during the period from ca 11,000 to ca 10,000 years ago. This is consistent with geologic evidence that the discharge of meltwaters via glacial Lake Agassiz was diverted from the Mississippi to the St Lawrence River ca 11,000 years ago and diverted back to the Mississippi ca 10,000 years ago. As summarized by Broecker *et al* (1989a), these results are consistent with the hypothesis that the Younger Dryas cold event was caused by a shutdown of the Atlantic's conveyor system caused by the increased meltwater flow via the St Lawrence River.

We redated one level in core EN32-PC6 to check several earlier results which gave anomalously young results, leading us to suspect that a hiatus existed in this core. The new date fits exactly with the results of core EN32-PC4 and suggests that some problem exists with the previous determinations. We have never before encountered such large differences between results generated by our AMS dating program. Further, as we ran the four anomalous samples at three different times spread over more than one year, the explanation cannot lie in a single episode of contamination.

TABLE 5
Results on cores from the Orca Basin of the Gulf of Mexico

ETH no.	Depth (cm)	Coarse fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
EN32-PC6 Orca Basin, Gulf of Mexico Location (26°57'N, 91°21'W) Depth 2280m									
4769	436-437	-	M plank	-	-	-	5.8	May 89	10,910±160
EN32-PC4 Orca Basin, Gulf of Mexico Location (26° 56'N, 91°22'W) Depth 2260m									
4767	94-96	-	M plank	-	-	-	7.9	Apr 89	9510±100
4194	144-146	-	"	-	-	-	6.2	Oct 88	10,490±90
4195	150-152	-	"	-	-	-	8.0	Oct 88	10,700±130
4196	164-166	-	"	-	-	-	8.2	Oct 88	11,030±90
4197	194-196	-	"	-	-	-	6.4	Oct 88	11,510±100
4198	214-216	-	"	-	-	-	8.0	Oct 88	12,450±90
4768	288-290	-	"	-	-	-	6.8	Apr 89	13,260±140
Gerg 87G13-31 Orca Basin, Gulf of Mexico Location (26° 56'N, 91° 21'W) Depth 2350m									
5447	330-335	0.8	M plank	-	-	-	9.3	Aug 89	10,570±110
5446	360-365	2.1	"	-	-	-	10.0	Aug 89	11,890±110
5449	480-485	0.5	"	-	-	-	8.8	Aug 89	14,380±140
5448	490-495	0.3	"	-	-	-	8.0	Aug 89	14,860±150

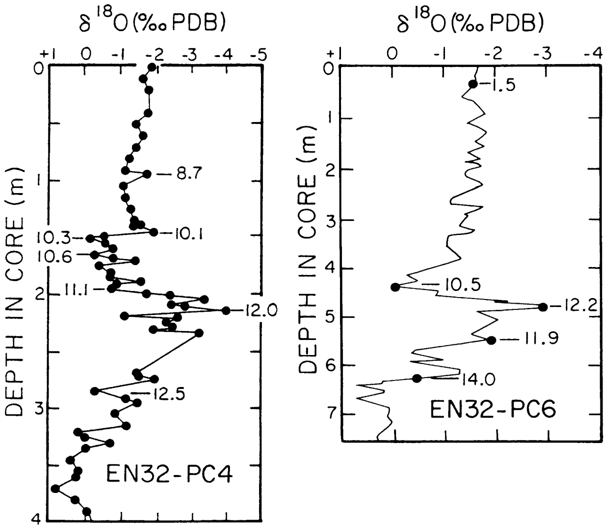

Fig 7. Plot *vs* depth of $\delta^{18}O$ on white *G ruber* from two Orca Basin cores. Four seemingly anomalous ages for core EN 32-PC6 were replaced with a new one of 10,500 (corrected for a 400-yr surface-water age). This new age conforms with those for core EN32-PC4.

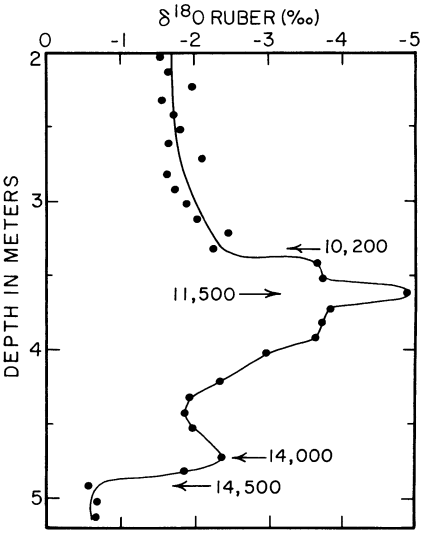

Fig 8. Oxygen isotope composition of *G ruber* as a function of depth in Texas A&M core 87G13-31 from the Orca Basin. The ^{14}C ages have been corrected for an assumed 400-yr age for surface-water ΣCO_2.

Jim Brooks of Texas A&M obtained a set of four piston cores for us from the same site in the Orca Basin. Delia Oppo and Chris Charles conducted oxygen isotope analyses on one of these cores in the LDGO laboratory of Richard Fairbanks in order to locate the meltwater event. Figure 8 shows the results. Four ^{14}C ages (Table 5) on mixed planktonics define the onset (~14,300 yr ago) and the termination (~10,500 yr ago) of this event.

CANARY ISLANDS RISE

Core V30-60 was selected to obtain a chronology for the pteropod preservation event seen in the early Holocene of the northern Atlantic. The results are listed in Table 6 and shown graphically in Figure 9. It is possible that this event was created by the increase in $CO_3^=$ ion concentration in the ocean associated with the drawdown in atmospheric CO_2 content brought about by the early Holocene reforestation of the areas covered by ice and tundra during glacial time. As Figure 10 shows, the preservation event appears to correspond to an early Holocene minimum in atmospheric CO_2 content.

TABLE 6
V30-60 North Atlantic in the vicinity of the Canary Islands
Location (25°41'N, 18°27'W) Depth 3177m

ETH no.	Depth (cm)	Coarse fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
4770	14-17	26.4	G sacc	72.7	6.1	125	10.5	Apr 89	4650±80
4771	20-23	28.5	Pteropods	-	-	-	7.3	Apr 89	7680±170
4209	23-24	29.9	Pteropods	-	-	-	7.4	Oct 88	8460±70
4210	26-27	30.4	Pteropods	-	-	-	7.0	Oct 88	9380±80
4211	29-30	24.0	Pteropods	-	-	-	8.0	Oct 88	9550±80
4212	32-33	20.6	Pteropods	-	-	-	8.1	Oct 88	9340±80

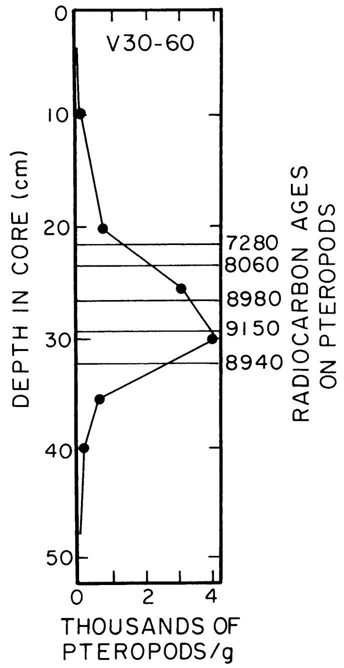

Fig 9. Pteropod abundance in Canary Islands Rise core V30-60 and AMS ^{14}C ages on hand-picked pteropods from this core. The ^{14}C ages are corrected for an assumed 400-yr air-sea difference.

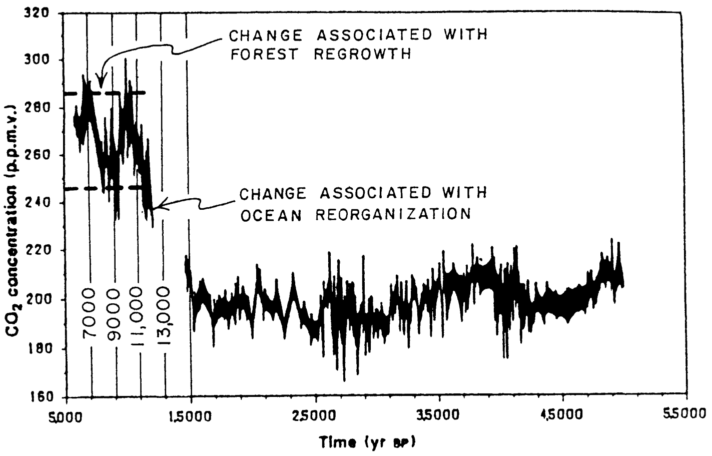

Fig 10. CO_2 record for the Byrd Antarctica ice core (Neftel *et al* 1988). The time scale is based on the current accumulation rate of ice and flow modeling. The early Holocene dip dropped the CO_2 content from ca 285 to ca 245μatm.

NORTHERN ATLANTIC

In order to resolve the discordance between two previous measurements (11,300 ± 140 and 10,230 ± 200, Broecker *et al* 1988c), we repeated the analysis of *N pachyderma* (left coiling) from a depth of 157-158cm, the peak of the Younger Dryas cold period. The new analysis yielded a result of 11,280 ± 90 years, confirming the first of the two previous results. Subtracting 400 years for the age of surface waters, we get 10,880 years for the Younger Dryas peak.

In a routine duplication, we dated one of the results published in our previous list (Broecker *et al* 1988c), *G bulloides* (V23-81, 172-173cm). The original sample run in August 1986 had an abundance of 3.6mg/gm and an age of 11,860 ± 170 years. The new sample run in December 1988 had an abundance of 3.1mg/gm and an age of 11,980 ± 110 years (Table 7).

TABLE 7
V23-81 North Atlantic from the Ruddiman-McIntyre Triangle
Location (54°18'N, 16°48'W) Depth 2393m

ETH no.	Depth (cm)	Coarse fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No. tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
4193	157-158	8.7	N pach s	4130	40.4	787	7.7	Jul 88	11,280±90
4656	172-173	2.4	G bull	219	3.14	460	6.6	Feb 89	11,980±110

RED SEA

Deuser and Degens (1969) showed that a marked transition in sediment diagenesis and in stable isotope ratio occurred in the Red Sea at the close of glacial time (Fig 11). Below this transition, pteropods are covered with thick coatings of secondary aragonite. The $\delta^{18}O$ for these coatings is 6‰ higher than for Holocene pteropods and the $\delta^{13}C$ is 3‰ higher (Fig 11). No forams are found below the boundary. We interpret these results to indicate hypersaline conditions in the Red Sea during glacial time. Working with Werner Deuser, we have attempted to establish more closely the date of the sharp transition from glacial to postglacial conditions (see Table 8 for results). Some of our results were published in our previous date list (Broecker *et al* 1988c); the rest are here. In Figure 12, we summarize these findings and show the best age estimate for termination of hypersaline conditions is ca 13,000 years.

SOUTH CHINA SEA

We previously studied two cores, V35-5 and V35-6, from 2km depth in the southern part of the South China Sea with the purpose of determining the age of deep Pacific water during glacial time (Broecker *et al* 1988b). We encountered a problem - *P obliquiloculata* was consistently older than *G sacculifer*. Since no way existed to determine which if either of these age sets was correct, we sought another core. Gerd Liebezeit of the Hamburg University group provided samples from Sonne 50 37KL, a piston core from 2695m in the central part of the basin (Table 9). For the glacial section of this core, we found no consistent bias between the *P obliquiloculata* and *G sacculifer* ages. The mean benthic-planktonic age difference for three pairs is ca 1700 years. These results are discussed in a separate publication (Broecker *et al*, in press).

TABLE 8
Results on Red Sea cores

ETH no.	Depth (cm)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No. tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
Ch61-118K Red Sea Location (21° 14.4'N, 38° 4.3'E) Depth 1989m								
3811	165-170	Pteropods >1000μm	–	--	--	7.5	May 88	11,980±120
3812	165-170	Pteropods 250-1000μm	–	--	--	10.2	May 88	11,520±100
3813	170-175	Pteropods > 1000μm	–	--	--	10.6	May 88	13,420±110
Ch61-119K Red Sea Location (21° 16.8'N, 38° 1.4'E) Depth 2175m								
4451	145-150	<u>G sacc</u>	–	--	--	8.3	Dec 88	8770±90
4452	215-220	Pteropods > 1000μm	–	--	--	8.2	Dec 88	13,640±110
4453	235-240	Pteropods > 1000μm	–	--	--	7.1	Dec 88	15,780±140

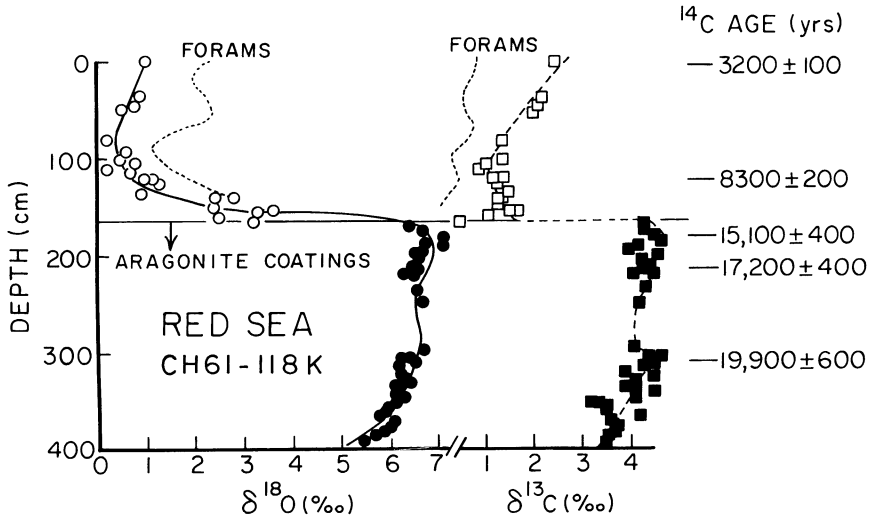

Fig 11. Oxygen and carbon isotope records on pteropods from Red Sea core CH61-118K (Deuser & Degens 1969; Ku, Thurber & Mathieu 1969). ○ = pteropods free of secondary coatings. ● = pteropods heavily coated with secondary aragonite. Also shown are decay counting ^{14}C ages obtained previously on bulk material (Ku, Thurber & Mathieu 1969).

TABLE 9
SONNE 50 37KL South China Sea
Location (18°55′N, 115°45′E) Depth 2695m

ETH no.	Depth (cm)	Coarse fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
5222	8-13	5.1	G sacc	3.0	0.15	191	9.4	Jul 89	2040±70
5221	"	"	P obliq	22.7	1.40	170	10.5	Jul 89	2430±60
5223	"	"	M benth	9.3	0.26	238	6.6	Jul 89	3970±80
4440	40-45	7.7	G sacc	34.5	1.35	197	6.5	Dec 88	5960±80
4439	"	"	P obliq	22.0	9.82	164	7.3	Dec 88	6510±80
4441	"	"	M benth	17.3	0.22	514	6.5	Dec 88	8270±100
5390	60-65	5.5	G sacc	55.8	2.59	164	7.6	Aug 89	8500±110
5391	"	"	P obliq	70.7	3.78	185	9.9	Aug 89	8500±110
5389	"	"	M benth	17.5	0.29	526	8.6	Aug 89	10,030±120
4445	80-85	7.1	G sacc	77.1	2.97	166	6.4	Dec 88	10,560±100
4446	"	"	P obliq	116	4.68	171	6.9	Dec 88	10,620±120
4447	"	"	M benth	14.2	0.22	488	7.4	Dec 88	11,890±110
4655	120-125	5.2	G sacc	119	4.60	176	6.8	Feb 89	13,940±120
4654	"	"	P obliq	17.5	0.68	166	6.4	Feb 89	13,240±120
----	"	"	M benth	20.0	0.29	553	7.9	-	Lost
3807	155-160*	6.7	G sacc	90.8	3.66	328	13.2	May 88	12,730±140
3806	"	"	P obliq	128	5.01	267	10.5	May 88	12,290±250
3808	"	"	M benth	8.3	0.23	396	11.0	May 88	13,710±120
5440	160-165	2.3	G sacc	30.3	1.44	179	8.5	Aug 89	15,140±150
5441	"	"	P obliq	12.1	0.65	148	7.9	Aug 89	15,300±150
5444	"	"	M benth	11.6	0.23	466	9.4	Aug 89	17,100±220
4650	165-170	2.2	G sacc	9.8	0.49	159	8.0	Feb 89	15,490±110
4651	"	"	P obliq	16.8	0.78	171	7.9	Feb 89	15,590±160
-----	"	"	M benth	12.6	0.16	575	7.2	-	Lost
4204	175-180	2.4	G sacc	9.0	0.46	165	8.5	Oct 88	15,910±110
4205	"	"	P obliq	17.3	0.73	179	7.6	Oct 88	15,890±120
4203	"	"	M benth	14.5	0.21	628	9.1	"	17,430±140
4207	185-190	3.2	G sacc	11.2	0.48	189	8.1	Oct 88	16,000±120
----	"	"	P obliq	19.5	0.79	178	7.2	-	Lost
5065	"	"	P obliq	19.5	0.79	210	7.1	May 89	16,860±150
4206	"	"	M benth	14.3	0.26	462	8.5	Oct 88	17,590±140
4449	195-200	2.9	G sacc	9.7	0.30	228	7.1	Dec 88	17,460±160
4450	"	"	P obliq	18.3	0.76	203	8.4	Dec 88	17,270±150
4448	"	"	M benth	16.2	0.20	613	7.5	Dec 88	18,940±160
5437	205-210	2.8	G sacc	2.4	1.27	180	9.5	Aug 89	17,660±180
5438	"	"	P obliq	7.3	0.38	146	7.5	Aug 89	17,255±190
5439	"	"	M benth	15.6	0.23	815	12.1	Aug 89	19,445±190

*Error in depth? Age fits better if 105-110 cm.

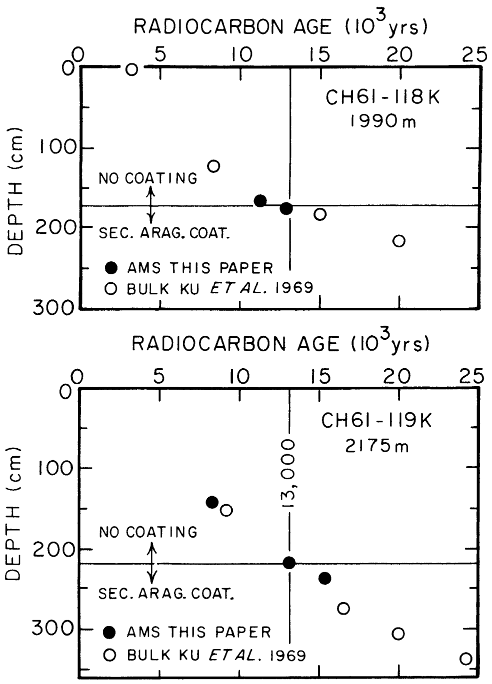

Fig 12. ^{14}C ages (corrected for a 400-yr age for surface-water) *vs* depth in two Red Sea cores previously studied by Deuser and Degens (1969). In both, the transition from conditions conducive to the generation of thick secondary coatings abruptly ended ca 13,000 years ago.

SULU BASIN

In searching for the source of the age differences between *P obliquiloculata* and *G sacculifer* observed in core V35-5 in the South China Sea, we chose core V24-135 in the Sulu Sea. Rather than shedding light on the problem, these samples yielded large age differences for which we have no satisfactory explanation (Table 10) (see Broecker *et al* 1989b, for discussion).

TABLE 10
V24-135 Sulu Basin, Sulu Sea
Location (07°21'N, 120°21'E) Depth 4276m

ETH no.	Depth (cm)	Coarse fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
3794	101-102	22.9	G sacc	272	17.3	170	10.8	May 88	14,410±160
4039	"	"	G sacc	272	22.0	100	8.1	Jul 88	14,650±130
3795	"	"	P obliq	78.3	3.01	323	12.4	May 88	10,660±130
4038	"	"	P obliq	78.3	2.2	289	8.1	Jul 88	10,390±100
3797	110-111	31.3	G sacc	156	10.3	170	11.2	May 88	17,870±160
3796	"	"	P obliq	56.1	2.97	100	5.3	May 88	16,320±150
3799	119-120	5.6	G sacc	29.4	1.55	232	12.2	May 88	13,940±140
3798	"	"	P obliq	28.2	1.17	200	8.3	May 88	11,670±110
3805	131-133	10.4	G sacc	101	8.02	200	15.9	May 88	20,670±210
3804	"	"	P obliq	16.8	0.66	154	6.0	May 88	21,060±220
3809	141-142	27.2	G sacc	139	8.46	215	13.1	May 88	19,220±210
3810	"	"	P obliq	32.1	1.43	157	7.0	May 88	18,750±170

MOROTAI BASIN

In yet another attempt to assess the age difference between *P obliquiloculata* and *G sacculifer* found in South China Sea core V35-5, we measured two pairs in core V33-88 from the Morotai Basin in the Philippine Sea (Table 11). Although in both cases *P obliquiloculata* was older than *G ruber*, the age differences of 300 and 210 years lie within the error of measurement. Since insufficient benthics were available in these samples for dating, we abandoned study of this core.

TABLE 11
V33-88 Morotai Basin, Philippine Sea
Location (2°42′N, 127°50′E) Depth 3237m

ETH no.	Depth (cm)	Coarse fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
-	135-136	9.7	G sacc	55.6	1.21	137	4.4	-	Lost
3708	"	"	G ruber	491	5.62	600	5.5	Mar 88	13,050±110
3699	"	"	P obliq	296	8.03	297	8.0	Mar 88	13,350±120
-	155-156	8.3	G sacc	6.2	0.22	92	4.5	-	Lost
3710	"	"	G ruber	236	2.25	740	7.8	Jul 88	14,180±120
3701	"	"	P obliq	150	4.31	428	8.2	Jul 88	14,370±150

EAST PACIFIC RISE

As a check on the reproducibility of our results, we repeated the analysis of two samples published in our previous list (Table 12). They were from 34-36cm in core TT154-10. For *G sacculifer*, we obtained 16,630 ± 140 years for a repick of a sample which previously had given 16,600 ± 340 years. For *P obliquiloculata*, we obtained 16,890 ± 140 years for a repick of a sample that had previously yielded an age of 16,530 ± 340.

TABLE 12
TT154-10 (Core 5) East Pacific Rise
Location (10°17.5′N, 111°20′W) Depth 3225m

ETH no.	Depth (cm)	Coarse fraction (%)	Foram sp	Abund (no/gm)	Abund (mg/gm)	No tests analyzed	Weight analyzed (mg)	Date of AMS analysis	Age (yr)
4434	34-36	47.5	G sacc	-	-	-	8.6	Dec 88	16,630±140
4435	"	"	P obliq	-	-	-	7.5	Dec 88	16,890±140

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