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27. MIOCENE BENTHIC FORAMINIFER OXYGEN AND CARBON ISOTOPES, SITE 709, INDIAN OCEAN[1]

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ABSTRACT

The benthic isotopic record of Miocene *Cibicidoides* from Site 709 provides a record of conditions in the Indian Ocean at a depth of about 3200 mbsf. As expected, the record qualitatively resembles those of other Deep Sea Drilling Project and Ocean Drilling Program sites. The data are consistent with the scenario for the evolution of thermohaline circulation in the Miocene Indian Ocean proposed by Woodruff and Savin (1989). Further testing of that scenario, however, requires isotopic data for *Cibicidoides* from other Indian Ocean sites. There is a correlation between $\delta^{13}C$ values of *Cibicidoides* and planktonic:benthic (P:B) ratios of Site 709 sediments, implying a causal relationship between the corrosiveness of deep waters and concentration of CO_2 derived from oxidation of organic matter.

INTRODUCTION

In this paper, we report the results of oxygen and carbon isotopic analyses of the tests of Miocene benthic foraminifers from Ocean Drilling Program (ODP) Site 709. Site 709 is located near the summit of the Madingley Rise in the western Indian Ocean. Present-day water depth is 3041 m. Back-tracked Miocene depths of the site are between about 2550 and 2900 m, making it the deepest Indian Ocean site for which Miocene benthic isotope data are available.

Woodruff and Savin (1989) presented a global synthesis of Miocene benthic foraminiferal carbon isotopic data and interpreted directions of deep- and intermediate-water flow from variations in $\delta^{13}C$ values of the tests. They concluded that early Miocene thermohaline circulation was very different from that of today. They proposed that during early Miocene time a plume of warm, saline water from the Tethys entered the northern Indian Ocean in the region of the Red Sea and Persian Gulf. This plume would have sunk to intermediate depths in the Indian Ocean, entraining warm surface water as it sank and forming a water mass they called Tethyan Indian Saline Water (TISW). The TISW would have flowed southward to high southern latitudes where it would have welled up into the circumantarctic surface circulation. There, they proposed, it would have become refrigerated and sunk to the ocean bottom, flowing northward in the Atlantic, Pacific, and Indian oceans analogous to modern Antarctic Bottom Water (AABW). Thus, the proposed Tethyan outflow water and the resulting TISW would have played an early Miocene role similar in some respects to that of North Atlantic Deep Water (NADW) in the modern ocean.

Of all benthic foraminiferal taxa commonly used in isotopic reconstructions of oceanographic conditions, carbon isotopic ratios of the genus *Cibicidoides* appear to reflect the $\delta^{13}C$ values of dissolved HCO_3^- in seawater at the sediment-water interface most closely (Duplessy et al., 1984; Shackleton et al., 1984; Savin and Woodruff, 1990, unpubl. data, and others). Miocene isotopic data are available for only a few sites in the Indian Ocean and most of the available data are for *Oridorsalis umbonatus* (Vincent et al., 1985). It is critical to the testing of our early Miocene scenario, or any other model of Miocene thermohaline circulation, to enlarge the data base of isotopic compositions of Miocene *Cibicidoides* from the Indian Ocean. This brief paper represents a small step toward compilation of that data base.

METHODS AND PROCEDURES

Benthic foraminifers were prepared for isotopic analysis following procedures described by Woodruff and Savin (1989). Preparation of CO_2 for isotopic analysis was done with a modified version of the technique of Epstein et al. (1951). These modifications are especially useful in the analysis of small (< 500 μg) samples of $CaCO_3$.

Samples weighing between a few tens of micrograms and 1 mg were placed in a miniaturized Rittenberg tube (Fig. 1) with 0.5 ml of 100% phosphoric acid. The tubes were evacuated overnight, and then placed in a thermostated water bath at 25°C. No more than 24 hr before the CO_2 was to be collected, the Rittenberg tube was tipped, which allowed the acid to contact the $CaCO_3$. After a reaction time of 2–24 hr at 25°C, the tube was plunged into a Dewar flask containing a slush made from a mixture of ethanol and finely ground dry ice. The tube, still in the Dewar, was then attached directly to a mass spectrometer sample inlet system of our own design, and the CO_2 was distilled into the variable volume inlet where it was frozen with liquid N_2 and analyzed isotopically.

This technique yields cleaner CO_2 and isotopic analyses of small samples of higher precision than we could obtain with more conventional multistage cryogenic distillation procedures. We routinely achieved precision of $\delta^{18}O$ and $\delta^{13}C$ analyses of better than 0.1‰ with samples weighing as little as 150 μg.

RESULTS

Isotopic Time Series

Isotopic results, as well as planktonic:benthic (P:B) ratios of samples from Holes 709A and 709B are tabulated in Table 1. Isotopic data are plotted as a function of depth (meters below sea floor [mbsf]) in Figures 2a and 2b. At this time only a few biostratigraphic ages of Miocene Site 709 samples have been determined. We have assigned ages based upon correlations between oxygen and carbon isotopic curves from Holes 709A and 709B and those of high-resolution Pacific ^{18}O and ^{13}C records for which there are well-determined nannofossil, radiolarian, diatom, and planktonic foraminifer datums (Woodruff and Savin,

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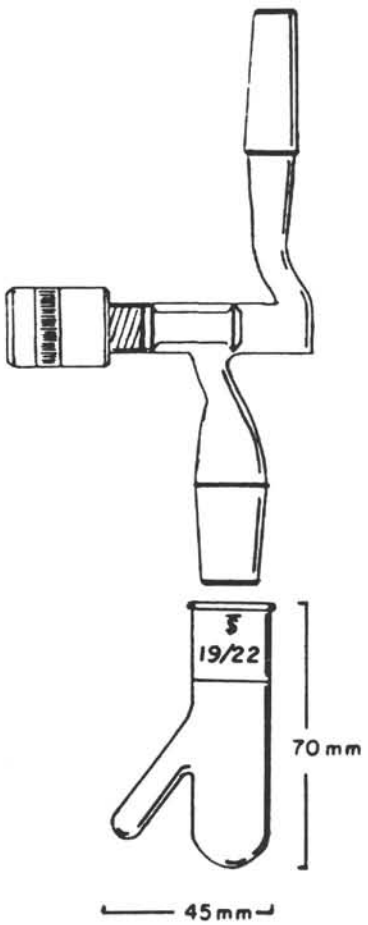

Figure 1. Miniature Rittenberg tube used for reaction of small carbonate samples. The lower portion of the vessel fits easily inside a standard 265-ml Dewar.

unpubl. data). The ages of datums we used are based on those listed in Barron et al., 1985. The early Miocene isotopic patterns are not sufficiently distinct to permit their use for making age assignments. We have a high degree of confidence in the ages of the middle Miocene section between 119 and 150 mbsf from Holes 709A and 709B. We correlated sediments at a depth of 132.5 mbsf from Hole 709A with those from 136 mbsf in Hole 709B as well as sediments from a depth of 151.5 mbsf at Hole 709A with those at 150.5 mbsf at Hole 709B. Thus, the section from Hole 709A fills a gap that we think resulted from sediment missing between Cores 115-709B-15H and -16H. Age determinations based upon the isotopic record and also upon biostratigraphy (Backman, Duncan, et al., 1988; Rio et al., this volume; Johnson, this volume) are indicated in Figure 2; age determinations based on the isotopic record are listed in Table 2. Biostratigraphic age datums from Backman, Duncan, et al. (1988) that appear compatible with the isotopic data are listed in Table 3.

Backman, Duncan, et al. (1988) inferred from whole-core magnetic susceptibility profiles that the early Miocene section from 163.3 to 168.0 mbsf in Hole 709B is a repetition of the interval immediately overlying it. The isotopic patterns (Fig. 3) are consistent with, but do not require, this interpretation. Core 115-709B-20H (177.6–187.2 mbsf) was not recovered.

Qualitatively, the major features of the oxygen and carbon isotopic records resemble those of other Miocene sites. These will not be detailed here. Mean $\delta^{18}O$ and $\delta^{13}C$ values of *Cibicidoides* deposited during several Miocene intervals are listed in Table 4. The mean values, when plotted on the depth vs. latitude transects of Woodruff and Savin (1989), agree for the most part with the patterns and contours suggested by analyses of *Cibicidoides* and adjusted analyses of *Oridorsalis* from the shallower sites in the Indian Ocean and by analyses of *Cibicidoides* from a range of depths in the Atlantic and Pacific oceans. That is, the $\delta^{13}C$ values are only slightly lower than those of shallower benthic foraminifers from the Indian Ocean. However, between 15 and 17 Ma, *Cibicidoides* from Site 709 are depleted in ^{13}C by several tenths of a per mil relative to benthic foraminifers from shallower Indian Ocean sites, and their $\delta^{13}C$ values are among the lowest found in any ocean during that interval. Interpretation of these unexpectedly low $\delta^{13}C$ values awaits completion of isotopic analyses of *Cibicidoides* from other Indian Ocean sites.

Interspecific Isotopic Variations

The data set provides several opportunities to compare $\delta^{18}O$ and $\delta^{13}C$ values of different benthic taxa from within the same sample. The results of these comparisons are listed in Tables 5 and 6. Although there are not a large number of comparisons, the data indicate the possibility that *Cibicidoides wuellerstorfi* may be depleted in ^{18}O and enriched in ^{13}C by small amounts (0.0‰–0.2‰) relative to *Cibicidoides kullenbergi* and *Cibicidoides lamontdohertyi* (named by Miller and Katz, 1987). Additional comparisons are necessary to determine whether these isotopic differences are indeed significant. *Cibicidoides* are depleted in ^{18}O by 0.18–0.49‰ (mean 0.38‰ ± 0.11‰) relative to *Oridorsalis umbonatus* from the same samples. *Cibicidoides* are enriched in ^{13}C relative to *Oridorsalis* by amounts ranging from −0.56‰ to −1.22‰ (mean 0.96‰ ± 0.26‰). The mean differences are similar to the adjustments used by Woodruff and Savin (1989) to adjust *Oridorsalis* δ values to those expected for *Cibicidoides* from the same samples (0.60 for oxygen and −1.10 for carbon. The standard deviation about the mean difference for carbon is large, however.

Relation between $\delta^{13}C$ Values and Planktonic:Benthic Ratios

Planktonic:benthic ratios depend in part upon productivity and the rate of sedimentation of planktonic foraminifers, and in part on the degree of preservation of carbonate on the seafloor. Because planktonic tests are, in general, more readily dissolved than benthic tests, the P:B ratio decreases as foraminifers are dissolved at the sediment-water interface. At Site 709 there is a striking correlation between P:B ratios and the $\delta^{13}C$ values of *Cibicidoides*. This may be seen in the time series graph of Figure 4. (The logarithm of the P:B ratio is plotted because of the extremely wide range of variability of the ratio.). Although the P:B record is especially noisy, it is clear that higher $\delta^{13}C$ values correspond to higher P:B ratios. A linear regression indicates a correlation between $\delta^{13}C$ and a 5-point running average of log P:B (Fig. 5) that is significant at the 99% level. This correlation strongly suggests that P:B ratios at Site 709 reflect conditions at the sediment-water interface to a significant extent.

The $\delta^{13}C$ values of deep and intermediate waters are affected by a complex of factors related to the input of organic and inorganic carbon to the oceans, the oxidation of organic carbon in seawater, and removal of carbon into sediments. In a global synoptic view, $\delta^{13}C$ values of dissolved HCO_3^- in deep and intermediate waters are negatively correlated with the amount of dissolved respiratory CO_2 in the water. The dissolution of respiratory CO_2 also enhances the solubility of $CaCO_3$ in the water.

Temporal variations in the $\delta^{13}C$ value of dissolved HCO_3^- at a single site cannot be interpreted so simply. However, the correlation between $\delta^{13}C$ and P:B ratios at Site 709, and the general similarity between the $\delta^{13}C$ record of Site 709 and those of other Atlantic, Pacific, and Indian ocean sites imply that intervals in

Table 1. Oxygen and carbon isotope ratios of Miocene benthic foraminifers from Site 709A and 709B.

Core, section, interval (cm)	Depth (mbsf)	Species	$\delta^{18}O$	$\delta^{13}C$	P:B ratio
115-709A-					
14H-5, 2–5	131.8	*Cibicidoides kullenbergi*	1.59	0.75	371
14H-5, 50–53	132.3	*Cibicidoides kullenbergi*	1.69	1.01	796
14H-5, 94–97	132.7	*Cibicidoides kullenbergi*	1.44	0.59	351
14H-6, 1–4	133.31	*Cibicidoides kullenbergi*	1.76	0.86	365
14H-6, 50–53	133.80	*Cibicidoides kullenbergi*	1.54	0.67	230
14H-6, 100–103	134.30	*Cibicidoides kullenbergi*	1.78	0.80	430
14H-7, 3–6	134.83	*Cibicidoides kullenbergi*	1.76	0.73	484
14H-7, 47–50	135.3	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	1.53	0.31	103
15H-1, 5–8	135.55	*Cibicidoides kullenbergi*	1.76	0.88	180
15H-1, 50–53	136.00	*Cibicidoides kullenbergi*	1.86	0.85	145
15H-1, 101–104	136.51	*Cibicidoides kullenbergi*	1.75	0.77	208
15H-2, 2–5	137.02	*Cibicidoides kullenbergi*	1.70	0.56	150
15H-2, 50–53	137.501	*Cibicidoides lamontdohertyi*	1.74	0.81	52
15H-2, 94–97	137.94	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	1.73	0.78	29
15H-3, 2–5	138.52	*Cibicidoides lamontdohertyi*	1.99	0.64	74
15H-3, 2–5	138.52	*Cibicidoides kullenbergi*	1.79	0.65	74
15H-3, 50–53	139.00	*Cibicidoides kullenbergi*	1.99	0.86	95
15H-3, 50–53	139.00	*Cibicidoides lamontdohertyi*	2.12	0.70	95
15H-3, 100–103	139.50	*Cibicidoides kullenbergi*	1.67	0.87	102
15H-4, 2–5	140.02	*Cibicidoides kullenbergi*	1.83	0.90	201
15H-4, 50–53	140.50	*Cibicidoides kullenbergi*	1.84	0.72	154
15H-4, 94–97	140.94	*Cibicidoides kullenbergi*	1.89	1.53	167
15H-5, 2–5	141.52	*Cibicidoides kullenbergi*	1.59	1.64	106
15H-5, 50–53	142.00	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	1.72	1.84	137
15H-5, 94–97	142.54	*Cibicidoides kullenbergi*	1.75	1.76	390
15H-6, 2–5	143.02	*Cibicidoides kullenbergi* + *C.* sp. S + *C. trinitatensis*	1.44	1.80	545
15H-6, 50–53	143.50	*Cibicidoides kullenbergi*	1.76	1.63	566
15H-6, 100–103	144.00	*Cibicidoides kullenbergi* + *C. lamontdohertyi* + *C. trinitatensis*	1.34	1.59	404
15H-7, 2–5	144.52	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	1.54	1.58	461
15H-7, 50–52	145.00	*Cibicidoides kullenbergi* + *C.* sp. S	1.50	1.58	493
16H-1, 2–5	145.22	*Cibicidoides kullenbergi* + *C.* sp. S	1.65	1.54	181
16H-1, 50–53	145.70	*Cibicidoides kullenbergi* + *C.* sp. S	1.42	1.25	696
16H-1, 94–97	146.14	*Cibicidoides kullenbergi* + *C.* sp. S	1.46	1.20	294
16H-2, 2–5	146.72	*Cibicidoides kullenbergi* + *C.* sp. S + *C. lamontdohertyi*	1.66	1.51	465
16H-2, 50–52	147.20	*Cibicidoides kullenbergi*	1.19	0.97	416
16H-2, 94–97	147.64	*Cibicidoides wuellerstorfi* + *C. lamontdohertyi*	1.37	0.99	199
16H-3, 2–5	148.22	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	1.87	1.08	241
16H-3, 50–53	148.70	*Cibicidoides kullenbergi*	1.71	0.97	557
16H-3, 101–104	149.21	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	1.73	1.03	131
16H-4, 2–5	149.72	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	1.98	1.10	519
16H-4, 50–53	150.20	*Cibicidoides kullenbergi*	1.52	0.81	347
16H-4, 102–105	150.72	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	1.86	0.80	423
16H-5, 2–5	151.22	*Planulina renzi*	1.50	0.85	249
16H-5, 2–5	151.22	*Cibicidoides kullenbergi*	1.70	0.76	249
16H-5, 50–53	151.70	*Cibicidoides kullenbergi*	1.64	0.76	189
16H-5, 94–97	152.20	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	1.86	0.85	273
16H-6, 2–5	152.70	*Cibicidoides kullenbergi*	1.60	0.66	278
16H-6, 53–56	153.23	*Cibicidoides kullenbergi*	1.69	0.79	287
16H-6, 100–103	153.73	*Cibicidoides kullenbergi*	1.53	0.70	227
16H-7, 2–5	154.22	*Cibicidoides kullenbergi*	1.80	0.69	157
16H-7, 50–53	154.70	*Cibicidoides kullenbergi*	1.51	0.45	111
17H-1, 50–53	155.3	*Cibicidoides kullenbergi* + *Planulina renzi*	1.87	1.02	
17H-1, 100–103	155.9	*Cibicidoides kullenbergi* + *Planulina renzi*	1.87	1.11	
17H-2, 4–7	156.5	*Cibicidoides kullenbergi* + *Planulina renzi*	1.64	0.91	

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	Species	$\delta^{18}O$	$\delta^{13}C$	P:B ratio
115-709B-					
7H-2, 75–80	54.2	*Cibicidoides wuellerstorfi*	2.63	0.03	167
7H-4, 70–75	57.2	*C. wuellerstorfi* + *C. kullenbergi* + *Planulina bradyi*	2.84	0.37	244
7H-5, 125–130	59.2	*C. wuellerstorfi* + *Planulina bradyi*	2.62	0.24	357
8H-2, 25–30	61.9	*Cibicidoides kullenbergi* + *C. wuellerstorfi*	2.73	0.16	57
8H-4, 70–75	66.9	*Cibicidoides wuellerstorfi*	2.68	−0.12	274
8H-5, 125–130	68.9	*Cibicidoides wuellerstorfi*	2.74	0.22	34
9H-2, 25–30	71.9	*Cibicidoides wuellerstorfi*	2.71	0.27	25
9H-4, 70–75	76.5	*Cibicidoides rugosa* + *C. kullenbergi*	2.89	0.29	262
9H-5, 125–130	78.3	*Cibicidoides wuellerstorfi*	2.81	0.05	87
10H-2, 25–30	82.7	*Cibicidoides wuellerstorfi* + *C. rugosa*	2.66	0.04	57
10H-4, 70–75	86.2	*Cibicidoides wuellerstorfi*	2.61	0.71	231
10H-5, 125–130	88.2	*Cibicidoides kullenbergi*	2.66	0.54	175
11H-2, 25–30	92.3	*Oridorsalis umbonatus*	2.97	−1.10	289
11H-2, 25–30	92.3	*Cibicidoides wuellerstorfi*	2.53	0.12	289
11H-2, 25–30	92.3	*Cibicidoides* sp. B	2.57	0.15	289
11H-2, 25–30	92.3	*Planulina bradyi*	2.98	0.78	289
11H-4, 25–30	95.3	*Cibicidoides kullenbergi* + *C. wuellerstorfi* + *C.* sp. B	2.67	1.10	250
11H-4, 70–75	95.8	*Cibicidoides wuellerstorfi*	2.53	1.11	221
11H-6, 25–30	98.3	*Oridorsalis umbonatus*	3.08	0.42	270
11H-6, 25–30	98.3	*Cibicidoides wuellerstorfi*	2.59	0.76	270
11H-6, 25–30	98.3	*Cibicidoides kullenbergi*	2.67	0.63	270
12H-2, 25–30	102.0	*C. wuellerstorfi* + *Planulina bradyi*	2.51	0.94	301
12H-3, 70–75	104.0	*Cibicidoides wuellerstorfi*	2.72	0.60	670
12H-4, 25–30	105.0	*Cibicidoides wuellerstorfi*	2.55	0.70	329
12H-7, 25–30	109.2	*Cibicidoides kullenbergi*	2.78	0.72	202
13H-1, 75–80	110.6	*Cibicidoides wuellerstorfi*	2.68	0.54	74
13H-1, 125–130	111.1	*Cibicidoides wuellerstorfi*	2.49	0.59	135
13H-2, 25–30					38
13H-2, 75–80	112.15	*Cibicidoides wuellerstorfi*	2.52	0.70	37
13H-2, 125–130	112.65	*Cibicidoides wuellerstorfi*	2.39	0.56	43
13H-3, 25–30	113.15	*Cibicidoides kullenbergi*	2.58	0.45	80
13H-3, 70–75	113.60	*Cibicidoides wuellerstorfi*	2.52	0.90	490
13H-3, 70–75	113.60	*Cibicidoides kullenbergi*	2.63	0.86	490
13H-3, 75–80	113.65	*Cibicidoides kullenbergi*	2.48	0.78	69
13H-3, 75–80	113.65	*Cibicidoides wuellerstorfi*	2.56	0.93	69
13H-3, 125–130	114.1	*Cibicidoides wuellerstorfi*	2.32	0.80	41
13H-4, 25–30	114.7	*Cibicidoides wuellerstorfi*	2.53	0.71	113
13H-4, 75–80	115.1	*Cibicidoides wuellerstorfi*	2.46	0.77	33
13H-4, 125–130	115.6	*Cibicidoides kullenbergi*	2.56	0.62	58
13H-4, 125–130	115.6	*Cibicidoides wuellerstorfi*	2.33	0.86	58
13H-5, 25–30	116.1	*Cibicidoides lamontdohertyi*	2.62	0.60	140
13H-5, 25–30	116.1	*Cibicidoides wuellerstorfi*	2.37	0.93	140
13H-5, 75–80	116.6	*Cibicidoides lamontdohertyi*	2.57	0.67	148
13H-5, 75–80	116.6	*Cibicidoides kullenbergi*	2.65	0.78	148
13H-5, 75–80	116.6	*Cibicidoides wuellerstorfi*	2.33	0.72	148
13H-5, 125–130	117.1	*Cibicidoides wuellerstorfi*	2.38	1.14	75
13H-6, 25–30	117.6	*Cibicidoides wuellerstorfi*	2.59	1.05	353
13H-6, 75–80	118.1	*Cibicidoides wuellerstorfi*	2.34	1.21	272
13H-6, 125–130	118.6	*Cibicidoides wuellerstorfi*	2.38	0.97	266
13H-7, 25–30	119.1	*Cibicidoides wuellerstorfi*	2.37	0.94	303
14H-1, 75–80	120.3	*Cibicidoides wuellerstorfi* + *C.* sp. C + *C. kullenbergi*	2.33	1.56	601
14H-1, 125–130	120.8	*Cibicidoides wuellerstorfi*	2.50	0.99	114
14H-1, 125–130	120.8	*Cibicidoides lamontdohertyi*	2.57	0.72	114
14H-2, 25–30	121.3	*Cibicidoides wuellerstorfi* + *C. kullenbergi*	2.29	0.67	386
14H-2, 75–80	121.8	*Cibicidoides kullenbergi* + *C. wuellerstorfi*	2.56	0.92	302
14H-2, 125–130	122.3	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	2.60	0.82	309
14H-3, 25–30	122.8	*Cibicidoides lamontdohertyi*	2.66	0.81	372
14H-3, 70–75	123.2	*Oridorsalis umbonatus*	2.65	−0.85	210
14H-3, 75–80	123.3	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	2.36	0.78	127
14H-3, 125–130	123.8	*Cibicidoides kullenbergi*	2.49	0.99	142
14H-4, 25–30	124.3	*Cibicidoides kullenbergi* + *C. wuellerstorfi*	2.51	0.95	322
14H-4, 75–80	124.8	*Cibicidoides kullenbergi* + *C. wuellerstorfi* + *C. lamontdohertyi*	2.49	0.99	481
14H-4, 125–130	125.3	*Cibicidoides kullenbergi*	2.28	1.05	198

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	Species	$\delta^{18}O$	$\delta^{13}C$	P:B ratio
115-709B- (Cont.)					
14H-5, 25–30	125.7	*Cibicidoides kullenbergi + C. wuellerstorfi*	2.12	1.65	591
14H-5, 125–130	126.8	*Cibicidoides kullenbergi + C. wuellerstorfi*	2.22	1.79	1294
14H-6, 25–30	127.2	*Cibicidoides kullenbergi + C. wuellerstorfi + C. lamontdohertyi*	2.38	1.01	398
14H-6, 75–80	127.8	*Cibicidoides kullenbergi + C. wuellerstorfi + C. lamontdohertyi*	2.25	1.19	390
14H-6, 125–130	128.3	*Cibicidoides wuellerstorfi + C. kullenbergi*	2.11	1.25	423
14H-7, 25–30	128.7	*Cibicidoides wuellerstorfi + C. kullenbergi*	2.13	1.80	579
15H-1, 75–80	130.0	*Cibicidoides kullenbergi + C.* sp. C	1.66	1.38	200
15H-1, 125–130	130.5	*Cibicidoides kullenbergi*	1.70	1.33	
15H-2, 25–30	130.9	*Cibicidoides kullenbergi + C. lamontdohertyi + Planulina bradyi*	1.69	1.19	442
15H-2, 70–75	131.5	*Cibicidoides kullenbergi*	1.50	1.56	75
15H-2, 125–130	132.0	*Cibicidoides kullenbergi*	1.84	1.46	
15H-3, 25–30	132.4	*Cibicidoides kullenbergi*	1.19	1.41	
15H-3, 70–75	132.9	*Cibicidoides kullenbergi*	1.32	1.08	152
15H-3, 75–80	133.0	*Cibicidoides kullenbergi*	1.56	1.35	
15H-3, 125–130	133.5	*Planulina bradyi*	2.00	1.11	70
15H-3, 125–130	133.5	*Cibicidoides kullenbergi*	1.82	1.47	70
15H-4, 25–30	133.9	*Oridorsalis umbonatus*	2.29	0.94	262
15H-4, 25–30	133.9	*Cibicidoides kullenbergi*	1.80	1.53	262
15H-4, 75–80	134.5	*Cibicidoides lamontdohertyi*	2.15	1.12	65
15H-4, 125–130	135.0	*Cibicidoides kullenbergi*	1.90	1.08	
15H-5, 23–30	135.4	*Oridorsalis umbonatus*	2.10	0.27	233
15H-5, 25–30	135.4	*Cibicidoides kullenbergi*	1.75	1.03	433
15H-5, 75–80	136.0	*Cibicidoides kullenbergi + C. lamontdohertyi*	1.47	0.57	70
15H-5, 125–130	136.5	*Cibicidoides kullenbergi*	1.52	0.64	
15H-6, 25–30	136.9	*Cibicidoides kullenbergi + C. lamontdohertyi + Planulina renzi*	1.80	0.70	247
15H-6, 70–75	137.5	*Cibicidoides kullenbergi*	1.82	0.60	30
15H-6, 125–130	138.0	*Cibicidoides kullenbergi + C. lamontdohertyi*	1.75	0.79	
15H-7, 25–30	138.4	*Cibicidoides kullenbergi*	1.76	0.88	256
16H-1, 25–30	139.2	*Oridorsalis umbonatus*	1.76	0.05	498
16H-1, 25–30	139.2	*Cibicidoides kullenbergi + C. lamontdohertyi*	1.48	1.06	498
16H-1, 75–80	139.7	*Cibicidoides kullenbergi*	1.49	1.34	146
16H-1, 125–130	140.2	*Cibicidoides kullenbergi* >250 μm	1.77	1.38	437
16H-1, 125–130	140.2	*Cibicidoides kullenbergi* <250 μm	1.80	1.49	437
16H-2, 25–30	140.6	*Cibicidoides kullenbergi*	1.26	1.35	91
16H-2, 25–30	140.6	*Planulina renzi*	1.49	1.66	91
16H-2, 70–75	141.1	*Cibicidoides kullenbergi*	1.61	1.71	482
16H-2, 125–130	141.7	*Cibicidoides kullenbergi*	1.78	1.93	435
16H-3, 25–30	142.1	*Cibicidoides kullenbergi*	1.60	1.70	496
17H-2, 70–75	149.3	*Oridorsalis umbonatus*	2.27	0.17	297
18H-1, 25–30	158.5	*Cibicidoides kullenbergi + Planulina renzi*	1.76	0.67	195
18H-1, 75–80	159.0	*Cibicidoides kullenbergi*	1.68	0.83	230
18H-1, 125–130	159.5	*Cibicidoides kullenbergi*	1.37	0.63	113
18H-2, 25–30	160.0	*Cibicidoides kullenbergi*	1.68	0.45	111
18H-2, 70–75	160.5	*Cibicidoides kullenbergi*	1.65	0.62	196
18H-2, 125–130	161.0	*Cibicidoides kullenbergi + C. lamontdohertyi*	1.78	0.71	320
18H-3, 25–30	161.5	*Cibicidoides kullenbergi + C.* sp. S	1.78	0.73	137
18H-3, 75–80	162.0	*Cibicidoides kullenbergi + C. lamontdohertyi*	1.86	0.75	263
18H-3, 125–130	162.5	*Cibicidoides kullenbergi + C. lamontdohertyi*	1.79	0.84	597
18H-4, 25–30	163.0	*Cibicidoides kullenbergi*	1.47	0.72	183
18H-5, 25–30	164.5	*Cibicidoides kullenbergi*	1.53	0.49	63
18H-6, 25–30	166.0	*Cibicidoides kullenbergi*	1.70	0.77	117
18H-7, 25–30	167.5	*Cibicidoides kullenbergi*	1.75	0.75	132
19H-1, 25–30	168.2	*Cibicidoides lamontdohertyi*	1.89	0.73	162
19H-1, 25–30	168.2	*Cibicidoides kullenbergi*	1.74	0.83	162
19H-1, 75–80	168.7	*Cibicidoides kullenbergi + C. lamontdohertyi*	1.82	0.57	151
19H-1, 125–130	169.2	*Cibicidoides kullenbergi*	1.85	0.61	88
19H-2, 25–30	169.7	*Cibicidoides kullenbergi*	1.76	0.77	32
19H-2, 25–30	169.7	*Cibicidoides lamontdohertyi*	1.65	0.71	32
19H-2, 70–75	170.2	*Cibicidoides lamontdohertyi*	1.76	0.57	352

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	Species	$\delta^{18}O$	$\delta^{13}C$	P:B ratio
115-709B- (Cont.)					
19H-2, 70–75	170.2	*Cibicidoides kullenbergi*	2.06	0.77	352
19H-2, 125–130	170.7	*Cibicidoides kullenbergi*	1.83	0.89	98
19H-2, 125–130	170.7	*Cibicidoides lamontdohertyi*	2.03	0.58	98
19H-3, 25–30	171.2	*Cibicidoides* sp. C	1.73	0.76	64
19H-3, 25–30	171.2	*Cibicidoides kullenbergi*	1.80	0.72	64
19H-3, 25–30	171.2	*Cibicidoides lamontdohertyi*	1.86	0.82	64
19H-3, 75–80	171.7	*Cibicidoides* sp. S	2.01	0.93	160
19H-3, 125–130	172.2	*Cibicidoides kullenbergi*	2.10	0.89	189
19H-4, 25–30	172.7	*Cibicidoides kullenbergi*	2.06	0.90	138
19H-4, 75–80	173.2	*Cibicidoides kullenbergi*	1.85	0.65	122
19H-4, 125–130	173.7	*Cibicidoides kullenbergi*	1.61	0.58	114
19H-5, 25–30	174.2	*Oridorsalis umbonatus*	2.08	-0.10	67
19H-5, 25–30	174.2	*Cibicidoides kullenbergi*	1.90	0.98	67
19H-5, 75–80	174.7	*Cibicidoides lamontdohertyi*	2.09	0.91	105
19H-5, 75–80	174.7	*Cibicidoides kullenbergi*	2.07	0.90	105
19H-5, 125–130	175.2	*Cibicidoides lamontdohertyi*	1.96	0.74	229
19H-5, 125–130	175.2	*Cibicidoides kullenbergi*	1.87	0.68	229
19H-6, 25–30	175.7	*Cibicidoides kullenbergi*	1.65	0.48	185
19H-6, 75–80	176.2	*Cibicidoides kullenbergi*	1.55	0.57	108
19H-6, 125–130	176.7	*Cibicidoides* sp. S	1.90	0.86	409
19H-7, 27–30	177.2	*Cibicidoides kullenbergi*	1.69	0.66	372
21H-1, 25–30	187.4	*Cibicidoides kullenbergi*	2.09	1.50	210
21H-1, 25–30	187.4	*Cibicidoides lamontdohertyi*	2.03	1.19	210
21H-1, 75–80	187.9	*Cibicidoides lamontdohertyi*	1.96	1.30	178
21H-1, 125–130	188.4	*Cibicidoides kullenbergi*	1.88	1.34	124
21H-2, 25–30	188.9	*Cibicidoides lamontdohertyi*	2.32	1.64	387
21H-2, 25–30	188.9	*Cibicidoides kullenbergi*	1.99	1.47	387
21H-2, 75–80	189.4	*Cibicidoides lamontdohertyi*	2.15	1.50	280
21H-2, 125–130	189.9	*Planulina renzi*	1.71	1.21	432
21H-3, 25–30	190.4	*Cibicidoides kullenbergi* + *C. lamontdohertyi* + *Planulina renzi*	1.93	1.57	822
21H-3, 75–80	190.9	*Cibicidoides lamontdohertyi*	1.84	1.06	223
21H-3, 123–128	191.4	*Cibicidoides lamontdohertyi* + *Planulina renzi*	1.81	1.42	162
21H-4, 25–30	191.9	*Cibicidoides kullenbergi* + *C. lamontdohertyi*	1.73	1.30	185
21H-4, 75–80	192.4	*Cibicidoides lamontdohertyi*	2.12	1.40	551
21H-4, 125–130	192.9	*Cibicidoides kullenbergi* + *Planulina renzi*	1.64	0.90	278
21H-5, 25–30	193.4	*Cibicidoides lamontdohertyi* + *C. kullenbergi*	2.01	1.30	273
21H-5, 25–30	193.4	*Cibicidoides kullenbergi*	2.18	1.46	273
21H-5, 75–80	193.9	*Cibicidoides kullenbergi*	1.88	1.35	440
21H-6, 25–30	194.9	*Cibicidoides kullenbergi*	2.12	1.53	234
21H-6, 75–80	195.4	*Cibicidoides kullenbergi*	2.00	1.12	305
21H-7, 15–20	196.4	*Cibicidoides lamontdohertyi* + *C. kullenbergi*	1.98	1.09	206
22H-1, 25–30	197.0	*Cibicidoides kullenbergi*	1.74	1.05	231
22H-1, 75–80	197.5	*Cibicidoides kullenbergi*	1.71	1.18	135
22H-1, 125–130	198.0	*Cibicidoides kullenbergi* + *Planulina renzi*	1.50	1.14	161
22H-2, 25–30	198.5	*Cibicidoides kullenbergi*	1.66	0.89	264
22H-2, 75–80	199.0	*Cibicidoides kullenbergi*	1.61	0.58	288
22H-2, 125–130	199.5	*Cibicidoides kullenbergi*	1.66	0.62	147
22H-3, 75–80	200.5	*Cibicidoides kullenbergi*	1.65	0.72	218

which the corrosiveness of Miocene intermediate and deep water are low may be intervals in which the waters have decreased concentrations of CO_2 formed by oxidation of organic matter. Conversely, periods of poorer carbonate preservation may have been ones in which the concentration of respiratory CO_2 in deep and intermediate water was higher.

CONCLUSIONS

The benthic isotopic record of Miocene *Cibicidoides* from Site 709 provides a record of oceanographic conditions at that location throughout the epoch. As expected, the record qualitatively resembles those of other DSDP and ODP sites. The data are consistent with the scenario for the evolution of thermohaline circulation in the Miocene Indian Ocean proposed by Woodruff and Savin (1989). Further testing of that scenario, however, requires isotopic data from other sites as well as resolution of the reasons for variability in interspecific differences between $\delta^{18}O$ and $\delta^{13}C$ values of different benthic taxa, especially *Cibicidoides* and *Oridorsalis*, from the same sample.

Correlation between $\delta^{13}C$ values of *Cibicidoides* and P:B ratios at Site 709 suggests that Miocene intervals of poorer carbonate preservation at Site 709 are also intervals of increased concentration of respiratory CO_2 in intermediate and deep waters.

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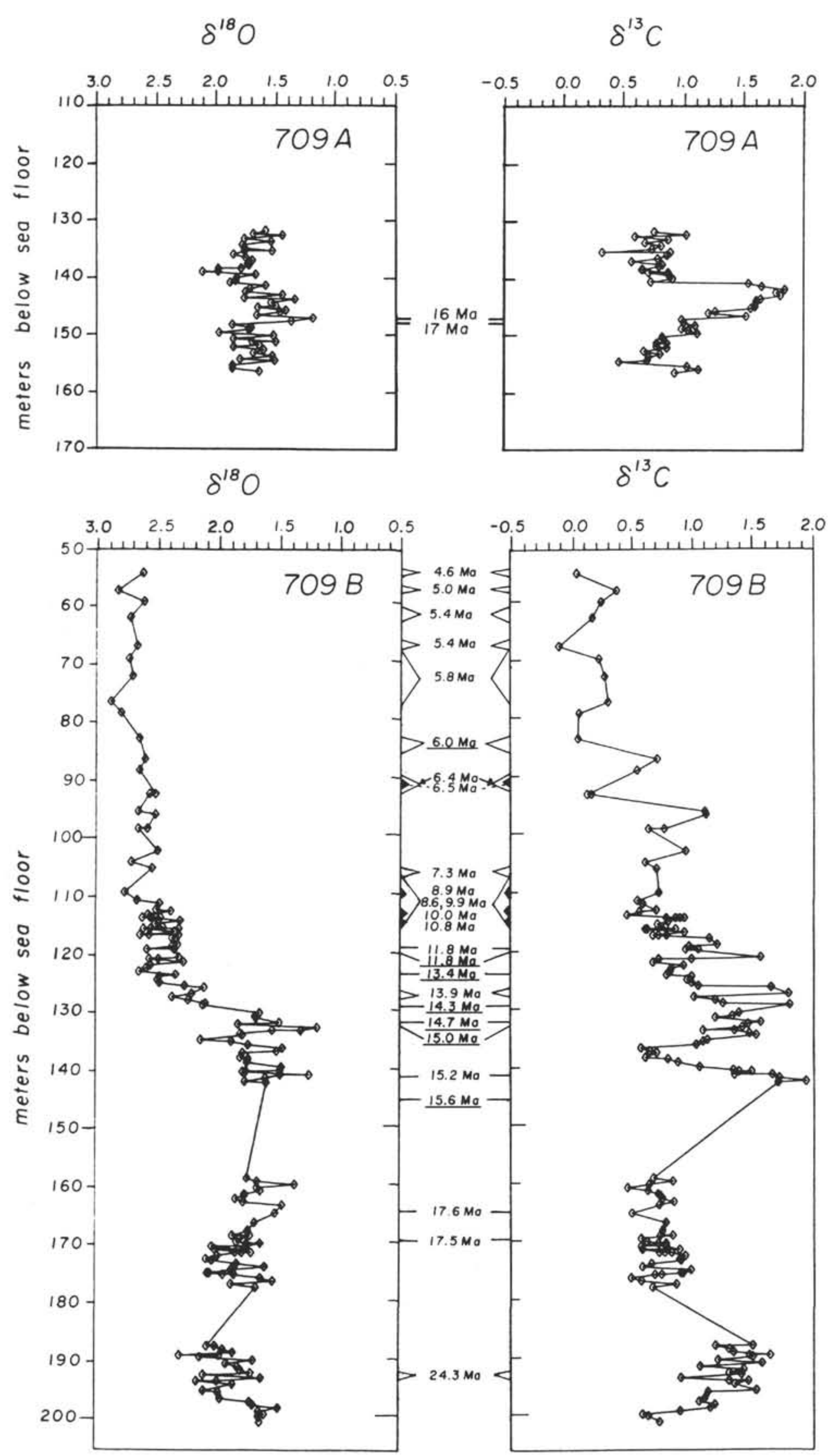

Figure 2. **A.** The $\delta^{18}O$ and $\delta^{13}C$ values of *Cibicidoides* from the Miocene section of Hole 709A. Inferred ages are shown. **B.** The $\delta^{18}O$ and $\delta^{13}C$ values of *Cibicidoides* from the Miocene section of Hole 709B. Isotopically derived ages (see text and Table 2) are underlined. Other ages are inferred from biostratigraphic data sources listed in Table 3.

Table 2. Age determinations for Hole 709B based on the isotopic record (see text).

Depth (mbsf)	Age (Ma)
83–86	6.0
120	11.8
124	13.4
129	14.3
132	14.7
133	15.0
146	15.6

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Table 3. Hole 709B Biostratigraphic age datums from Backman, Duncan, et al. (1988), Rio et al. (this volume), and Johnson (this volume) that are consistent with the isotopic data.

Depth (mbsf)	Age (Ma)	Datum	Zonal boundary
53.3–54.8	4.6	*Ceratolithus rugosus* (N)(B)	CN10c/CN10b, NN13/NN12
56.3–57.8	5.0	*Ceratolithus acutus* (N)(B)	CN10b/CN10a
60.8–63.0	5.4	*Discoaster quinqueramus* (N)(T)	CN10a/CN9
66.5–68.0	5.4	*Acrobotrys tritubus* (R)	
68.0–77.6	5.8	*Pulleniatina primalis* (F)(B)	N17b/N17a
89.5–92.5	6.4	*Stichocorys delmontensis* to *S. peregrina* (R)	
90.2–91.9	6.5	*Amaurolithus primus* (N)(B)	CN9b/CN9a
105.8–107.3	7.3	*Discoaster quinqueramus* (N)(B)	NN11/NN10
107–116	8.6	*Neogloquadrina acostaensis* (F)(B)	N16/N15
107–116	9.9	*Globorotalia siakensis* (F)(T)	N15/N14
109.1–111.1	8.9	*Discoaster hamatus* (N)(T)	CN8a/CN7, NN10/NN9
112.7–114.2	10.0	*Discoaster hamatus* (N)(B)	CN7a/CN6, NN9/NN8
114.2–115.7	10.8	*Catinaster coalitus* (N)(B)	CN6/CN5, NN8/NN7
119	11.8	*Sphaeroidinella subdehiscens* (F)(T)	N13/N12
126.5–127.7	13.9	*Sphenolithus heteromorphus* (N)(T)	CN5A/CN4, NN6/NN5
141	15.2	*Orbulina suturalis* (F)(B)	N9/N8
164.6	17.6	*Catapsydrax dissimilis* (F)(T)	N7/N6
169.8–169.9	17.5	*Sphenolithus heteromorphus* (N)(B)	CN3/CN2
192.2–193.5	24.3	*Lychnocanoma elongata* (R)(B)	Zonal base

Notes: F = foraminifer, R = radiolarian, N = nannoplankton, T = range top, and B = range bottom.

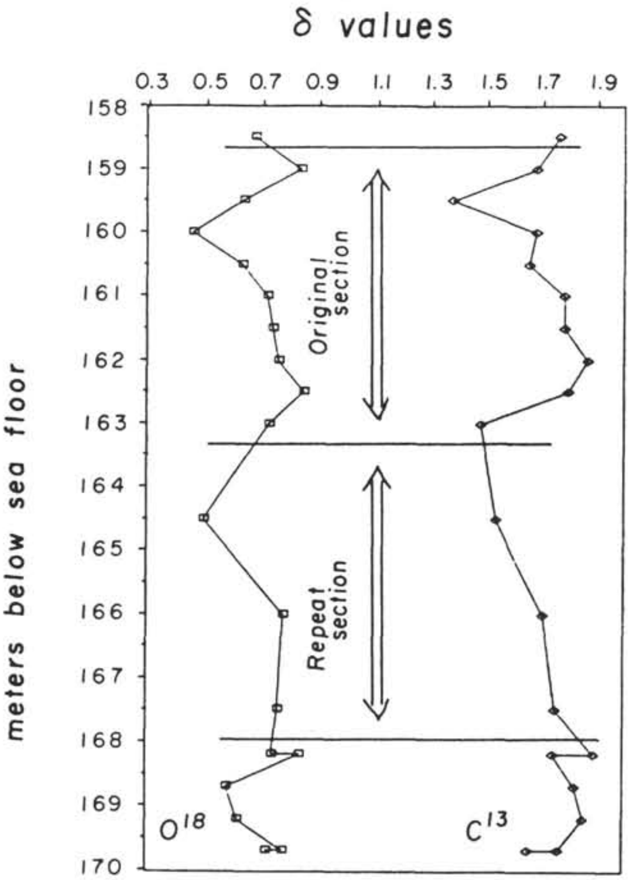

Figure 3. Detail of the oxygen and carbon isotopic records of Hole 709B *Cibicidoides* over the interval from 155 to 170 mbsf. Backman, Duncan, et al. (1988) inferred from whole-sample magnetic susceptibility data that the section between 163.3 and 168 mbsf was a repeat of the immediately overlying interval. The isotopic data are consistent with, but do not require, that interpretation. Squares = $\delta^{18}O$ values, and diamonds indicate $\delta^{13}C$ values.

Table 4. Mean $\delta^{18}O$ and $\delta^{13}C$ values of *Cibicidoides* from Miocene time intervals, Site 709.

Interval	$\delta^{18}O$			$\delta^{13}C$		
(Ma)	Average	SD	*N*	Average	SD	*N*
5-6	2.74	0.09	9	0.17	0.15	9
6-7	2.60	0.06	10	0.61	0.38	10
7-10	2.59	0.13	7	0.63	0.07	7
10-12	2.48	0.11	20	0.83	0.18	20
12-14	2.41	0.15	16	1.06	0.32	16
14-15	1.68	0.30	9	1.38	0.20	9
15-16	1.69	0.18	53	1.10	0.42	53
16-17	1.41	0.19	3	1.16	0.25	3
17-18	1.72	0.13	36	0.77	0.16	36
18-20	1.88	0.16	21	0.75	0.14	21
21-23	1.99	0.08	4	1.33	0.11	4
23-24	1.95	0.21	9	1.36	0.23	9

Note: SD = standard deviation and *N* = number of comparisons.

Table 5. Intra-sample comparisons of $\delta^{18}O$ values of Miocene benthic foraminifers, Site 709.

	Cibicidoides kullenbergi	*Cibicidoides wuellerstorfi*	*Cibicidoides lamontdohertyi*	*Oridorsalis umbonatus*
Cibicidoides kullenbergi	—	−0.11 ± 0.14 *N* = 4	+0.03 ± 0.17 *N* = 10	+0.34 ± 0.11 *N* = 5
Cibicidoides wuellerstorfi		—	+0.19 ± 0.08 *N* = 3	+0.47 ± 0.03 *N* = 2
Cibicidoides lamontdohertyi			—	No comparison
Oridorsalis umbonatus				—

Note: Differences are calculated as the $\delta^{18}O$ value of species in column minus species in row and are listed as averages ± 1 SD. For example, the average of $\delta^{18}O_{wuellerstorfi}$ minus $\delta^{18}O_{kullenbergi}$ is +0.11 ± 0.14. *N* = number of comparisons.

Table 6. Intra-sample comparisons of $\delta^{13}C$ values of Miocene benthic foraminifers, Site 709.

	Cibicidoides kullenbergi	*Cibicidoides wuellerstorfi*	*Cibicidoides lamontdohertyi*	*Oridorsalis umbonatus*
Cibicidoides kullenbergi	—	−0.07 ± 0.08 *N* = 4	−0.10 ± 0.14 *N* = 12	+0.90 ± 0.19 *N* = 5
Cibicidoides wuellerstorfi		—	−0.22 ± 0.12 *N* = 3	−1.20 ± 0.02 *N* = 2
Cibicidoides lamontdohertyi			—	No comparison
Oridorsalis umbonatus				—

Note: Differences are listed as averages ± 1 SD. *N* = number of comparisons.

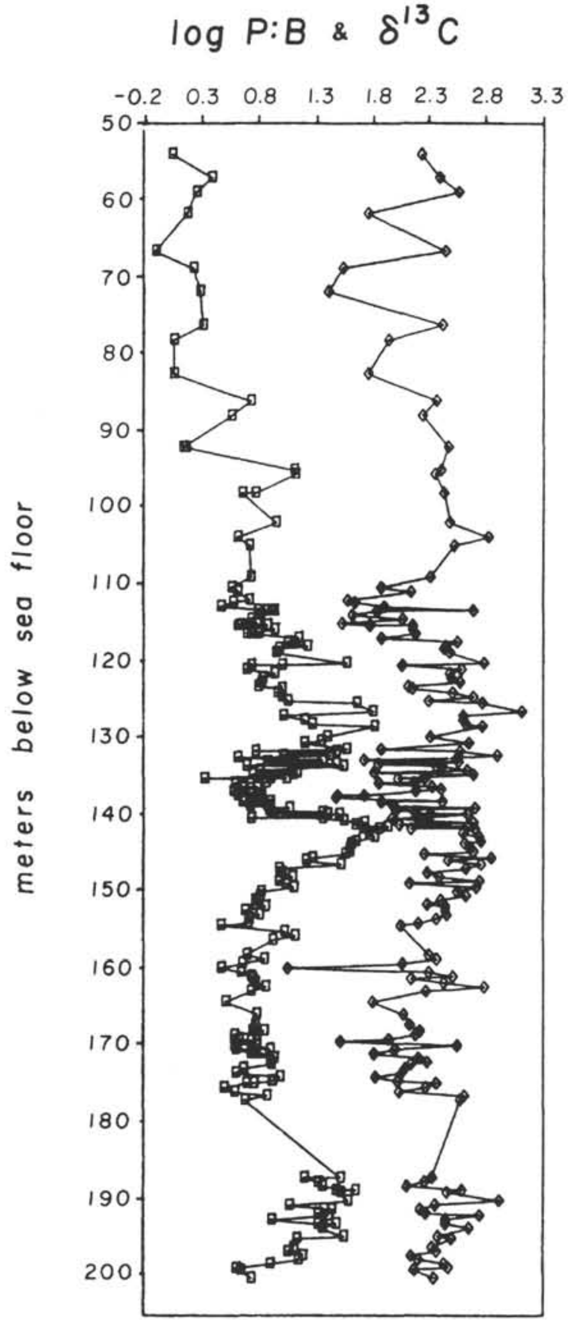

Figure 4. Time-series plot of $\delta^{13}C$ values of *Cibicidoides* from Holes 709A and 709B (squares) compared with planktonic:benthic ratios of the sediment samples (diamonds). P:B ratios are plotted on a logarithmic scale. Major increases in $\delta^{13}C$ correspond to increases in P:B ratio.

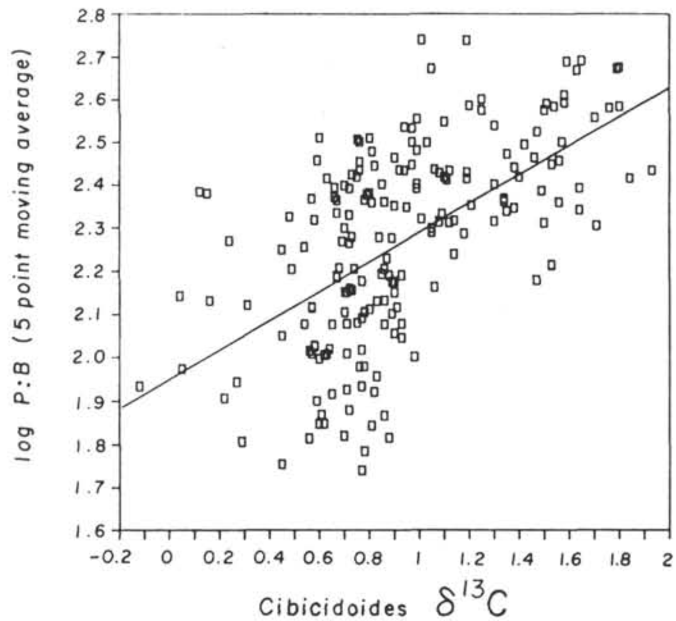

Figure 5. Scatter plot of $\delta^{13}C$ values of *Cibicidoides* vs. the logarithm of the P:B ratio (5-point moving average). The regression line is significant at the 99% level.