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# 10. OXYGEN AND CARBON ISOTOPIC RECORDS FROM THE OOZES OF SITES 752, 754, 756, AND 757, EASTERN INDIAN OCEAN[1]

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## ABSTRACT

Oxygen and carbon isotopic records have been developed for the Cenozoic carbonate oozes of Sites 752, 754, 756, and 757 based on the analysis of monospecific benthic foraminifers. The intent of this report is to provide a basic isotopic stratigraphy for use in other paleoceanographic studies. The oxygen isotope record displays the enrichments associated with cooling or ice volume buildup at the Eocene/Oligocene boundary, in the middle Miocene, and in the upper Pliocene. The carbon isotopic record contains the Chron 16 enrichment in the lower Miocene and the Chron 6 depletion in the uppermost Miocene.

## INTRODUCTION

The upper sedimentary unit recovered in each of the Ocean Drilling Program (ODP) Leg 121 drill sites is a carbonate ooze. We have chosen the stratigraphically longer cores from Broken Ridge, Sites 752 and 754, and Sites 756 and 757 from the southern end of the Ninetyeast Ridge for an isotopic survey of these Cenozoic materials (Fig. 1, Table 1). The intent of our analyses is to provide a carbon and oxygen isotopic stratigraphy for these low sedimentation-rate cores so that any paleoceanographic observations derived from them can be placed into the global record of climatic and oceanographic changes. The general depositional records of these sites were described by Peirce, Weissel, et al. (1989); Rea et al. (1990) presented an overview of the paleoceanographic record of the eastern Indian Ocean interpreted from the sedimentary section of Broken Ridge.

## SEDIMENTS

The plateau region of Broken Ridge is underlain by a foraminifer or foraminifer-bearing nannofossil ooze. This ooze reaches a maximum thickness of about 120 m at Site 754, near the center of the platform, and thins to the north and south. A layer of sand and limestone pebbles denotes a lower Oligocene disconformity and divides the ooze into upper and lower portions. The upper ooze unit, from which most of our samples are derived, ranges in age from Pleistocene to middle Oligocene. The ooze below the Oligocene disconformity, of late Eocene age, was poorly recovered and we have only a few samples from that interval. The scientists of Deep Sea Drilling Project (DSDP) Leg 26, which also drilled on Broken Ridge, believed that those carbonate oozes, now at 1050 to 1100 m water depth, showed evidence of winnowing (Davies, Luyendyk, et al., 1974). Our shipboard work tended to confirm that observation (Rea et al., 1990; House et al., this volume). The implication of important amounts of winnowing to this work is that in these slowly accumulating sediments there may be small hiatuses that are unrecognized at the relatively widely spaced sampling intervals used by the several investigators.

At Site 756 on the southern end of Ninetyeast Ridge, 144.5 m of nannofossil ooze containing 5% to 20% foraminifers overlies about 6 m of foraminifer limestone, which rests on basalt. The foraminifer-bearing nannofossil ooze is Pleistocene to late Eocene in age. Trace amounts of volcanic ash occur throughout the ooze, with enhanced ash concentrations between about 50 and 63 m below seafloor (mbsf). At Site 757, 212 m of nannofossil ooze, becoming more micritic and chalky below about 169 mbsf, overlie basalt. The ooze at Site 757 ranges in age from Pleistocene to early Eocene.

The depths of the Broken Ridge drill sites have always been relatively shallow. The ridge was uplifted and exposed to erosion in the middle Eocene and probably was exposed again in the middle Oligocene (Peirce, Weissel, et al., 1989; Rea et al., 1990). Since then the ridge crest has subsided to its present depth of about 1100 m. The depth of 1100 m approximates that of the boundary between the Surface Water and Antarctic Intermediate Water masses, near the bottom of the main thermocline. The significance of the subsidence history is that these sites have always been in the Surface Water Mass and so the benthic foraminifers record that isotopic history rather than the record of deep or bottom waters. Site 756 on Ninetyeast Ridge is at 1529 m and Site 757 is at 1652 m, both within the Antarctic Intermediate Water Mass. The volcanic rocks beneath the sediments at Sites 756 and 757, of Eocene and late Paleocene age, respectively, show evidence for subaerial eruption and weathering (Peirce, Weissel, et al., 1989) suggesting that the materials at these sites also represent in large part a record of the Surface Water Mass.

In this discussion we will refer to the nannofossil stratigraphy as determined aboard the *JOIDES Resolution* and reported by Peirce, Weissel, et al. (1989). The zonations were referred to the mid-latitude biostratigraphic scheme of Bolli et al. (1985), which is slightly different than the time scale of Berggren et al. (1985), especially in the Miocene. For instance, the lower/middle Miocene boundary in the Bolli et al. (1985) time scale is at the CN4/CN5 boundary, 15.4 Ma; the same boundary in the Berggren et al. (1985) time scale is between nannofossil Zones CN3 and CN4, at 16.5 Ma. Persons interested in the details of the biostratigraphy should consult Peirce, Weissel, et al. (1989). Additional information on nannofossil zonations in the Miocene was provided by P. Resiwati (pers. comm., 1990).

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[1] Weissel, J., Peirce, J., Taylor, E., Alt, J., et al., 1991. *Proc. ODP, Sci. Results,* 121: College Station, TX (Ocean Drilling Program).

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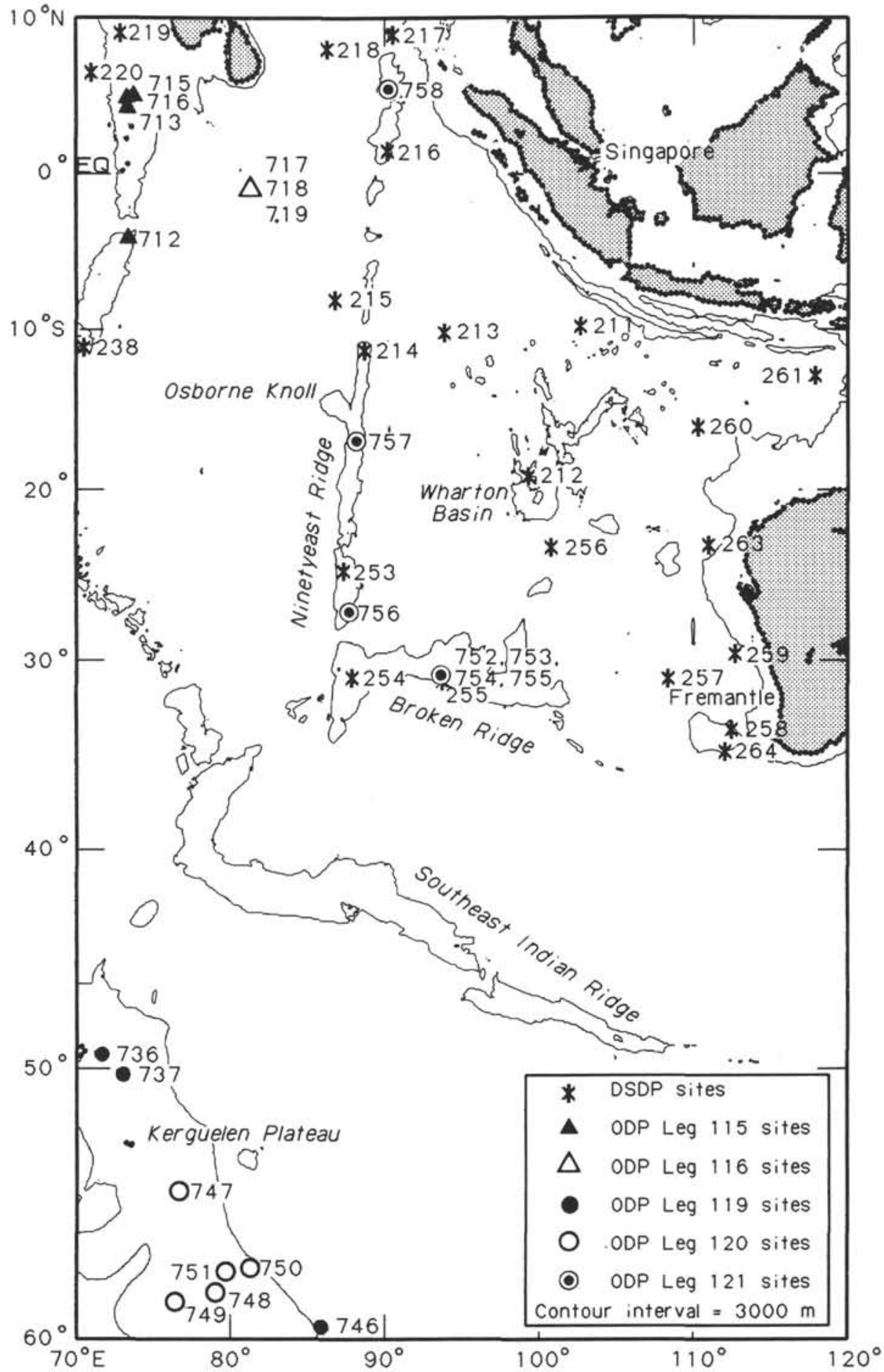


Figure 1. Index map of the eastern Indian Ocean showing the location of Leg 121 drill sites and other ODP/DSDP sites.

**Table 1. Location and water depth of Leg 121 drill sites studied.**

| Hole | Latitude (S) | Longitude (E) | Water depth (m) |
|---|---|---|---|
| 752A | 30°53.48′ | 93°34.65′ | 1086 |
| 754A | 30°56.44′ | 93°33.99′ | 1064 |
| 756B | 27°21.33′ | 87°35.80′ | 1518 |
| 756C | 27°21.25′ | 87°35.89′ | 1516 |
| 757B | 17°01.46′ | 88°10.90′ | 1652 |

## METHODOLOGY

Samples entering our laboratory were freeze-dried, split, and then sieved and passed through 425-μm, 150-μm, and 63-μm sieves. The benthic foraminifer *Cibicidoides* sp. was picked from the fraction coarser than 150 μm from the Broken Ridge samples. At Sites 756 and 757 *Cibicidoides* sp. was not present throughout the core, so we picked *Uvigerina* sp. and *Gyroidinoides* sp. for our analyses.

All samples were roasted in vacuo at 380°C for 1 hr to remove volatile organic contaminants. Foraminiferal samples of one to four or five individuals, ranging in weight from 50 to 300 μg $CaCO_3$ were individually reacted at 73°C with anhydrous phosphoric acid (density 1.90–1.92 g/cm$^3$) in an online extraction device (CarboKiel), which allows for the reaction of samples within separate reaction vessels. Four drops of acid were added to each vessel containing carbonate while under vacuum. Such a procedure eliminates progressive $CO_2$ contamination inherent in common acid bath reaction systems; thus, samples as small as 50 μg can be sequentially analyzed without loss of analytical accuracy. Analyses were performed on a Finnegan MAT 251 mass spectrometer.

Isotopic enrichments were measured relative to a laboratory $CO_2$ reference gas and corrected for $^{17}O$ contributions. Measured values were then converted to per mil enrichments relative to the PDB standard through calibration with NBS-20 powdered carbonate (−4.14 $\delta^{18}O$ and −1.06 $\delta^{13}C$ published values). Precision of analysis (1-sigma) was calculated from daily analyses of NB-20 which bracketed and were intermixed within the sample analysis sequence (mean and 1-sigma values for the standard are $\delta^{13}C$ = −1.03 (0.07); $\delta^{18}O$ = −4.14 (.07); $n$ = 261). Analyses were excluded only when machine operational errors were evident.

## OXYGEN AND CARBON ISOTOPE RECORD

### Oxygen Isotopes

The $\delta^{18}O$ values from all four sites show the important Neogene changes in the isotopic chemistry of the oceans (Tables 2–6) The *Cibicidoides* record from Hole 752A (Fig. 2, Table 2) shows the heaviest values, averaging about 2.4 per mil in the uppermost 10 m, values averaging about 1.6 to 1.8 per mil between 10 and 52 m, a sharp decline to values averaging about 0.8 per mil (excluding the "peak" at 78 mbsf) that extends downcore to 95 mbsf, and the lowermost values decline to about −0.5 per mil. Hole 754A contains a very similar *Cibicidoides* record (Fig. 3, Table 3); the upper 10 m have average $\delta^{18}O$ values of about 2.6 per mil. A transition between 10 and 18 mbsf occurs and from 18 to about 72 mbsf the $\delta^{18}O$ values average about 1.7 to 1.8 per mil. Between 72 and 78 mbsf a second transition occurs as values decline to an average of about 1 per mil in the lower portion of the core.

The records at Holes 756B, 756C, and 757B were obtained from different genera than those analyzed at the Broken Ridge sites. The record from Holes 756B and 756C (Figs. 4 and 5, Tables

**Table 2. Oxygen and carbon isotopic data from Hole 752A.**

| Core, section, interval (cm) | Depth (mbsf) | Oxygen-18 | Carbon-13 |
|---|---|---|---|
| 121-752A- | | | |
| 1H-1, 80-82 | 0.80 | 2.26 | 0.99 |
| 1H-2, 80-82 | 2.30 | 2.05 | 1.36 |
| 1H-3, 80-82 | 3.80 | 2.27 | 1.32 |
| 1H-4, 80-82 | 5.30 | 2.65 | 0.75 |
| 1H-5, 80-82 | 6.80 | 2.38 | 0.84 |
| 2H-1, 80-82 | 9.10 | 2.07 | 0.80 |
| 2H-2, 80-82 | 10.60 | 1.92 | 0.92 |
| 2H-3, 80-82 | 12.10 | 1.88 | 0.69 |
| 2H-4, 80-82 | 13.60 | 1.72 | 0.52 |
| 2H-5, 80-82 | 15.10 | 1.68 | 0.82 |
| 2H-6, 80-82 | 16.60 | 1.89 | 0.76 |
| 3H-1, 80-82 | 18.60 | 1.68 | 1.02 |
| 3H-2, 78-80 | 20.08 | 1.86 | 0.85 |
| 3H-3, 80-82 | 21.60 | 1.84 | 0.77 |
| 3H-4, 78-80 | 23.08 | 1.79 | 1.01 |
| 3H-5, 80-82 | 24.60 | 1.61 | 0.83 |
| 3H-6, 80-82 | 26.10 | 1.79 | 1.43 |
| 4H-1, 80-82 | 28.10 | 1.81 | 1.35 |
| 4H-2, 80-82 | 29.60 | 1.78 | 1.28 |
| 4H-3, 80-82 | 31.10 | 1.80 | 1.45 |
| 4H-4, 78-80 | 32.58 | 1.55 | 1.01 |
| 4H-5, 80-82 | 34.10 | 1.82 | 1.32 |
| 4H-6, 80-82 | 35.60 | 1.69 | 1.24 |
| 5H-1, 85-87 | 37.65 | 0.58 | 0.35 |
| 5H-2, 85-87 | 39.15 | 1.54 | 1.36 |
| 5H-3, 85-87 | 40.65 | 1.56 | 1.61 |
| 5H-4, 85-87 | 42.15 | 1.65 | 1.33 |
| 5H-5, 85-87 | 43.65 | 1.62 | 1.44 |
| 5H-6, 85-87 | 45.15 | 1.61 | 1.57 |
| 6H-1, 85-87 | 47.25 | 1.62 | 1.88 |
| 6H-2, 85-87 | 48.75 | 1.68 | 1.46 |
| 6H-3, 85-87 | 50.25 | 1.62 | 1.48 |
| 6H-4, 85-87 | 51.75 | 1.63 | 1.70 |
| 6H-5, 85-87 | 53.25 | 1.66 | 1.68 |
| 7H-1, 85-87 | 56.95 | 1.34 | 1.87 |
| 7H-2, 85-87 | 58.45 | 1.24 | 2.14 |
| 7H-3, 85-87 | 59.95 | 1.08 | 1.95 |
| 7H-4, 85-87 | 61.45 | 0.74 | 1.59 |
| 7H-5, 85-87 | 62.95 | 1.14 | 2.20 |
| 7H-6, 85-87 | 64.45 | 1.05 | 2.03 |
| 8H-1, 85-87 | 66.65 | 0.77 | 1.71 |
| 8H-2, 85-87 | 68.15 | 0.62 | 1.26 |
| 8H-3, 85-87 | 69.65 | 0.38 | 1.38 |
| 8H-4, 85-87 | 71.15 | 0.73 | 1.69 |
| 8H-5, 85-87 | 72.65 | 1.03 | 1.58 |
| 8H-6, 85-87 | 74.15 | 0.78 | 1.06 |
| 9H-1, 85-87 | 76.25 | 2.76 | 0.95 |
| 9H-2, 85-87 | 77.75 | 1.66 | 0.96 |
| 9H-3, 85-87 | 79.25 | 1.03 | 1.39 |
| 9H-4, 85-87 | 80.75 | 1.10 | 1.26 |
| 9H-5, 85-87 | 82.25 | 0.92 | 1.36 |
| 9H-6, 85-87 | 83.75 | 0.70 | 1.29 |
| 10H-1, 85-87 | 85.85 | 1.08 | 1.42 |
| 10H-3, 85-87 | 88.85 | 0.07 | 1.11 |
| 10H-4, 85-87 | 90.35 | 1.24 | 1.80 |
| 10H-5, 85-87 | 91.85 | 0.93 | 1.72 |
| 10H-6, 85-87 | 93.40 | 0.76 | 1.33 |
| 11H-1, 85-87 | 95.55 | 0.26 | 1.37 |
| 11H-2, 90-92 | 97.10 | 0.10 | 1.41 |
| 11H-3, 85-87 | 98.55 | 0.16 | 1.31 |
| 11H-4, 85-87 | 100.05 | −0.53 | 1.64 |
| 11H-5, 85-87 | 101.55 | −0.24 | 1.83 |
| 11H-5, 135-137 | 102.05 | −0.45 | 1.74 |

Note: All analyses were conducted on the benthic foraminifer *Cibicidoides* sp.

**Table 3. Oxygen and carbon isotopic data from Hole 754A.**

| Core, section interval (cm) | Depth (mbsf) | Oxygen-18 | Carbon-13 |
|---|---|---|---|
| 121-754A- | | | |
| 1H-1, 78-80 | 0.78 | 2.72 | 0.94 |
| 1H-2, 78-80 | 2.28 | 2.57 | 1.03 |
| 1H-3, 78-80 | 3.78 | 2.58 | 0.96 |
| 1H-4, 78-80 | 5.28 | 2.52 | 1.11 |
| 2H-1, 78-80 | 6.88 | 2.67 | 1.06 |
| 2H-2, 78-80 | 8.38 | 2.62 | 1.07 |
| 2H-3, 78-80 | 9.88 | 2.51 | 0.95 |
| 2H-4, 78-80 | 11.38 | 2.46 | 0.77 |
| 2H-5, 78-80 | 12.88 | 2.34 | 0.83 |
| 2H-6, 78-80 | 14.38 | 2.23 | 0.80 |
| 3H-1, 78-80 | 16.48 | 2.12 | 0.70 |
| 3H-2, 78-80 | 17.98 | 2.03 | 0.70 |
| 3H-3, 78-80 | 19.48 | 1.77 | 1.00 |
| 3H-4, 78-80 | 20.98 | 1.79 | 0.70 |
| 3H-5, 78-80 | 22.48 | 2.07 | 0.75 |
| 3H-6, 78-80 | 23.98 | 2.21 | 0.88 |
| 4H-1, 78-80 | 26.08 | 2.06 | 0.87 |
| 4H-2, 78-80 | 27.58 | 1.93 | 0.79 |
| 4H-3, 78-80 | 29.08 | 2.07 | 1.03 |
| 4H-4, 78-80 | 30.58 | 1.75 | 0.87 |
| 4H-5, 78-80 | 32.08 | 1.84 | 1.11 |
| 4H-6, 78-80 | 33.58 | 1.81 | 1.24 |
| 5H-1, 78-80 | 35.68 | 1.98 | 1.34 |
| 5H-2, 78-80 | 37.18 | 1.81 | 1.37 |
| 5H-3, 78-80 | 38.68 | 2.04 | 1.13 |
| 5H-4, 78-80 | 40.18 | 1.74 | 1.48 |
| 5H-5, 78-80 | 41.68 | 1.79 | 1.33 |
| 5H-6, 78-80 | 43.18 | 1.78 | 1.45 |
| 6H-1, 78-80 | 45.28 | 2.10 | 1.17 |
| 6H-2, 78-80 | 46.78 | 2.06 | 0.82 |
| 6H-3, 78-80 | 48.28 | 1.86 | 1.16 |
| 6H-4, 78-80 | 49.78 | 1.57 | 1.10 |
| 6H-5, 78-80 | 51.28 | 1.82 | 1.16 |
| 6H-6, 78-80 | 52.78 | 1.85 | 1.44 |
| 7H-1, 78-80 | 54.88 | 1.56 | 1.34 |
| 7H-2, 78-80 | 56.38 | 1.65 | 1.08 |
| 7H-3, 78-80 | 57.88 | 1.77 | 1.55 |
| 7H-4, 78-80 | 59.38 | 1.74 | 1.48 |
| 7H-5, 78-80 | 60.88 | 1.87 | 1.96 |
| 7H-6, 78-80 | 62.38 | 1.62 | 1.51 |
| 8H-1, 78-80 | 64.58 | 1.54 | 1.63 |

**Table 3 (Continued).**

| Core, section interval (cm) | Depth (mbsf) | Oxygen-18 | Carbon-13 |
|---|---|---|---|
| 121-754A-(Cont.) | | | |
| 8H-2, 78-80 | 66.08 | 1.92 | 1.75 |
| 8H-3, 78-80 | 67.58 | 1.69 | 1.74 |
| 8H-4, 78-80 | 69.08 | 1.68 | 1.81 |
| 8H-5, 78-80 | 70.58 | 1.67 | 1.69 |
| 8H-6, 78-80 | 72.08 | 1.58 | 1.74 |
| 8H-7, 78-80 | 73.58 | 1.60 | 1.83 |
| 9H-1, 78-80 | 74.28 | 1.23 | 1.84 |
| 9H-2, 78-80 | 75.78 | 1.24 | 1.95 |
| 9H-3, 78-80 | 77.28 | 0.80 | 2.00 |
| 9H-4, 78-80 | 78.78 | 0.99 | 2.26 |
| 9H-5, 78-80 | 80.28 | 0.87 | 1.91 |
| 9H-6, 78-80 | 81.78 | 1.29 | 2.41 |
| 10H-1, 78-80 | 83.98 | 0.82 | 1.58 |
| 10H-2, 78-80 | 85.48 | 1.23 | 1.51 |
| 10H-3, 78-80 | 86.98 | 0.91 | 0.93 |
| 10H-4, 78-80 | 88.48 | 1.16 | 1.43 |
| 10H-5, 78-80 | 89.98 | 1.02 | 1.35 |
| 10H-6, 78-80 | 91.48 | 0.96 | 1.50 |
| 11H-1, 78-80 | 93.68 | 1.25 | 1.27 |
| 11H-2, 78-80 | 95.18 | 1.23 | 1.49 |
| 11H-3, 78-80 | 96.68 | 1.11 | 1.38 |
| 11H-4, 80-82 | 98.2 | 1.28 | 1.45 |
| 11H-5, 78-80 | 99.68 | 0.88 | 1.40 |
| 11H-6, 78-80 | 101.18 | 0.97 | 1.50 |
| 12H-1, 78-80 | 103.38 | 1.29 | 1.69 |
| 12H-2, 78-80 | 104.88 | 1.20 | 1.79 |
| 12H-3, 78-80 | 106.38 | 1.24 | 1.40 |
| 12H-4, 78-80 | 107.88 | 0.67 | 1.24 |
| 12H-5, 78-80 | 109.38 | 0.79 | 1.26 |
| 12H-6, 78-80 | 110.88 | 1.11 | 1.23 |
| 13H-1, 78-80 | 113.08 | 1.08 | 0.78 |
| 13H-2, 78-80 | 114.58 | 1.06 | 1.22 |
| 13H-3, 78-80 | 116.08 | 1.06 | 1.05 |
| 14H-1, 78-80 | 122.78 | 0.60 | 1.52 |
| 14H-2, 78-80 | 124.28 | 0.18 | 1.75 |
| 14H-3, 78-80 | 125.78 | 1.65 | 1.46 |

Note: All analyses were conducted on the benthic foraminifer *Cibicidoides* sp.

4 and 5) show the uppermost few samples to have average $\delta^{18}O$ values of about 3 per mil, a sequence of values near 2.5 per mil, and a transition between about 42 and 52 mbsf to values averaging 1.5 to 1.7 per mil. The lowest 15 m (in Hole 756C) are characterized by the lightest values, about 0.4 per mil for the Uvigerinids and 0.8 per mil for the Gyroidinoidids. The oxygen isotopic record from Hole 757B (Fig. 6, Table 6) is similar, exhibiting values in excess of 3 per mil in the upper 15 m, a series of values averaging 2.7 per mil, a transition at approximately 85 mbsf to values of 1.8 to 2.0 per mil, and a decline at about 120 mbsf to values of about 1.2 per mil in the lower portion of the measured section.

We can use the nannofossil zonations provided by Peirce, Weissel, et al. (1989), with augmentation by P. Resiwati (pers. comm., 1990), to determine when the transitions in isotopic values occurred. The lowest transition, best illustrated by the data from Sites 756 and 757, occurs at the Eocene/Oligocene boundary. At Site 756 this transition is marked by an overall enrichment of nearly 1.2 per mil in the Uvigerinid data and of about 1 per mil in the Gyroidinoidid data. At Site 757 the enrichments are similar. This increase of about 1 per mil represents the cooling of the Southern Ocean, formation of cold bottom water, and the creation of some to much of the ice on Antarctica (Kennett and Shackleton, 1976; Kennett, 1977; Matthews and Poore, 1980). The paleodepth of Sites 756 and 757 at the time of the Eocene/Oligocene boundary was within the Surface Water Mass, so the $\delta^{18}O$ shift recorded here is not a record of deep-ocean temperature; it may reflect either the whole-ocean response to ice formation, a sudden cooling of the surface waters at the paleolatitude of these sites, or a combination of effects. The isotopically light values from the lower samples of Holes 752A and 754A are also from Eocene sediments deposited above the Broken Ridge angular unconformity.

The middle Miocene oxygen isotopic enrichment occurs mostly in Zone CN5a, 14.4 to 13.0 Ma (Berggren et al., 1985), on Broken Ridge and Ninetyeast Ridge. This enrichment is about 0.8 to 1.0 per mil and reflects additional ice buildup on Antarctica, possibly associated with additional polar cooling (Kennett, 1977, 1985; Woodruff et al., 1981). Mid-Miocene depths of these drill sites would place them within the Surface Water Mass then.

The upper Pliocene oxygen isotopic enrichment occurs in Zones CN11 and CN12, 3.6 to 2.0 Ma (Berggren et al., 1985), and is 0.7 to 0.8 per mil in these sites. It reflects the oceanic response to the formation of Northern Hemisphere ice.

## Carbon Isotopes

The $\delta^{13}C$ record from Hole 752A (Fig. 2, Table 2) on Broken Ridge decreases from core-top values to a low of about 0.5 per mil near 14 mbsf. From that low, values increase downcore to a maximum at roughly 60 mbsf; an important increase of about 0.7 per mil occurs at 27 mbsf. At about 62 mbsf, the $\delta^{13}C$ values

**Table 4. Oxygen and carbon isotopic data from Hole 756B.**

| Core, section interval (cm) | Depth (mbsf) | *Gyroidinoides* sp. Oxygen-18 | *Gyroidinoides* sp. Carbon-13 | *Uvigerina* sp. Oxygen-18 | *Uvigerina* sp. Carbon-13 |
|---|---|---|---|---|---|
| 121-756B- | | | | | |
| 1H-1, 80-82 | 0.80 | | 3.12 | 0.32 | |
| 1H-2, 80-82 | 2.30 | | 3.50 | −0.02 | |
| 1H-3, 80-82 | 3.80 | | 2.38 | −0.08 | |
| 1H-4, 80-82 | 5.30 | | 3.04 | −0.04 | |
| 1H-5, 80-82 | 6.80 | | 2.24 | 0.78 | |
| 2H-1, 80-82 | 9.30 | | 2.80 | 0.25 | |
| 2H-2, 80-82 | 10.80 | | 2.72 | 0.53 | |
| 2H-3, 80-82 | 12.30 | | 2.65 | 0.36 | |
| 2H-4, 80-82 | 13.80 | | 2.78 | 0.25 | |
| 2H-5, 80-82 | 15.30 | | 2.73 | 0.17 | |
| 2H-6, 80-82 | 16.80 | | 2.71 | 0.49 | |
| 3H-1, 80-82 | 18.90 | 2.94 | −0.03 | 2.21 | 0.20 |
| 3H-2, 80-82 | 20.40 | | 2.79 | 0.32 | |
| 3H-3, 80-82 | 21.90 | | 2.27 | 0.13 | |
| 3H-4, 80-82 | 23.40 | | 2.68 | 0.27 | |
| 3H-5, 80-82 | 24.90 | | 2.45 | 0.32 | |
| 3H-6, 80-82 | 26.40 | 2.36 | 0.33 | 2.40 | 0.56 |
| 4H-1, 80-82 | 28.50 | 2.77 | 0.72 | 2.49 | 0.72 |
| 4H-3, 80-82 | 31.50 | | 2.60 | 0.91 | |
| 4H-5, 80-82 | 34.50 | | 2.49 | 0.64 | |
| 4H-6, 80-82 | 36.00 | | 2.52 | 1.01 | |
| 5H-1, 80-82 | 38.10 | | 2.34 | 0.66 | |
| 5H-2, 80-82 | 39.60 | | 2.39 | 0.77 | |
| 5H-4, 80-82 | 42.60 | 2.48 | 0.55 | 2.18 | 1.09 |
| 5H-5, 80-82 | 44.10 | | 2.23 | 0.93 | |
| 5H-6, 80-82 | 45.60 | 1.78 | 0.80 | | |
| 6H-2, 80-82 | 49.20 | 1.70 | 1.34 | | |
| 6H-3, 80-82 | 50.70 | | 1.10 | 1.76 | |
| 6H-5, 80-82 | 53.70 | 1.24 | 0.47 | 1.38 | 1.39 |
| 7H-1, 80-82 | 57.00 | 1.64 | 0.50 | 1.18 | 1.06 |
| 7H-3, 80-82 | 60.00 | 1.89 | 0.96 | | |
| 7H-4, 80-82 | 61.50 | | 1.80 | 1.01 | |
| 7H-5, 84-86 | 63.04 | 1.74 | 0.99 | 1.41 | 0.80 |
| 7H-6, 80-82 | 64.50 | | 1.73 | 1.28 | |
| 8H-1, 80-82 | 66.40 | 1.84 | 1.26 | 1.62 | 1.20 |
| 8H-2, 80-82 | 67.90 | 1.95 | 1.31 | | |
| 8H-3, 80-82 | 69.40 | 1.68 | 1.00 | 1.59 | 1.19 |
| 8H-4, 80-82 | 70.90 | 1.54 | 0.54 | 1.41 | 0.66 |
| 8H-5, 80-82 | 72.40 | 1.57 | 0.64 | | |
| 8H-6, 80-82 | 73.90 | 1.64 | 0.63 | | |
| 9H-1, 80-82 | 76.00 | 1.62 | 0.42 | 1.77 | 0.73 |
| 9H-2, 80-82 | 77.50 | 1.86 | 0.67 | 1.38 | 0.42 |
| 9H-3, 80-82 | 79.00 | 1.82 | 0.26 | | |
| 9H-4, 80-82 | 80.50 | | 1.36 | 0.29 | |
| 9H-5, 80-82 | 82.00 | 1.71 | 0.36 | | |
| 9H-6, 80-82 | 83.50 | 1.77 | 0.45 | 1.62 | 0.46 |
| 10H-1, 80-82 | 85.70 | 1.73 | 0.54 | 1.56 | 0.65 |
| 10H-2, 80-82 | 87.20 | 1.77 | 0.52 | 1.47 | 0.55 |
| 10H-3, 30-32 | 88.20 | 1.65 | 0.46 | | |
| 10H-3, 80-82 | 88.70 | | 1.38 | 0.66 | |
| 10H-4, 80-82 | 90.20 | 1.54 | 0.57 | 1.44 | 0.47 |
| 10H-5, 80-82 | 91.70 | 1.65 | 0.21 | 1.29 | 0.35 |
| 10H-6, 80-82 | 93.20 | | | | |
| 11H-1, 80-82 | 95.40 | 1.55 | 0.94 | | |
| 11H-2, 80-82 | 96.90 | | 1.60 | 1.18 | |
| 11H-3, 80-82 | 98.40 | 1.20 | 0.77 | | |
| 11H-4, 80-82 | 99.90 | 1.16 | 0.63 | 1.34 | 0.73 |
| 11H-5, 80-82 | 101.40 | | 1.14 | 0.72 | |
| 11H-6, 80-82 | 102.90 | | 1.37 | 1.17 | |

Note: Analyses were conducted on the benthic foraminifers *Gyroidinoides* sp. and *Uvigerina* sp.

decline by approximately 0.8 per mil to values averaging about 1.4 per mil in the lower portion of the sequence. Site 754 contains a similar record (Fig. 3, Table 3). Values decline gently from the top of the core to a low of about 1.7 per mil near 20 mbsf, and then increase to a maximum of 2.5 per mil near 80 mbsf. Approximately 0.6 per mil of this increase occurs near 35 mbsf. Between 82 and 87 mbsf the $\delta^{13}C$ values decline nearly 0.9 per mil to values of about 1.4 per mil that characterize the lower portion of the core.

At Site 756 the same aspects of the $\delta^{13}C$ record occur (Figs. 4 and 5, Tables 4 and 5), with low values near the top, increasing downcore to a maximum of 1.8 per mil at about 52 mbsf, and an increase of 0.7 per mil centered near 27 mbsf. Between about 52 and 57 mbsf the carbon isotopic values decline by about 0.8 per mil and fluctuate around values of 0.5 to 1.0 per mil through the lower half of the record. Both genera show very similar $\delta^{13}C$ fluctuations in the lower 80 m at Site 756, and record a modest

Table 5. Oxygen and carbon isotopic data from Hole 756C.

| Core, section interval (cm) | Depth (mbsf) | *Gyroidinoides* sp. Oxygen-18 | *Gyroidinoides* sp. Carbon-13 | *Uvigerina* sp. Oxygen-18 | *Uvigerina* sp. Carbon-13 |
|---|---|---|---|---|---|
| 121-756C- | | | | | |
| 4X-1, 80-82 | 101.70 | 1.76 | 0.35 | 1.72 | 0.60 |
| 4X-2, 80-82 | 103.20 | 1.76 | 0.64 | 1.52 | 0.49 |
| 4X-3, 80-82 | 104.70 | 1.66 | 0.31 | 1.35 | 0.39 |
| 4X-4, 80-82 | 106.20 | 1.73 | 0.40 | 1.69 | 0.34 |
| 4X-5, 80-82 | 107.20 | 1.44 | 0.52 | | |
| 4X-6, 80-82 | 109.20 | 1.64 | 0.49 | 2.64 | 1.15 |
| 5X-3, 80-82 | 112.32 | 1.57 | 0.55 | 1.24 | 0.26 |
| 5X-5, 80-82 | 114.26 | 1.45 | 0.62 | | |
| 5X-6, 80-82 | 115.08 | 1.56 | 0.89 | 0.67 | 1.04 |
| 5X-7, 80-82 | 116.41 | 1.41 | 0.86 | | |
| 5X-8, 80-82 | 117.91 | 1.13 | 0.58 | | |
| 6X-1, 80-82 | 121.00 | 1.60 | 1.14 | 1.41 | 1.15 |
| 6X-2, 80-82 | 122.50 | 1.69 | 1.37 | 1.38 | 1.55 |
| 6X-4, 80-82 | 125.50 | 1.08 | 1.02 | 0.72 | 0.85 |
| 6X-5, 80-82 | 127.00 | 1.02 | 0.67 | 0.46 | 0.79 |
| 7X-1, 80-82 | 130.60 | 1.10 | 1.13 | 0.48 | 0.98 |
| 7X-2, 80-82 | 132.10 | | 0.65 | 0.96 | |
| 7X-3, 80-82 | 133.60 | | 0.58 | 1.07 | |
| 7X-4, 80-82 | 135.10 | 0.65 | 1.18 | 0.54 | 1.41 |
| 7X-5, 80-82 | 136.60 | 0.89 | 0.79 | 0.34 | 1.34 |
| 7X-6, 80-82 | 138.10 | | 0.39 | 0.93 | |
| 8X-1, 80-82 | 140.20 | | 0.53 | 0.81 | |

Note: Analyses were conducted on the benthic foraminifers *Gyroidinoides* sp. and *Uvigerina* sp.

decrease of perhaps 0.5 per mil in $\delta^{13}C$ at 68 to 75 mbsf and a similar increase at 112 to 122 mbsf. Carbon isotopic values at Hole 757B (Fig. 6, Table 6) display a general downcore increase in $\delta^{13}C$ values, with the largest step at 51 to 57 mbsf.

The lower enrichment of $\delta^{13}C$ occurs in nannofossil zone CN4 at Sites 752 and 754 and within Zones CN2 to CN4 at Site 756. This enrichment of 0.8 or 0.9 per mil in $\delta^{13}C$ values that occurred about 15 to 17 Ma occurs in both planktonic and benthic foraminifers and thus represents oceanic exchange with a marine or terrestrial sedimentary reservoir. Carbon storage on land or in marine sediments removes isotopically light organic carbon from the ocean, resulting in an increase in marine $\delta^{13}C$; this inter-reservoir transfer is similar in concept to the effect of the storage of isotopically light ice away from the marine system and its effect on oxygen isotopes. This early/middle Miocene carbon isotopic shift coincides with a period of generally high sea-level (Haq et al., 1987) and the deposition of large amounts of organic carbon in basins around the North Pacific (the Chron 16 carbon shift, Vincent et al., 1985; Monterey event, Berger and Vincent, 1986).

The late Miocene depletion of 0.7 per mil in $\delta^{13}C$ values occurs in Zone CN9 at Sites 754, 756, and 757, and within Zones CN9b to CN10a at Site 752. This depletion occurs throughout the oceans (Keigwin, 1979; Vincent et al., 1985; Kennett, 1985; Berger and Vincent, 1986; Keigwin et al., 1987) and has been demonstrated to occur within magnetic reversal Chron 6 (upper Zones CN9a and CN9b) at about 6.2 Ma (Keigwin and Shackleton, 1980).

## SUMMARY

Oxygen and carbon stable isotopic records from the carbonate oozes at Sites 752, 754, 756, and 757 provide the fundamental isotopic stratigraphy for these sediments. Oxygen isotopes provide evidence for cooling and/or ice volume increases at the Eocene/Oligocene boundary, in the middle Miocene, and in the late Pliocene. The carbon isotopic record contains the Chron 16 enrichment in the early/middle Miocene and the Chron 6 depletion in the latest Miocene.

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**Table 6. Oxygen and carbon isotopic data from Hole 757B.**

| Core, section interval (cm) | Depth (mbsf) | *Uvigerina* sp. Oxygen-18 | *Uvigerina* sp. Carbon-13 | *Gyroidinoides* sp. Oxygen-18 | *Gyroidinoides* sp. Carbon-13 |
|---|---|---|---|---|---|
| 121-757B- | | | | | |
| 1H-2, 80-82 | 2.13 | 3.01 | −0.09 | | |
| 1H-3, 80-82 | 3.63 | 3.22 | −0.01 | | |
| 2H-1, 80-82 | 5.30 | 3.37 | −0.38 | | |
| 2H-2, 80-82 | 6.80 | 3.77 | −0.56 | | |
| 2H-3, 80-82 | 8.30 | 3.02 | −0.02 | 3.33 | −0.36 |
| 2H-4, 80-82 | 9.80 | 3.30 | −0.19 | | |
| 2H-5, 80-82 | 11.30 | 3.30 | −0.27 | | |
| 2H-6, 80-82 | 12.80 | 3.17 | 0.10 | | |
| 3H-1, 80-82 | 14.80 | 3.27 | −0.07 | | |
| 3H-2, 80-82 | 16.30 | 2.81 | 0.11 | | |
| 3H-3, 80-82 | 17.80 | 2.83 | −0.14 | | |
| 3H-4, 80-82 | 19.30 | 2.84 | 0.35 | | |
| 3H-5, 80-82 | 20.80 | 3.07 | −0.17 | | |
| 3H-6, 80-82 | 22.30 | 2.56 | −0.15 | | |
| 4H-1, 80-82 | 24.40 | 2.81 | 0.06 | | |
| 4H-2, 80-82 | 25.90 | | 2.97 | −0.48 | |
| 4H-4, 80-82 | 28.90 | 2.62 | −0.06 | | |
| 4H-5, 80-82 | 30.40 | 2.67 | 0.31 | | |
| 5H-1, 80-82 | 34.00 | 2.87 | 0.12 | | |
| 5H-2, 80-82 | 35.50 | 2.74 | −0.02 | 2.74 | −0.60 |
| 5H-3, 80-82 | 37.00 | 2.55 | 0.21 | | |
| 5H-4, 80-82 | 38.50 | 2.76 | 0.07 | | |
| 5H-5, 80-82 | 40.00 | 2.68 | 0.28 | 2.79 | −0.08 |
| 6H-1, 80-82 | 43.60 | 2.85 | 0.18 | 2.79 | −0.34 |
| 6H-2, 80-82 | 45.10 | 2.66 | 0.25 | 2.72 | −0.28 |
| 6H-3, 80-82 | 46.60 | 2.76 | 0.11 | 2.88 | −0.24 |
| 6H-4, 80-82 | 48.10 | 2.82 | 0.08 | | |
| 6H-5, 80-82 | 49.60 | 2.83 | 0.09 | | |
| 6H-6, 80-82 | 51.10 | 2.75 | −0.08 | 2.82 | −0.09 |
| 7H-1, 80-82 | 53.30 | 2.80 | 0.35 | | |
| 7H-2, 80-82 | 54.80 | 3.37 | 0.78 | | |
| 7H-4, 80-82 | 57.80 | 2.22 | 1.26 | | |
| 8H-1, 80-82 | 63.00 | 2.57 | 0.66 | 2.53 | 0.22 |
| 8H-2, 80-82 | 64.50 | 2.71 | 0.78 | | |
| 9H-1, 80-82 | 72.60 | 2.48 | 0.66 | | |
| 9H-3, 80-82 | 75.60 | 2.67 | 0.41 | | |
| 9H-4, 80-82 | 77.10 | | 2.74 | 0.37 | |
| 9H-5, 80-82 | 78.60 | 2.47 | 0.85 | 1.80 | 0.46 |
| 9H-6, 80-82 | 80.10 | 2.70 | 0.15 | | |
| 10H-1, 80-82 | 82.30 | 2.49 | 0.62 | | |
| 10H-2, 80-82 | 83.00 | | 2.23 | 0.84 | |
| 10H-4, 80-82 | 86.80 | | 1.55 | 0.74 | |
| 10H-5, 80-82 | 88.30 | 1.76 | 1.12 | 1.73 | 0.80 |
| 11H-1, 80-82 | 92.00 | 1.71 | 0.51 | 1.72 | 0.30 |
| 11H-2, 80-82 | 93.50 | | 2.04 | 0.53 | |
| 11H-3, 80-82 | 95.00 | 1.99 | 0.68 | 1.98 | 0.51 |
| 11H-4, 80-82 | 96.50 | | 2.04 | 0.48 | |
| 11H-5, 80-82 | 98.00 | 1.92 | 1.18 | 1.71 | 0.36 |
| 12H-1, 80-82 | 101.60 | | 1.98 | 0.58 | |
| 12H-2, 80-82 | 103.10 | 1.77 | 1.05 | 1.87 | 0.83 |
| 12H-3, 80-82 | 104.60 | 1.83 | 0.95 | 1.91 | 0.83 |
| 12H-4, 80-82 | 106.10 | 1.87 | 1.03 | 1.90 | 0.61 |
| 12H-5, 80-82 | 107.60 | 1.99 | 0.77 | 1.85 | 0.72 |
| 12H-6, 80-82 | 109.10 | | 1.99 | 0.68 | |
| 13H-3, 80-82 | 114.30 | | 1.89 | 1.01 | |
| 13H-4, 80-82 | 115.80 | | 1.79 | 0.99 | |
| 13H-5, 80-82 | 117.30 | | 2.03 | 1.27 | |
| 13H-6, 80-82 | 118.80 | | 1.76 | 1.39 | |
| 14H-1, 80-82 | 120.90 | | 1.59 | 1.06 | |
| 14H-2, 80-82 | 122.40 | 1.13 | 0.88 | | |
| 14H-3, 80-82 | 123.90 | 1.15 | 1.04 | 1.18 | 0.94 |
| 14H-4, 80-82 | 125.40 | | 1.40 | 1.05 | |
| 14H-5, 80-82 | 126.90 | | 1.30 | 1.19 | |
| 14H-6, 80-82 | 128.40 | | 1.29 | 1.28 | |
| 15H-1, 80-82 | 130.60 | | 1.15 | 1.11 | |
| 15H-3, 80-82 | 133.60 | | 1.23 | 0.61 | |
| 15H-4, 80-82 | 135.10 | | 1.14 | 0.69 | |
| 15H-6, 80-82 | 138.10 | | 1.22 | 1.05 | |
| 16H-2, 80-82 | 141.80 | | 1.23 | 1.04 | |
| 16H-6, 19-21 | 147.19 | | 0.96 | 1.19 | |
| 18H-4, 80-82 | 161.10 | | 0.70 | 0.96 | |

Note: Analyses were conducted on benthic foraminifers *Gyroidinoides* sp. and *Uvigerina* sp.

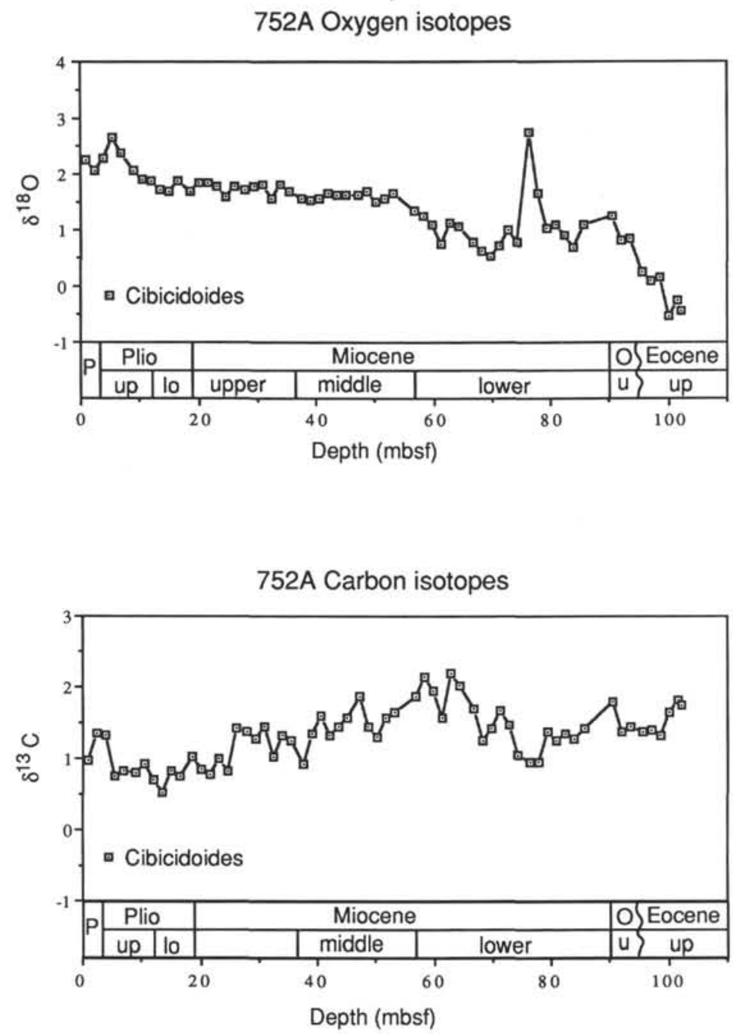
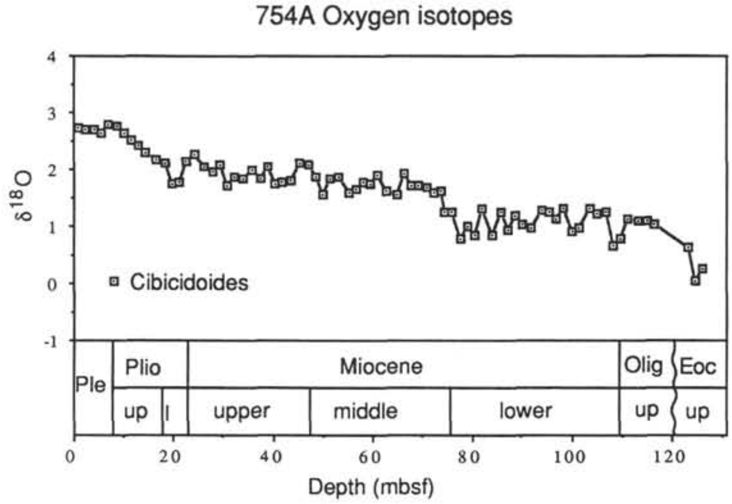


Figure 2. Oxygen and carbon isotopic record of Cenozoic oozes from Hole 752A.



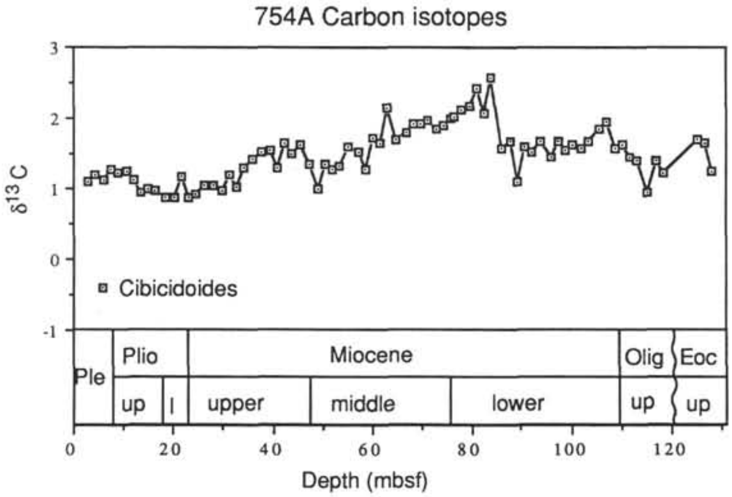
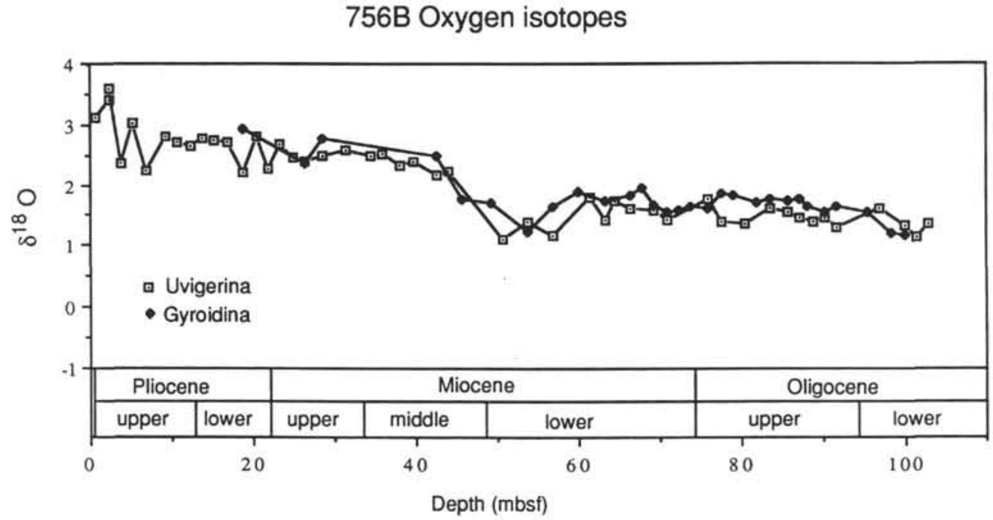




Figure 3. Oxygen and carbon isotopic record of Cenozoic oozes from Hole 754A.



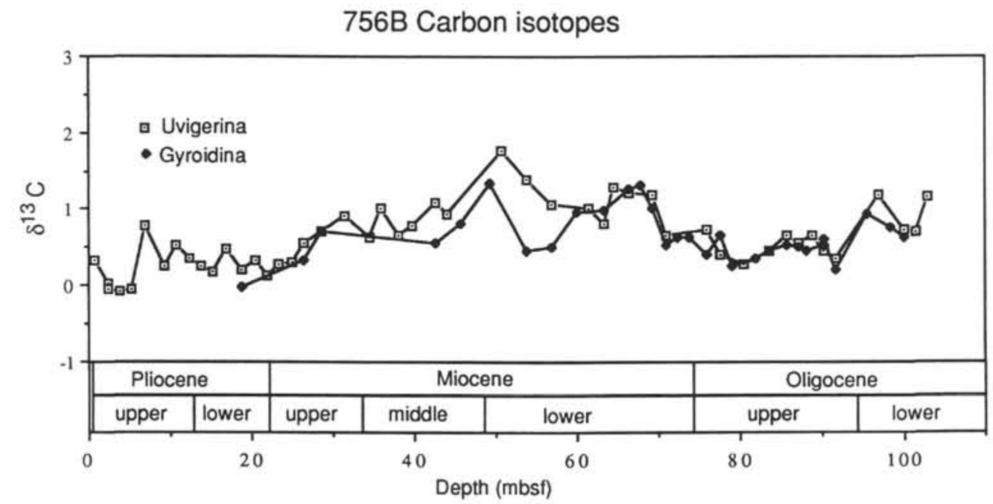




Figure 4. Oxygen and carbon isotopic record of Cenozoic oozes from Hole 756B.

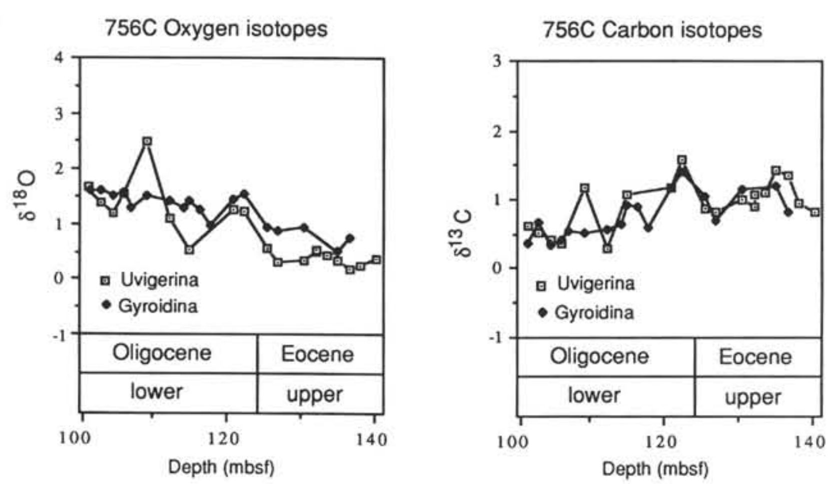



Figure 5. Oxygen and carbon isotopic record of Cenozoic oozes from Hole 756C.

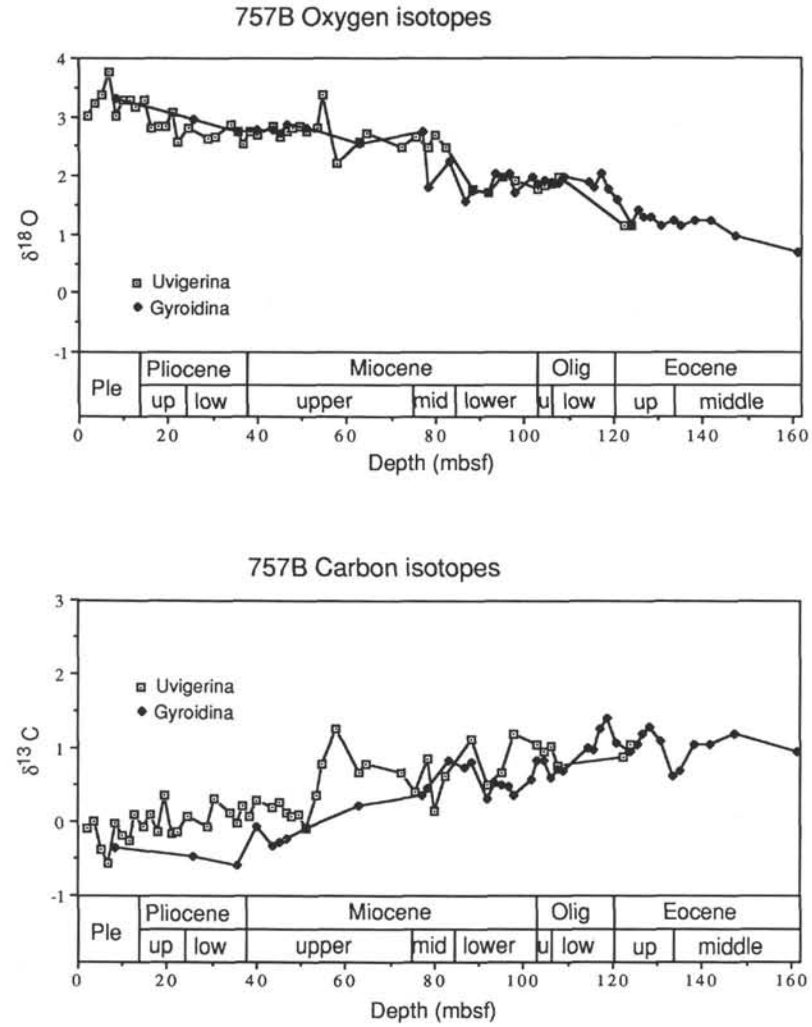


Figure 6. Oxygen and carbon isotopic record of Cenozoic oozes from Hole 757B.