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Evidence for Oligocene–Middle Miocene abyssal circulation changes in the western North Atlantic

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Previous studies of benthic foraminiferal isotopic composition have demonstrated that a latest Eocene–earliest Oligocene benthic foraminiferal $\delta^{18}O$ increase occurred in the Pacific, Southern and Atlantic Oceans[1–9]. A Middle Miocene $\delta^{18}O$ increase has been noted in the Pacific, Southern and South Atlantic Oceans[1–3,7,10,11] and tentatively identified in the North Atlantic[12,13]. Due to the incomplete nature of the North Atlantic stratigraphical record[14,15], however, the Oligocene to Middle Miocene isotopic record of this ocean is poorly understood. In the modern ocean, the North Atlantic and its marginal seas has a critical role in abyssal circulation, influencing deep- and bottom-water hydrography as far away as the North Pacific[16–18]. We now report oxygen isotope measurements on Oligocene to Middle Miocene (12–36 Myr BP) benthic foraminifera in the western North Atlantic which show two periods of enriched ^{18}O values: early Oligocene and early Middle Miocene. These enriched intervals are interpreted as resulting, in part, from the build-up of continental ice sheets. The Oligocene to Middle Miocene $\delta^{13}C$ record shows three cycles of enrichment and depletion of large enough magnitude to be useful for time-stratigraphical correlations. Within the biostratigraphical age resolution, $\delta^{18}O$ and $\delta^{13}C$ records correlate with records from other oceans, helping to establish a useful Tertiary isotopic stratigraphy. An Atlantic–Pacific $\delta^{13}C$ contrast of 0.3–0.9‰ during the latest Oligocene to Middle Miocene (12–26 Myr BP) indicates North Atlantic deep- and bottom-water production analogous to modern North Atlantic deep water (NADW).

Recent rotary drilling at DSDP Site 563, western North Atlantic (38°39′ N, 43°46′ W; 3,796 m present depth; palaeodepths: early Oligocene, 2.2 km; late Oligocene, 2.9 km; Middle Miocene, 3.4 km), provided the first continuously deposited, biostratigraphically well-controlled, abyssal Atlantic record adequate for inter-ocean isotopic comparisons. Figure 1 shows the $\delta^{18}O$ and $\delta^{13}C$ composition of earliest Oligocene (Zone P18) to late Middle Miocene (Zone N14) benthic foraminifera at North Atlantic Site 563. Biostratigraphical zonations are derived from planktonic foraminifera; absolute age control is obtained by interpolating between datum levels (Table 1) using the time scales of Berggren *et al.*[19,20]. Detailed biostratigraphical zonal age assignments will be presented elsewhere (K.G.M., in preparation). Isotopic analyses were performed on mixed species of the benthic foraminiferal genera *Cibicidoides* and *Planulina*. These taxa were selected because they secrete calcite tests that are apparently constantly offset from $\delta^{18}O$ equilibrium by 0.65‰ (refs 21–25). Also, studies of Holocene core tops show that these taxa accurately reflect the distribution of $\delta^{13}C$ of ΣCO_2 in the modern oceans[22–25].

At Site 563, oxygen isotopic values are enriched in the Lower Oligocene ($\delta^{18}O = 1.6$–2.5‰ between 341 and 360 m s.b. (metres subbottom); Table 1; Fig. 1) similar to lowermost Oligocene values reported elsewhere[1–9]. Middle to Upper Oligocene values (301–341 m s.b.) are lower ($\delta^{18}O =$ 1.3–1.7‰). The significance of an enriched value in the uppermost Oligocene cannot be evaluated at present. Lower and lower-Middle Miocene $\delta^{18}O$ values range from 1.4 to 1.9‰. A major ^{18}O enrichment occurs between 235 and 239 m s.b. (Fig. 1) in the lower Middle Miocene (between Zones N9 and N10/11; 14.9–15.2 Myr BP).

The benthic foraminiferal carbon isotopic record at Site 563 shows three cycles of enrichments and depletions (Fig. 1). Enriched intervals occur in the Lower Oligocene (348–360 m s.b.), uppermost Oligocene to lowermost Miocene (292–311 m s.b.), and lower Middle Miocene (235–264 m s.b.). Depleted intervals, indicated with stipples in Fig. 1, occur in the 'Middle'–Upper Oligocene (315–347 m s.b.), Lower Miocene (268–283 m s.b.), and Middle Miocene (207–230 m s.b.).

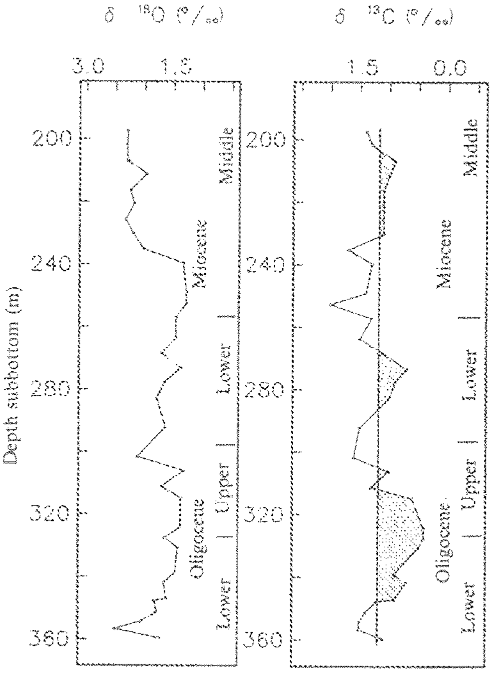

Fig. 1 Isotopic composition versus depth subbottom, Site 563, western North Atlantic. Solid line drawn through mean $\delta^{13}C$ of data in Table 1 (1.2‰) and intervals with depleted ^{13}C are indicated with stipples. Stratigraphical boundaries drawn using the zonations given in Table 1 and the time scales of Berggren *et al.*[19,20].

The $\delta^{18}O$ and $\delta^{13}C$ records at western North Atlantic Site 563 show a similar pattern as the Oligocene record at Site 119 in the Bay of Biscay[8] (4,447 m present depth; >3 km palaeodepth). Enriched ^{13}C values occurred in the early Oligocene at both sites and depleted values occurred in the late Oligocene. This carbon isotopic pattern may also be seen at Pacific Site 574 (K.G.M. and E. Thomas, in preparation), South Atlantic Site 522 (ref. 26) and Leg 74 sites[27]. The Miocene pattern of enrichments and depletions is also observed at Sites 289 and 77 in the Pacific (2,206 m and 4,291 m present depth, respectively[10,11]).

Comparison of Atlantic Site 563 and Pacific isotopic records (all data derived from analyses of *Cibicidoides* and *Planulina*, Fig. 2) shows that although similar $\delta^{13}C$ patterns are observed at all three locations, the Pacific sites are depleted in ^{13}C relative to the Atlantic site throughout the latest Oligocene through Middle Miocene (12–26 Myr BP). Before the ^{18}O enrichment of the Middle Miocene, Atlantic $\delta^{18}O$ values also are enriched by ~0.25–0.50‰ over Pacific values. After the Middle Miocene ^{18}O enrichment, $\delta^{18}O$ values are similar at all three sites, although $\delta^{13}C$ values remain depleted in the Pacific throughout the interval examined here.

The Middle Miocene $\delta^{18}O$ increase noted here has generally been attributed to the development of the Antarctic ice cap, while the latest Eocene–earliest Oligocene increase has been ascribed to a major bottom-water temperature drop[1–5,10,11]. In contrast, Matthews and Poore[28] argued that the inverse was true. If a $\delta^{18}O$ increase is due to increased ice volume, then it should be globally synchronous. The slight apparent offset in time between the Middle Miocene enrichment at Site 289 and Site 563 (Fig. 2) is well within the errors of the biostratigraphical age assignments. The enrichments may be considered synchronous between oceans, as was suggested for the latest Eocene–earliest Oligocene enrichment[9]. Thus the synchrony or diachrony of the ^{18}O enrichment cannot apparently be used

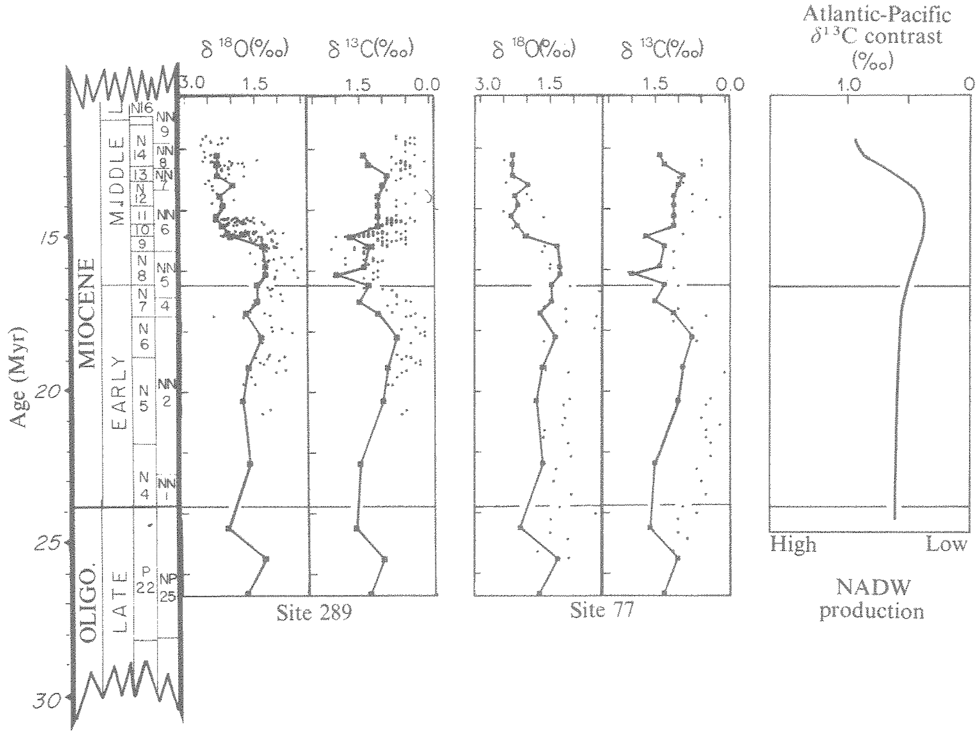

Fig. 2 Comparison of isotopic composition at Atlantic Site 563 (solid line with squares) and Pacific Sites 289 and 77 (points). Note that the Pacific $\delta^{13}C$ data (points) are depleted relative to the Atlantic data (squares). All isotopic data from analyses of *Cibicidoides* and *Planulina*; data from Sites 289 and 77 after ref. 11. Contrast obtained by fitting a hand-drawn curve through mean difference of Atlantic and Pacific data for the time intervals 12.2–12.4, 12.5–14.5, 14.5–17.0, 17.0–20.3, and 22.3–26.6 Myr BP. Ages obtained by interpolating between following datums using the time scale of Berggren *et al.*[20]: Site 563, Table 1; Site 289, FA *G. nepenthes*, 348 m subbottom, FA *Praeorbulina*, 510 m s.b., FA *G. dehiscens*, 654 m s.b. (datums after ref. 40); Site 77, FA *G. nepenthes*, 289 m s.b., FA *G. sicanus*, 17 m s.b., 16.6 Myr BP, FA *G. dehiscens*, 289 m s.b. (datums after ref. 41).

here to differentiate causal mechanisms for these two time intervals.

Constraints still may be placed on the interpretation of the Middle Miocene ^{18}O enrichment at Site 563. If the Middle Miocene enrichment is ascribed to an increase in $\delta^{18}O$ of seawater of 0.5–0.6‰ (ref. 10) (equivalent to a sea-level drop of ~60 m, ref. 30), then the enrichment at Site 563 (~0.7‰) represented little or no bottom-water temperature drop. A 2–3 °C bottom-water temperature drop must have occurred in the Pacific given these assumptions (that is, the Pacific enrichment is larger[10,11]). On the other hand, if the Middle Miocene enrichment is due to temperature alone, bottom-water temperatures dropped in the western North Atlantic by ~3 °C and in the Pacific by 5 °C.

The $\delta^{18}O$ values noted in the early Oligocene (values for Zones P18 and P19/20 = 1.6–2.5‰) are slightly lower than modern *Cibicidoides* from the western North Atlantic (~2.6‰, ref. 23). The effect of melting the modern ice sheets would result in a decrease of mean oceanic $\delta^{18}O$ by 0.9‰ (ref. 3). Therefore, the assumption of an essentially ice-free world before the Middle Miocene[1–3,10,11] would require early Oligocene bottom waters at Site 563 that were as cold or colder than at present (2.4–2.6 °C modern potential temperature[29]; early Oligocene bottom-water estimates of 1–2 °C). In fact, such cold early Oligocene bottom-water temperatures are probably not compatable with an ice-free world. Thus, we suggest that significant ice volume existed during the early Oligocene.

Comparisons of Atlantic and Pacific $\delta^{13}C$ records can be used to infer abyssal circulation. Based on the correlation of lower $\delta^{13}C$ values of Holocene benthic foraminifera with older bottom waters[22,23] (higher apparent oxygen utilization, higher CO_2, and lower *p*H, refs 31–33), Curry and Lohmann[34] used carbon isotopic comparisons to decipher Quaternary abyssal circulation changes. Variations in $\delta^{13}C$ may be caused by: (1) global changes in the ^{13}C budget[35,36]; (2) abyssal circulation changes[31–33]; and (3) local changes in productivity[36,37]. Global changes in $\delta^{13}C$ which are caused by mechanisms such as increased input ^{13}C depleted terrestrial organic matter to the oceans, possibly due to sea-level changes[35,36], must be synchronous within and between oceans. The close correlations of $\delta^{13}C$ cycles observed in the Miocene of Pacific and Atlantic sites (Fig. 2) suggest that these changes are due to global changes in oceanic $\delta^{13}C$. Similar Oligocene $\delta^{13}C$ cycles noted in the Atlantic and Pacific suggest that these also were due to global changes. Such widely-distributed $\delta^{13}C$ patterns will be useful in future time–stratigraphical correlations.

Table 1 Oxygen and carbon isotopic data for Site 563, reported to PDB standard

Sample	Depth subbottom (m)	Zonal age* (Myr BP)	$\delta^{18}O$	$\delta^{13}C$
5-2 130–136 cm	197.30	N14 (12.2)	2.30	1.44
5-5 130–136 cm	201.80	N14 (12.5)	2.31	1.36
6-2 130–136 cm	206.80	N12/N13 (12.9)	2.30	0.97
6-5 121–127 cm	211.21	N12/N13 (13.2)	1.97	1.06
7-2 131–136 cm	216.31	— (13.6)	2.25	1.15
7-5 110–116 cm	220.60	— (13.9)	2.18	1.10
8-2 114–120 cm	225.64	— (14.2)	2.33	1.12
8-5 114–120 cm	230.14	— (14.5)	2.20	1.18
9-2 114–120 cm	235.14	N10/N11 (14.9)	2.02	1.73
9-5 114–120 cm	239.64	N9 (15.2)	1.34	1.32
10-5 110–116 cm	249.10	N8 (15.9)	1.28	1.43
11-1 110–116 cm	252.60	N8 (16.1)	1.28	2.01
11-4 112–118 cm	257.12	N8 (16.5)	1.46	1.33
12-2 110–116 cm	263.60	N7 (17.0)	1.46	1.56
12-5 124–130 cm	268.24	N7 (17.4)	1.70	1.17
13-2 124–130 cm	273.24	N6 (18.2)	1.37	0.71
13-5 124–130 cm	277.74	N5 (19.2)	1.72	0.80
			1.58	1.01
14-2 129–135 cm	282.79	N4 (20.3)	1.78	1.00
15-2 117–123 cm	292.17	N4 (22.4)	1.50	1.62
			1.76	1.42
16-2 117–123 cm	301.67	P22 (24.5)	2.11	1.60
16-5 117–123 cm	306.14	P22 (25.5)	1.31	1.05
17-2 117–123 cm	311.17	P21b/P22 (26.7)	1.70	1.34
17-5 24–30 cm	314.74	P21b/P22 (27.5)	1.36	0.62
18-5 23–29 cm	324.23	P21b (29.6)	1.37	0.43
19-1 12–18 cm	327.62	P21a (30.3)	1.64	0.45
19-3 12–18 cm	330.62	P21a (30.7)	1.41	0.54
20-2 41–47 cm	338.91	P21a (32.0)	1.46	0.93
20-4 20–26 cm	341.70	P19/20 (32.4)	1.65	0.70
20-7 4–10 cm	347.04	P19/20 (33.2)	1.61	0.92
21-1 110–116 cm	347.60	P19/20 (33.3)	1.81	1.29
21-4 31–37 cm	351.31	P19/20 (33.8)	1.77	1.40
21-6 22–28 cm	354.22	P18 (34.3)	2.04	1.54
22-1 110–116 cm	356.60	P18 (34.6)	2.49	1.50
22-3 110–116 cm	359.60	P18 (35.1)	1.73	1.19

* Age estimated by interpolation of sedimentation rates between datums: FA *G. nepenthes*, 204.3 m, 12.7 Myr BP; FA *Praeorbulina*, 255.0 m, 16.3 Myr BP; LA *C. dissimilis*, 270.5 m, 17.6 Myr BP; FA *G. dehiscens*, 296.0 m s.b., 23.2 Myr BP; LA *Chiloguembelina*, 325.9 m, 30.0 Myr BP; LA *Pseudohastigerina*, 352.5 m, 34.0 Myr BP. In samples with replicates, mean values were plotted on Figs 1, 2.

The Oligocene to Middle Miocene Atlantic–Pacific δ^{13}C differences are interpreted as resulting from Atlantic to Pacific abyssal circulation. At present, the North Atlantic is enriched in ^{13}C relative to the Pacific by 1.0‰; this results from the production of NADW which is enriched in ^{13}C (refs 31–33). By analogy, we suggest that the western North Atlantic was enriched in ^{13}C relative to the Pacific in the Oligocene to Middle Miocene due to the production of young (high O_2, low CO_2; high δ^{13}C, refs 31–33) bottom waters analogous to NADW.

The Atlantic–Pacific δ^{13}C contrast was high in the latest Oligocene to early Miocene (0.7‰ average difference between 17 and 27 Myr BP) (Fig. 2). This contrast apparently decreased in the Middle Miocene (0.3–0.4‰ average differences between Site 563 and Pacific Sites 289 and 77, respectively, 15–17 Myr BP). The records subsequently diverged again in the later Middle Miocene. We interpret this as reduced production of bottom water analogous to NADW in the early Middle Miocene and subsequent increased production in the later Middle Miocene (Fig. 2).

The later Middle Miocene difference can be observed at other North Atlantic locations. Typical δ^{13}C values for *Cibicidoides* from the later Middle Miocene at Sites 116 and 366 are 1.2‰ (ref. 13) versus 0.6‰ for Pacific sites[10,11]. Blanc *et al.*[12] and Blanc and Duplessy[13] noted this offset of later Middle Miocene Pacific and Atlantic benthic foraminiferal δ^{13}C records, and suggested that the formation of bottom water analogous to modern NADW began near 12 Myr BP. However, in the early and Middle Miocene, Atlantic both Sites 563 and 366 are enriched in ^{13}C relative to the Pacific, although Site 116 yields values similar to Pacific values[12,13]. Given the shallow location of Site 116 (1 km present and Oligo-Miocene palaeodepth; ref. 38) and its modern association with a region of high productivity[39], we suggest that the early Miocene depleted ^{13}C values at Site 116 represent local δ^{13}C variations in intermediate water, and that a significant δ^{13}C difference existed between the Atlantic and Pacific bottom water before 12 Myr BP. Thus our interpretation extends the production of bottom water analogous to NADW back until at least the Oligocene (older than 26 Myr BP).

Our interpretations of the δ^{13}C records are consistent with other monitors of abyssal circulation. Based on seismic stratigraphical studies, Miller and Tucholke[15] suggested that northern sources for vigorously circulating bottom water (analogous to NADW) began near the end of the Eocene. They suggested that strong erosional conditions, together with the development of current-controlled sedimentation, indicated that such northern sources continued to influence the geological record throughout the Oligocene and early Miocene. However, a change to more widespread depositional conditions occurred in the latest early to Middle Miocene in the North Atlantic. They interpreted this as a reduction in intensity of abyssal circulation in the North Atlantic. The ^{13}C comparisons made here are consistent with this abyssal circulation model. The change to more depositional conditions near the early/Middle Miocene boundary appears to coincide with a convergence of Atlantic and Pacific δ^{13}C records which may be related to reduced production of NADW-like bottom water. Studies of Pacific Oligocene records are needed to establish whether the difference between Atlantic and Pacific carbon isotopic records began near the end of the Eocene, as predicted by the abyssal circulation model of Miller and Tucholke[15].

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1. Douglas, R. G. & Savin, S. M. *Init. Rep. DSDP* Leg **17,** 591–605 (1973).
2. Savin, S. M., Douglas, R. G. & Stehli, F. G. *Bull. geol. Soc. Am.* **86,** 1499–1510 (1975).
3. Shackleton, N. J. & Kennett, J. P. *Init. Rep. DSDP* Leg **29,** 743–755 (1975).
4. Kennett, J. P. & Shackleton, N. J. *Nature* **260,** 513–515 (1976).
5. Savin, S. M. *A. Rev. Earth planet. Sci.* **5,** 319–355 (1977).
6. Keigwin, L. D. *Nature* **287,** 722–725 (1980).
7. Boersma, A. & Shackleton, N. J. *Init. Rep. DSDP* Leg **39,** 911–924 (1979).
8. Miller, K. G. & Curry, W. B. *Nature* **296,** 347–352 (1982).
9. Miller, K. G., Curry, W. B. & Ostermann, D. R. *Init. Rep. DSDP* Leg **80** (in the press).
10. Woodruff, F., Savin, S. M. & Doublas, R. G. *Science* **212,** 665–668 (1981).
11. Savin, S. M. *et al. Mar. Micropaleont.* **6,** 423–450 (1981).
12. Blanc, P.-L. *et al. Nature* **283,** 553–555 (1980).
13. Blanc, P.-L. & Duplessy, J.-C. *Deep-Sea Res.* **29**A, 1391–1414 (1982).
14. Moore, T. C. *et al. Micropaleontology* **24,** 113–138 (1978).
15. Miller, K. G. & Tucholke, B. E. *NATO Conf. Ser.* Vol. 4, 549–589 (Plenum, New York, 1983).
16. Reid, J. L. & Lynn, R. J. *Deep-Sea Res.* **18,** 1063–1088 (1971).
17. Worthington, L. V. *Johns Hopkins Oceanogr. Stud.* **6** (1976).
18. Reid, J. L. *Deep-Sea Res.* **26,** 1199–1223 (1980).
19. Berggren, W. A., Kent, D. & Flynn, J. *Geol. Soc. Lond. Spec. Pap.* (in the press).
20. Berggren, W. A., Kent, D. & van Couvering, J. *Geol. Soc. Lond. Spec. Pap.* (in the press).
21. Shackleton, N. J. & Opdyke, N. D. *Quat. Res.* **3,** 39–55 (1973).
22. Belanger, P. E., Curry, W. B. & Matthews, R. K. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **33,** 205–220 (1981).
23. Graham, D. *et al. Mar. Micropaleont.* **6,** 483–497 (1981).
24. Woodruff, F., Savin, S. M. & Douglas, R. G. *Mar. Micropaleont.* **5,** 3–13 (1980).
25. Duplessy, J.-C., Moyes, J. & Pujol, C. *Nature* **286,** 479–482 (1980).
26. Poore, R. Z. & Matthews, R. K. *Init. Rep. DSDP* Leg **73** (in the press).
27. Shackleton, N. J., Hall, M. A. & Boersma, A. *Init. Rep. DSDP* Leg **74** (in the press).
28. Matthews, R. K. & Poore, R. Z. *Geology* **8,** 501–504 (1980).
29. Fuglister, F. C. *Woods Hole Oceanogr. Instn. Atlas Ser.* 1 (1960).
30. Fairbanks, R. G. & Matthews, R. K. *Quat. Res.* **10,** 181–196 (1978).
31. Kroopnick, P. *Deep-Sea Res.* **21,** 211–217 (1974).
32. Kroopnick, P. *Earth planet. Sci. Lett.* **49,** 469–484 (1980).
33. Kroopnick, P., Weiss, R. F. & Craig, H. *Earth planet Sci. Lett.* **16,** 103–110 (1972).
34. Curry, W. B. & Lohmann, G. P. *Quat. Res.* **18,** 218–235 (1982).
35. Shackleton, N. J. in *Fate of Fossil Fuel CO_2 in the Oceans* 401–427 (Plenum, New York, 1977).
36. Broecker, W. *Geochim. cosmochim. Acta* **46,** 1689–1705 (1982).
37. Berger, W. H., Diester-Haas, L. & Killingley, J. S. *Oceanol. Acta* **1,** 3–7 (1978).
38. Berggren, W. A. *Init. Rep. DSDP* Leg **12,** 965–1001 (1972).
39. Milliman, J. D. *Deep-Sea Res.* **27**A, 959–963 (1980).
40. Srinivasan, M. S. & Kennett, J. P. *Mar. Micropaleont.* **6,** 535–552 (1981).
41. Keller, G. *Mar. Micropaleont.* **6,** 535–552 (1981).