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52. MIDDLE MIOCENE BENTHIC FORAMINIFERAL OXYGEN AND CARBON ISOTOPES AND STRATIGRAPHY: SOUTHERN OCEAN SITE 744[1]

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ABSTRACT

We present carbon and oxygen isotope values and planktonic/benthic ratios for middle Miocene (11–17.5 Ma) foraminifers deposited at Ocean Drilling Program Hole 744B in the Southern Ocean. Major features of the isotope records are similar to those of other middle Miocene open-ocean records. The portion of the sequence containing the major middle Miocene $\delta^{18}O$ increase (between 60 and 52 m below seafloor) is a relatively condensed zone characterized by low planktonic/benthic ratios and several hiatuses.

The isotopic record is of sufficiently high resolution to date the $\delta^{18}O$ minima and the $\delta^{13}C$ maxima to within 200,000 yr. Ages determined using the oxygen and carbon isotope stratigraphy are similar to those obtained using diatom, radiolarian, and paleomagnetic stratigraphy, but are approximately 1 m.y. younger than those determined using the strontium isotope stratigraphy published in this volume.

The average middle Miocene sediment-accumulation rate for Hole 744B is approximately 4 m/m.y.

INTRODUCTION

Ocean Drilling Program (ODP) Site 744 is located in the Southern Ocean at 61°34′S, 80°35′E on the southern Kerguelen Plateau. The modern water depth at Site 744 is 2307 m. Using data from the preliminary reports for ODP Leg 119 (Barron, Larsen, et al., 1989), the backtracked middle Miocene water depth was approximately 2150 m, making this the deepest site in the Southern ocean for which middle Miocene isotopic data are available.

ISOTOPIC METHODS AND PROCEDURES

Benthic foraminifer samples were analyzed at the Stable Isotope Laboratory, University of Michigan. All calcite samples were roasted at 380°C to remove volatile contaminants. Samples ranging in weight from 100 to 300 μg were individually reacted at 73°C with 4 drops of anhydrous phosphoric acid in a Finnigan MAT carbonate extraction system ("Keil" device) coupled directly to the inlet of a Finnigan MAT 251 isotope ratio mass spectrometer. Isotopic enrichments were corrected for acid fractionation and ^{17}O contribution. Data are reported in the standard delta (δ) notation representing the per mil deviation of the sample from the Peedee Belemnite (PDB) standard. Precision and calibration of data were monitored through daily analysis of NBS-20 powdered carbonate, which bracketed sample analyses. The measured analytical precision was better than 0.1‰ for both carbon and oxygen isotope analyses.

The oxygen and carbon isotopic values for benthic foraminifers at Hole 744B are listed in Table 1 and shown in Figures 1 and 2. We only use the tests of *Cibicidoides* species because modern species of this genus live at or above the sediment/water interface and should, therefore, record the physical and chemical states of ocean bottom waters (Lutze and Thiel, 1987).

RESULTS AND DISCUSSION

Carbonate Preservation

The preservation state of middle Miocene foraminifers at Site 744 is fair. The benthic foraminifers are etched and have a milky luster. Many of the less robust species have been removed by dissolution. The planktonic foraminifers are highly fragmented. Middle Miocene planktonic/benthic ratios are low at Site 744, ranging from less than 1:1 to 971:1 and averaging 80:1 (Table 1). These values are particularly low when compared to other middle Miocene Indian Ocean sites closer to the equator. Average planktonic/benthic ratios are 320:1 at Hole 709B (backtracked water depth 2.8 km, located 4°S, 6°E) and are 1400:1 at Site 237 (backtracked water depth 1.4 km, located at 7°S, 58°E; Woodruff et al., in press). The calcium carbonate contents of sediments representing this period at Site 744 are low, ranging from 60.7% to 80.6% (Barron, Larsen, et al., 1989). The sediment-accumulation rates for middle Miocene time are also low and are calculated to be 3.7 m/m.y using isotopic stratigraphy.

Stratigraphy

The core depth of the middle Miocene stratigraphic ages assigned at Hole 744B are listed in Table 2 and are shown in Figure 2. Figure 2 shows the $\delta^{13}C$ isotopic record superimposed on the $\delta^{18}O$ record with the isotopic scales reversed (i.e., low $\delta^{18}O$ values are scaled with high $\delta^{13}C$ values). The six "$\delta^{13}C$ maxima" of the Monterey Excursion are shown by large numbers and the "$\delta^{18}O$ events" are shown by large letters with the age interpretation of Woodruff and Savin (in press) below. Biostratigraphic age datums from the stratigraphic synthesis of Barron et al. (this volume) are shown as triangles below the isotopic curves for comparison with the "$\delta^{18}O$ event" stratigraphy. The stratigraphic ages assigned to the oxygen and carbon isotope data are based on the correlation of detailed isotopic records from six sites in the Pacific and Indian oceans with the biostratigraphies of radiolarians, nannofossils, diatoms, and planktonic foraminifers by many authors (Woodruff and Savin, 1989; Woodruff and Savin, in press). The other stratigraphies are as follows: diatoms (Baldauf and Barron, this volume), radiolarians (Lazarus, in press), strontium isotopes (Barrera et al., this volume), and paleomagnetic stratigraphy (Barron et al., this volume; Keating, this volume).

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Table 1. Benthic foraminifer (*Cibicidoides*) $\delta^{18}O$ and $\delta^{13}C$ values and planktonic to benthic foraminifer ratios for Hole 744B.

Core, section, interval (cm)	Depth (mbsf)	Species	$\delta^{18}O$ (‰, PDB)	$\delta^{13}C$ (‰, PDB)	Planktonic/ benthic ratios	Sample size (cm³)
5H-1, 105–107	32.05	*Cibicidoides* sp. B	[a]Lost	Lost	1	10
5H-2, 93–95	33.43	*Cibicidoides kullenbergi* and sp. B	Lost	Lost	1	10
5H-3, 105–107	35.05	Rare	Not sent	Not sent	641	10
5H-4, 105–107	36.55	*Cibicidoides kullenbergi* and sp. B	Lost	Lost	64	10
5H-5, 105–107	38.05	*Cibicidoides kullenbergi* and sp. B	2.37	1.00	5	10
5H-6, 105–107	39.55	*Cibicidoides kullenbergi* and sp. B	Lost	Lost	1	10
6H-1, 105–106	41.55	*Cibicidoides kullenbergi* and sp. B	Lost	Lost	19	10
6H-2, 105–107	43.05	*Cibicidoides* sp. B	Lost	Lost	21	10
6H-3, 105–107	44.55	*Cibicidoides* sp. B	Lost	Lost	26	10
6H-4, 105–107	46.05	*Cibicidoides* sp. B	Lost	Lost	7	10
6H-5, 105–107	47.55	*Cibicidoides* sp. B	Lost	Lost	57	10
6H-6, 105–107	49.05	*Cibicidoides* sp. B	Not sent	Not sent	24	10
7H-1, 23–28	50.23	*Cibicidoides* sp. B	2.57	1.24	188	25
7H-1, 74–79	50.74	*Cibicidoides* sp. B	2.73	1.21	361	25
7H-1, 105–110	51.05	*Cibicidoides* sp. B	2.41	1.15	127	10
7H-1, 120–125	51.20	*Cibicidoides kullenbergi*	2.33	0.88	[b]n.d.	10
7H-2, 23–28	51.73	*Cibicidoides* sp. B	Too small	Too small	22	25
7H-2, 74–79	52.24	*Cibicidoides* sp. B	2.54	1.56	58	25
7H-2, 105–110	52.55	*Cibicidoides kullenbergi* and sp. B	3.37	1.66	971	10
7H-2, 120–125	52.70	*Cibicidoides* sp. B	2.57	1.29	n.d.	10
7H-3, 23–28	53.23	*Cibicidoides kullenbergi* and sp. B	2.29	1.12	26	25
7H-3, 74–79	53.74	*Cibicidoides kullenbergi*	2.27	0.94	2	25
7H-3, 105–110	54.05	*Cibicidoides kullenbergi* and *wuellerstorfi*	Lost	Lost	61	10
7H-4, 23–28	54.73	*Cibicidoides wuellerstorfi* and *kullenbergi*	2.30	1.38	n.d.	25
7H-4, 74–77	55.24	*Cibicidoides wuellerstorfi*	1.75	1.76	29	25
7H-4, 105–110	55.55	*Cibicidoides kullenbergi*	1.89	1.43	7	10
7H-5, 24–29	56.24	*Ciicidoides wuellerstorfi* and *kullenbergi*	1.75	1.78	20	10
7H-5, 74–79	56.74	*Cibicidoides kullenbergi* and *wuellerstorfi*	1.65	1.52	29	25
7H-5, 105–110	57.05	*Cibicidoides kullenbergi* and *wuellerstorfi*	1.76	1.61	21	10
7H-6, 25–30	57.75	*Cibicidoides kullenbergi*	1.59	1.82	1	25
7H-6, 25–30	57.75	*Cibicidoides kullenbergi*	0.37	1.38	1	25
7H-6, 25–30	57.75	*Cibicidoides wuellerstorfi*	1.91	1.88	1	25
7H-6, 25–30	57.75	*Cibicidoides wuellerstorfi*	1.40	1.73	1	25
7H-6, 74–79	58.24	*Cibicidoides kullenbergi* and *wuellerstorfi*	1.43	1.48	1	25
7H-6, 105–110	58.55	*Cibicidoides kullenbergi* and *wuellerstorfi*	1.52	1.55	n.d.	10
7H-6, 120–125	58.70	*Cibicidoides kullenbergi* and *wuellerstorfi*	1.95	1.38	n.d.	10
7H-7, 23–28	9.23	*Cibicidoides kullenbergi*	1.71	1.46	10	25
7H-7, 72–76	59.72	*Cibicidoides kullenbergi* and *wuellerstorfi*	1.39	1.73	11	25
8H-1, 24–29	59.74	*Cibicidoides kullenbergi*	1.29	1.39	11	25
8H-1, 74–79	60.24	*Cibicidoides kullenbergi*	1.27	1.82	272	25

The isotopic ages assigned to the events in the oxygen and carbon isotopic curves are in close agreement with those indicated by diatom, radiolarian, and paleomagnetic stratigraphy. However, the strontium isotope dates are generally at least 1 m.y. older. The paleomagnetic stratigraphy tends to give slightly older ages than the oxygen and carbon isotope stratigraphy in the earliest middle Miocene portion of the record. Although the age of each particular paleomagnetic reversal has been dated by geochronologic methods, the identification of each reversal in a sedimentary section is performed by the biostratigrapher. The relatively old strontium isotopes ages are probably a result of the fact that the early middle Miocene strontium isotope record has only been correlated to microfossil stratigraphy at one site (Site 590) where there is disagreement between the foraminiferal and the nannofossil biostratigraphies. Furthermore, the isotopic record at Site 590 (Kennett, 1986) suggests that there is a large hiatus or condensed zone in the sedimentary record at the interval in question.

Hiatuses

Hiatuses, low planktonic/benthic ratios, and condensed sections are often associated in the sedimentary record. The core depths of hiatuses and intense dissolution intervals (low planktonic/benthic ratios) identified in the sedimentary record of Hole 744B are shown in Table 2. Several of the intervals of intense dissolution discovered at Hole 744B are correlated with the Neogene hiatus (NH) scheme constructed by Keller and Barron (1983). The presence of hiatuses interpreted from the oxygen and carbon isotopic record (NH3A at 55 m below seafloor (mbsf) and NH3B at 53 mbsf) and the diatom record (Baldauf and Barron, this volume) may explain the spread of age determinations in the diatom and radiolarian records (11.9, 12.3, 12.45, and 13.4 Ma) for the interval between 52.2 and 55.23 mbsf (Table 2). At Site 744, middle Miocene intervals with low calcium carbonate contents correlate well with intervals of low planktonic/benthic ratios. The dissolution interval (55–53 mbsf) containing hiatuses NH3A and NH3B has particularly low calcium carbonate abundances for this site (64%–78%; Dorn, this volume). Planktonic/benthic ratios are generally better indicators of intense dissolution than carbonate contents because a severely dissolved interval can still have high calcium carbonate abundances. The lowest planktonic/benthic ratios within this interval (2:1) are found at 53.7 mbsf. The designation of NH2B at 59.23–57.75 mbsf is suggested by the isotopic record, the particularly low planktonic/benthic ratios (1:1 to 10:1) and the particularly low carbonate abundances (51%–85%; Dorn, this volume). Hiatus NH2A was not recognized in the isotopic record but the low planktonic/benthic ratios (2:1 to 27:1) and the low calcium carbonate abundances (40%–78%; Dorn, this volume) suggest a dissolution interval at 65.96–63.44 mbsf.

Stable Isotope Data

The middle Miocene oxygen and carbon isotopic curves for Hole 744B (Figs. 1 and 2) show similar trends to those described

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	Species	$\delta^{18}O$ (‰, PDB)	$\delta^{13}C$ (‰, PDB)	Planktonic/ benthic ratios	Sample size (cm^3)
8H-1, 74–79	60.24	*Cibicidoides kullenbergi*	1.21	1.49	272	25
8H-1, 105–107	60.55	*Cibicidoides kullenbergi*	1.87	1.82	108	10
8H-2, 24–29	61.24	*Cibicidoides kullenbergi*	1.61	1.70	119	25
8H-2, 74–79	61.74	*Cibicidoides kullenbergi*	1.41	1.66	244	25
8H-2, 105–107	62.05	*Cibicidoides* spp.	2.09	1.84	85	10
8H-3, 24–29	62.75	*Cibicidoides kullenbergi*	1.78	1.80	38	25
8H-3, 74–77	63.24	*Cibicidoides kullenbergi*	Too small	Too small	128	25
8H-3, 105–107	63.55	*Cibicidoides kullenbergi* and *wuellerstorfi*	1.07	1.39	20	10
8H-4, 24–29	64.24	*Cibicidoides kullenbergi*	1.74	1.83	22	25
8H-4, 74–79	64.74	*Cibicidoides kullenbergi*	1.93	1.90	27	25
8H-4, 74–79	64.74	*Cibicidoides kullenbergi*	1.86	1.91	27	25
8H-4, 105–107	65.05	*Cibicidoides kullenbergi*	1.78	2.10	2	10
8H-5, 24–27	65.74	*Cibicidoides kullenbergi*	1.14	1.45	75	25
8H-5, 69–74	66.19	*Cibicidoides kullenbergi*	1.46	1.79	122	25
8H-5, 105–107	66.55	*Cibicidoides kullenbergi*	1.42	1.72	105	10
8H-6, 24–27	67.24	*Cibicidoides kullenbergi*	1.55	1.59	13	25
8H-6, 70–75	67.70	*Cibicidoides kullenbergi*	1.27	1.52	2	25
8H-6, 105–107	68.05	*Cibicidoides kullenbergi*	Lost	Lost	10	10
8H-7, 24–29	68.74	*Cibicidoides kullenbergi*	0.72	1.29	27	25
9H-1, 24–29	69.24	*Cibicidoides kullenbergi*	1.51	1.29	65	25
9H-1, 74–79	69.74	*Cibicidoides kullenbergi*	1.64	1.56	16	25
9H-1, 125–130	70.25	*Cibicidoides kullenbergi*	2.04	1.59	n.d.	10
9H-2, 24–29	70.74	*Cibicidoides kullenbergi*	Lost	Lost	2	25
9H-2, 77–81	71.27	*Cibicidoides kullenbergi*	Lost	Lost	1	25
9H-2, 125–130	71.75	*Cibicidoides kullenbergi*	1.79	1.47	n.d.	10
9H-3, 24–29	72.24	*Cibicidoides kullenbergi*	1.93	1.47	6	25
9H-3, 74–79	72.74	*Cibicidoides kullenbergi*	1.75	1.44	46	25
9H-3, 74–79	72.74	*Cibicidoides kullenbergi*	Lost	Lost	46	25
9H-3, 125–130	73.25	*Cibicidoides kullenbergi*	1.87	1.52	n.d.	10
9H-4, 24–29	73.74	*Cibicidoides kullenbergi*	Lost	Lost	33	25
9H-4, 74–79	74.24	*Cibicidoides kullenbergi*	1.82	1.51	15	25
9H-4, 125–130	74.75	*Cibicidoides kullenbergi*	2.05	1.56	n.d.	10
9H-5, 28–33	75.28	*Cibicidoides kullenbergi*	Lost	Lost	29	25
9H-5, 28–33	75.28	*Cibicidoides kullenbergi*	1.96	1.52	29	25
9H-5, 78–83	75.78	*Cibicidoides kullenbergi*	1.59	1.30	73	25
9H-5, 78–83	75.78	*Cibicidoides kullenbergi*	Lost	Lost	73	25
9H-5, 125–130	76.25	*Cibicidoides kullenbergi*	1.76	1.20	n.d.	10
9H-6, 23–28	76.73	*Cibicidoides kullenbergi*	2.05	1.46	422	25
9H-6, 23–28	76.73	*Cibicidoides kullenbergi*	Lost	Lost	422	25
9H-6, 74–79	77.24	*Cibicidoides kullenbergi*	1.69	1.12	123	25
9H-6, 74–79	77.24	*Cibicidoides kullenbergi*	1.60	1.04	123	25
9H-6, 125–126	77.75	*Cibicidoides kullenbergi*	1.74	1.20	n.d.	10

[a] "Lost" refers to data lost as a result of a computer failure during mass spectrometric analysis.
[b] n.d. = not determined.

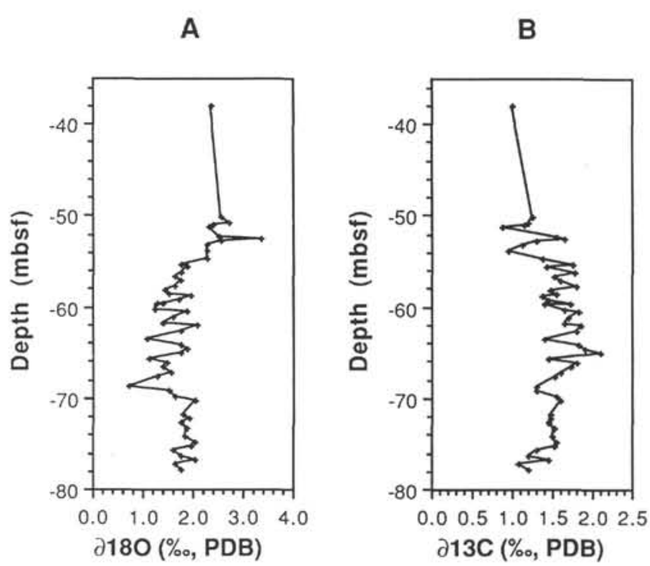

Figure 1. Plots of (**A**) $\delta^{18}O$ and (**B**) $\delta^{13}C$ values of benthic foraminifers (*Cibicidoides*) vs. depth below the seafloor at ODP Hole 744B.

for many other sites in the world ocean. Between 58 and 69 mbsf (approximately 14.3–16.6 Ma) foraminifer oxygen isotope ratios vary considerably but average +1.5. The 1‰ increase in foraminifer $\delta^{18}O$ values that has been identified in middle Miocene sections throughout the world ocean was also observed at Site 744. This major isotopic "event" begins at 60 mbsf in Hole 744B and continues to 50 mbsf, where $\delta^{18}O$ values exceed +2.5‰.

The carbon isotope curve for Site 744 exhibits the period of exceptionally high $\delta^{13}C$ values commonly referred to as the Monterey Excursion (Figs. 1B and 2; Vincent and Berger, 1985). The period begins with a 0.5‰ increase in $\delta^{13}C$ near 17 Ma (approximately 67 mbsf in Hole 744B) to values greater than 1.6‰. It continues with exceptionally high values, which average 1.65‰. The end of the Monterey Excursion is signaled by a 0.5‰ decrease in $\delta^{13}C$ values after 14 Ma (approximately 55 mbsf in Hole 744B).

Compared to other open-ocean middle Miocene records, the $\delta^{13}C$ values between 55.50 and 59.23 mbsf in Hole 744B are unexpectedly irregular. These values fall within an intense dissolution zone found between 53 and 59 mbsf as shown by the very low planktonic/benthic ratios (average 17:1) and the low abundance of calcium carbonate (60%–85%; Dorn, this volume). The $\delta^{13}C$ values therefore may reflect disturbances often associated with dissolution such as multiple slumps and turbidites (Woodruff and Savin, in press).

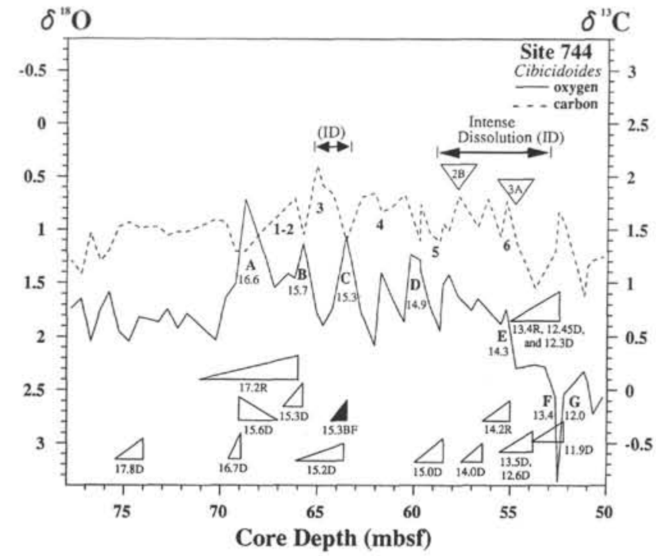

Figure 2. δ^{18}O and δ^{13}C isotope curves of *Cibicidoides* species vs. depth below seafloor for ODP Hole 744B. Note the difference in isotope scales. The letters beneath the δ^{13}C curve show the seven "^{18}O events" and their ages determined by Woodruff and Savin (in press) for the period of the Monterey Excursion. The triangles below the isotope curves show core depth of the top or bottom of each biostratigraphic range and the depth of uncertainty between the samples studied (from Barron et al., this volume). Below each triangle is the age (Ma) of the datum and a letter identifying its fossil group (diatom or radiolarian). The triangles above the isotopic curve show the location of hiatuses (see Table 2).

The isotope record suggests that there is a previously unidentified hiatus of approximately 400 k.y. somewhere within the interval 66–68 mbsf, based on the stable isotope stratigraphy developed by Woodruff and Savin (in press), perhaps associated with the extremely low planktonic/benthic ratios (<13:1) and low calcium carbonate abundance data (72%–79%; Dorn, this volume) between 68.1 and 67.0 mbsf. The periods of exceptionally high δ^{13}C values (>1.5) appear to be relatively less condensed than the intervening periods that are characterized by low δ^{18}O values (<1.4‰) when compared to high-resolution isotopic records in the equatorial Pacific Ocean (Woodruff and Savin, in press).

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Table 2. Stratigraphy and dissolution intervals for ODP Hole 744B.

Depth (mbsf)	Oxygen isotope stratigraphy[a]	Planktonic/ benthic ratios[a] <10:1	Planktonic datums[b, c]	Strontium isotopes[d]	Paleomagnetic ages[b, e]
50.0–50.7			10.9 Ma (D)		
50.4–51.39					11.03 Ma (C5N-3 top)
51.39–52.05					11.09 Ma (C5N-3 base)
52.0	12.0 Ma (^{18}O, G)				
52.2–53.7			11.9 Ma (D)		
52.65–55.23			12.3 Ma (D), 12.45 Ma (D), 13.4 Ma (R)		
52.7	13.4 Ma (^{18}O, F)				
53.0	hiatus NH3B		hiatus		
53.74		intense dissolution			
53.70–55.20			12.6 Ma (D), 13.5 Ma (D)		
54.5–55.2			hiatus		
54.73–55.24	hiatus NH3A				
54.91–55.38					13.69 Ma (C5AN-7 top)
55.23–56.73			14.2 Ma (R)		
55.24	14.3 Ma (^{18}O, E)				
55.55		intense dissolution			
56.7–58.2			14.0 Ma (D)	15.9	
57.75–59.23	hiatus NH2B	intense dissolution			
58.14–59.22					14.66 Ma (C5AN-8 base)
59.71				15.9 Ma	
59.75–60.38					14.87 Ma (C5BN-1 top)
60.1	14.9 Ma (^{18}O, D)				
60.11				15.9 Ma	
60.91–61.81					15.27 Ma (C5BN-2 base)
60.1–61.6			15.0 Ma (D)		
63.11				16.1 Ma	
63.55	15.3 Ma (^{18}O, C)				
64.6–66.1			15.2 Ma (D)		
64.84–65.37				16.22 Ma	(C5CN-1 top)
65.05		intense dissolution			
65.8	15.7 Ma (^{18}O, B)				
66.1–67.6			15.3 Ma (D), 15.6 Ma (D)		
66.11				17.0 Ma	
66.23–71.3			17.2(?) Ma (R)		
66.85–66.95					16.98 Ma (C5CN-3 base)
67.7		intense dissolution			
68.8	16.6 Ma (^{18}O, A)				
69.0–69.58			16.0 Ma (D), 16.7 Ma (D)		
69.59				17.6 Ma	
70.74–72.24		intense dissolution			
71.3–80.73			17.2–18.4 Ma (R)		
71.6–72.4					17.57 Ma (C5DN-1 top)
74.09				18.03 Ma	
75.25–75.76					17.9 Ma (C5DN-1 base)
77.09				18.1 Ma	
77.1					18.12 Ma (C5DN-2 top)
77.5					18.14 Ma (C5DN-2 base)

[a] Data are presented in this paper.
[b] Barron et al., this volume (D = diatoms).
[c] Lazarus, in press (R = radiolarians).
[d] Barrera et al., this volume.
[e] Keating, this volume.