Evolution of the Miocene ocean in the eastern North Pacific as inferred from oxygen and carbon isotopic ratios of foraminifera

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ABSTRACT

Oxygen and carbon isotopic ratios of planktonic and benthonic foraminifera have provided information about the evolution of the oceans at low- and mid-latitude sites in the Miocene eastern North Pacific Ocean.

DSDP Site 495 (12° N; 91° W) provides a record of early and middle Miocene oceanographic conditions in the eastern equatorial Pacific. Oxygen isotopic evidence indicates that *G. sacculifer, D. altispira* and *G. siakensis* were shallow-dwelling, tropical planktonic species. *G. venezuelana* deposited its test at greater depths, probably below the thermocline. Carbon isotopic evidence conflicts with that of the oxygen isotopes in that it suggests that *G. siakensis* calcified under conditions similar to those of *G. venezuelana.*

Temperature variability at Site 495 during early and middle Miocene time was relatively small. However, while middle Miocene deep waters at this site cooled, simultaneously with a major phase of growth of the Antarctic ice sheet, surface and near-surface waters warmed.

The oxygen isotopic record at Site 470 in the eastern North Pacific (29° N; 117° W) indicates that middle and late Miocene surface temperatures at this site were relatively stable, but were probably lower than modern surface temperatures.

At Site 173 (40° N; 125° W) middle and late Miocene surface temperatures were consistently lower than those at the more southerly Site 470, and were also significantly more variable. There is no indication that surface temperatures have changed significantly at Site 173 since late Miocene time. The inferred greater variability of surface temperatures at Site 173 may reflect greater variability of the intensity of upwelling at that site than at Site 470 during Miocene time.

At Site 495 both the planktonic and benthonic foraminiferal carbon isotopic records vary sympathetically with published benthonic foraminiferal isotopic records from the Atlantic and Pacific Oceans, indicating that the carbon isotopic ratios at that site largely reflect global fluctuations in the isotopic composition of dissolved inorganic carbon.

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At Site 470 the planktonic carbon isotopic record fluctuates sympathetically with published benthonic records, indicating that the middle and late Miocene $^{13}C/^{12}C$ ratios of dissolved inorganic carbon in surface waters at this site reflected global fluctuations in $^{13}C/^{12}C$. The planktonic carbon isotopic record at Site 173 could not be correlated with global carbon isotopic fluctuations, indicating that, in part, local effects controlled the $^{13}C/^{12}C$ ratio of dissolved inorganic carbon in surface waters at that site.

INTRODUCTION

The evolution of Miocene surface and deep waters in the eastern equatorial Pacific and northeastern Pacific Ocean has been investigated as part of a larger study of global Miocene oceanography (Cenozoic Paleoceanography Project, CENOP). Oxygen and carbon isotopic ratios of the tests of planktonic and benthonic foraminifera from Deep Sea Drilling Project (DSDP) Site 495 in the eastern equatorial Pacific, and from DSDP Sites 173 and 470 and the onshore Miocene section at Newport Beach, California in the northeast Pacific California Current system were measured. The locations of the sites discussed in this study, as well as of other relevant sites, are shown in Figure 1. Detailed information about the sites is given in Table 1.

Numerous studies have demonstrated that the $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios of the tests of foraminifera provide information about ocean waters at the time and place the tests were secreted (Emiliani, 1954, 1955; Savin and Douglas, 1973; Berger and Gardner, 1975; Duplessy, 1978). The $^{18}O/^{16}O$ ratio of a calcitic

foraminiferal test deposited in isotopic equilibrium with sea water reflects the temperature and the isotopic composition of the water in which the foraminifer grew. The $^{13}C/^{12}C$ ratio of a foraminiferal test reflects mainly the isotopic composition of the dissolved HCO_3^- in the water column.

Previous oxygen and carbon isotopic studies, as well as studies of the abundances of planktonic and benthonic foraminifera, have demonstrated that the Miocene epoch was a crucial episode in the Earth's climatic history. Isotopic records of benthonic and planktonic foraminifera have most often been interpreted as indicating that the early Miocene was a period characterized by limited Antarctic glaciation (Shackleton and Kennett, 1975; Woodruff et al., 1981; Savin et al., 1981), smaller equator-to-pole and tropical surface-to-bottom temperature gradients, and warmer high latitude surface waters than those of today (Savin et al., 1975). A worldwide rapid increase in $\delta^{18}O$ values of benthonic foraminifera during early middle Miocene time has gener-
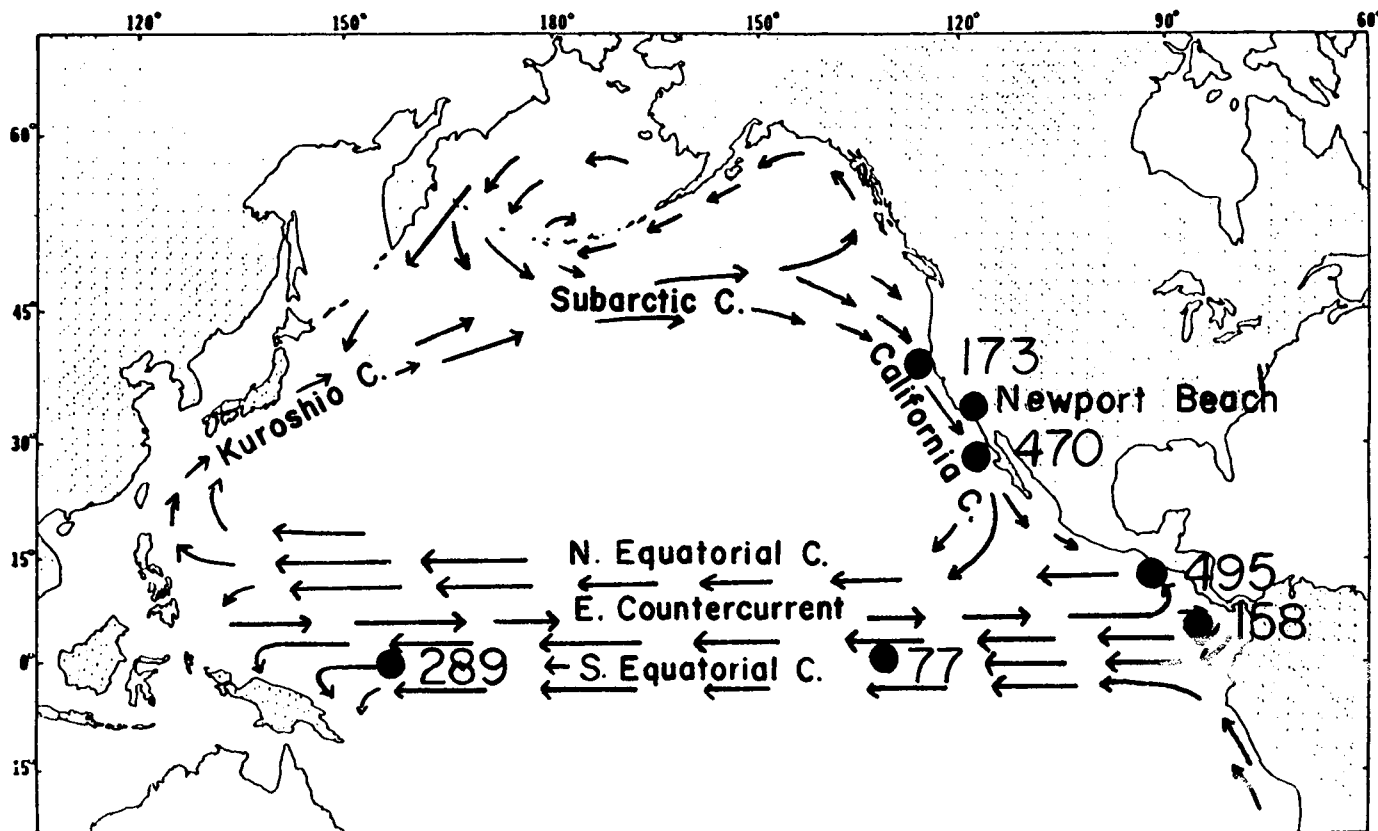

Figure 1. Locations of DSDP Sites discussed in this study.

TABLE 1. GEOGRAPHIC LOCATION OF SITES STUDIED

Site	Longitude	Latitude	Water depth
DSDP 173	125° 27.12'W	39° 57.71'N	2927 m
Newport Beach	117° 53'W	33° 38'N	onshore
DSDP 470	117° 31.11'W	28° 54.46'N	3549 m
DSDP 495	91° 2.26'W	12° 29.78'N	4150 m
DSDP 158	85° 14.16'W	6° 37.36'N	1953 m

TABLE 2. RELATIONSHIPS BETWEEN SEAWATER SALINITY AND $\delta^{18}O$*

Region	Relationship
California Current	$\delta^{18}O_{SMOW}$= 0.544(salinity)-18.63
Eastern Equatorial Pacific	$\delta^{18}O_{SMOW}$= 0.222(salinity)-7.50

*Inferred from data in Craig and Gordon (1965)

ally been interpreted as reflecting a combination of: a) an increase in the $^{18}O/^{16}O$ ratio of the oceans due to rapid growth of the Antarctic ice sheet; and b) cooling of high latitude surface waters and hence deep bottom waters (Shackleton and Kennett, 1975; Savin et al., 1975; Keigwin, 1979; Woodruff et al., 1981; Savin et al., 1981). An alternative interpretation has been proposed by Matthews and Poore (1980), who argued that the middle Miocene increase in $\delta^{18}O$ values reflects simply a drop in bottom water temperatures, and that large continental ice sheets have existed at least since early Oligocene time. Independent of these conflicting interpretations, the oxygen isotopic ratios of benthonic and planktonic foraminifera suggest a progressive increase in the equator-to-pole surface temperature gradient and the low latitude vertical thermal gradient throughout middle and late Miocene times (Savin et al., 1975, this volume).

Whereas the evolution of Miocene bottom waters has been relatively well-researched (e.g., Savin et al., 1981), there is little isotopic information documenting the details of the evolution of surface waters, particularly at mid-latitudes in the North Pacific. The isotopic data from Site 495 presented here document in detail the thermal evolution of the water column in the eastern equatorial Pacific in the interval from about 17 to 12.6 Ma. The isotopic record from this site can be correlated with those from Sites 470 and 173, which document changes in the vertical and the latitudinal thermal gradients in the California Current system during middle and late Miocene times. The ability to correlate the sites is enhanced by the availability of a high resolution biochronology (Keller and Barron, 1981).

METHODS

The techniques used in this study for processing and counting planktonic foraminifera are similar to those outlined by Keller (1980a). In this study, foraminifera larger than 150 μm were counted, and those between 150 and 250 μm were analyzed isotopically.

Isotopic analyses were performed using standard techniques (Epstein et al., 1953) and are reported in δ notation as per mil deviations from the PDB standard. Isotopic measurements were made relative to a standard CO_2 gas whose isotopic composition was related to PDB values through numerous analyses of NBS Isotopic Reference Material No. 20 (Solenhofen Limestone). NBS 20 is taken to have a $\delta^{18}O$ value of -4.14 per mil and a $\delta^{13}C$ value of -1.06 per mil (Craig, 1957). Isotopic analyses

typically have a precision of ±0.1 per mil. $\delta^{18}O$ values of calcite precipitated in equilibrium with sea water were calculated using the equation of Epstein et al. (1953) as modified by Epstein (unpublished)

$$t(°C)=16.4-4.2(\delta_c-\delta_w)+0.13(\delta_c-\delta_w)^2$$

where δ_c is the isotopic composition of the CO_2 gas evolved from the carbonate when reacted with H_3PO_4 at 25° C and δ_w is the isotopic composition of the CO_2 gas equilibrated at 25° C with the water in which the carbonate was deposited. The $\delta^{18}O$ values of present-day waters in the region were estimated using salinity and temperature data obtained from the National Oceanographic Data Center (NODC) and relationships between salinity and $\delta^{18}O$ inferred from the data of Craig and Gordon (1965) for sea water in the appropriate regions of the Pacific Ocean (Table 2).

In order to reflect fluctuations in the $^{18}O/^{16}O$ ratio of sea water caused by fluctuations in Antarctic ice volume, in some cases (where indicated) adjustments have been applied to the oxygen isotopic data. These adjustments are based on estimates by Woodruff et al. (1981), and on the suggestion of Shackleton and Kennett (1975) that pre-middle Miocene ocean water was 0.92 per mil depleted in ^{18}O relative to the present. Adjusted $\delta^{18}O$ values are intended to approximate the $\delta^{18}O$ values the foraminifera would have had if they had grown under Miocene oceanographic conditions but in sea water with today's $\delta^{18}O$ values.

ISOTOPIC SYSTEMATICS OF FORAMINIFERA

Planktonic foraminifera do not appear to deposit their tests in isotopic equilibrium with the dissolved HCO_3^- of ambient sea water (Vergnaud-Grazzini, 1976; Williams et al., 1977; Kahn and Williams, 1981). Evidence for this comes from the observation that $\delta^{13}C$ values of several planktonic species, including *Globigerinoides sacculifer*, are very close to the $\delta^{13}C$ values of total dissolved CO_2 (and HCO_3^-) in sea water at the depths at which calcification is inferred to have occurred (Williams et al., 1977). Calcite in equilibrium with sea water, however, is 1.26 to 2.38 per mil enriched in ^{13}C relative to the dissolved HCO_3^- in the temperature range from 0 to 30°C (Emrich et al., 1970).

"Vital effects" in the $^{18}O/^{16}O$ ratios of at least most planktonic foraminiferal species are apparently small (Williams et al., 1979; Curry and Matthews, 1981a). There is, however, conflict-

ing evidence about whether *Globigerina bulloides* (which has been analyzed extensively in this study) deposits its test in isotopic equilibrium with sea water. Kahn and Williams (1981) reported that $\delta^{18}O$ values of *G. bulloides* collected in plankton tows from the northeastern Pacific Ocean are lower (i.e. warmer) than those expected for calcite in isotopic equilibrium with sea water in the upper 100 meters during the months of June and July. Other studies of this species collected in plankton tows and in surface sediments from several localities suggest $\delta^{18}O$ values close to equilibrium (Curry and Matthews, 1981a, b) and further suggest that *G. bulloides* grows predominantly during seasons of upwelling (Prell and Curry, 1981; Ganssen and Sarnthein, 1983). However, it has been pointed out by Bender (personal communication, 1984) that while the mean difference between measured $\delta^{18}O$ values of *G. bulloides* and equilibrium $\delta^{18}O$ values for surface waters in the large Indian Ocean data set of Curry and Matthews (1981a) is close to 0.00, the standard deviation of the differences is 0.24. Therefore, if a parallel can be drawn with the isotopic behavior of Miocene *G. bulloides* from the northeastern Pacific Ocean, no paleoceanographic significance can be attributed to changes smaller than 0.25 per mil in the $\delta^{18}O$ values of *G. bulloides*.

Samples for isotopic analysis from Site 173 were mixtures of *Globigerina praebulloides* and *Globigerina bulloides* because specimens of neither one of these species were present in sufficient numbers to be analyzed throughout the whole interval sampled. It was therefore necessary to investigate whether Miocene *G. praebulloides* and *G. bulloides* exhibit similar oxygen and carbon isotopic systematics. When all Site 173 samples are considered together, no relation is found between the proportions of the two species and their $\delta^{13}C$ values, suggesting no systematic difference in their carbon isotopic ratios. However, *G. bulloides* is apparently enriched in ^{18}O relative to *G. praebulloides* by 0.7 per mil in the late Miocene samples and by 0.25 per mil in the middle Miocene samples. The implications of this are not clear. It is probable that the increase in the $\delta^{18}O$ values with time and the parallel increase in the abundance of *G. bulloides* at Site 173 reflect middle and late Miocene cooling at this site rather than differences in the oxygen isotopic systematics of the two species.

The tests of most deep-water benthonic foraminiferal species are in neither oxygen nor carbon isotopic equilibrium with ambient sea water (Duplessy et al., 1970; Shackleton, 1974; Woodruff et al., 1980; Vincent et al., 1981; Graham et al., 1981). Shackleton (1974) concluded that of the commonly analyzed benthonic taxa, *Uvigerina* spp. has $\delta^{18}O$ values closest to those expected for calcite in oxygen isotopic equilibrium with sea water. Other benthonic taxa depart from equilibrium by relatively constant amounts. All species of *Cibicidoides* investigated thus far appear to have similar isotopic behavior and to be depleted in ^{18}O by approximately 0.7 per mil relative to equilibrium values (Woodruff et al., 1980; Belanger et al., 1981; Savin et al., 1981). *Cibicidoides* have $\delta^{13}C$ values similar to those of dissolved HCO_3^- in ambient sea water (Belanger et al., 1981; Graham et al., 1981).

Sample preservation and dissolution

Calcium carbonate dissolution can significantly affect both the taxonomic composition and the isotopic composition of the residual fauna. Dissolution affects biostratigraphic results by shifting the first and last appearances of species and reducing the stratigraphic ranges and abundances of dissolution-susceptible species. The isotopic signal of selectively preserved specimens can be biased in the ^{18}O-rich (cold) direction since those individuals of a species which lived higher in the water column are often more readily dissolved than deeper-dwelling individuals (Savin and Douglas, 1973).

The preservation of samples from Sites 173 and 470 has been discussed by Barron and Keller (1983). At Site 495, planktonic foraminiferal assemblages are well-preserved, except in Cores 27 and 28 (within foraminiferal Zone N7) where they have been affected moderately, and in Core 20 and upwards (Zones N12 and above) where virtually all foraminifera have been dissolved.

BIOSTRATIGRAPHY

High resolution biostratigraphic correlations have been made between the eastern equatorial Miocene Pacific sections from Sites 495 and 158 and: a) the more westerly equatorial Pacific Site 77B (Figure 2); and b) California Current Site 470 (Figure 3). Biostratigraphy and correlation between California Current Sites 470 and 173 have already been published by Keller and Barron (1981). Biostratigraphy of Site 158 was worked out by Kaneps (1973), Keigwin (1976), Keller et al. (1982) and in the present study. Biostratigraphy of Site 495 was previously examined by Thompson (1982) and was worked out in greater detail in this study.

Age assignments at Sites 495 and 158 are based on foraminiferal datum levels indirectly tied to diatom, radiolarian and coccolith datum levels calibrated with the paleomagnetic time scale as outlined by Keller (1981). Diatom datum levels of Sites 77B and 495 are from Barron (personal communication, 1983). Early and middle Miocene age assignments for Site 495 appear to be confirmed independently by comparison of the abundance curve for *Globorotalia siakensis* at that site with that for Site 77B. The faunal abundance counts for Site 77B by Keller (1980b) were used. Correlation between the eastern tropical Pacific sites and Site 470 made use of the faunal abundance data of Barron and Keller (1983) for Site 470. Faunal abundance data for Sites 495 and 158 were determined in this study and are listed in Appendix I. Only minor differences were observed between the faunal census obtained for Site 158 in this study and that published by Keigwin (1976).

The foraminiferal assemblages at Sites 495 and 77B are characterized by high abundances of warm-water species of the genera *Globorotalia* and *Globoquadrina*, in particular, *Globorotalia siakensis*, *Globorotalia peripheroronda*, *Globorotalia continuosa*, *Dentoglobigerina altispira* and *Globoquadrina venezue-*
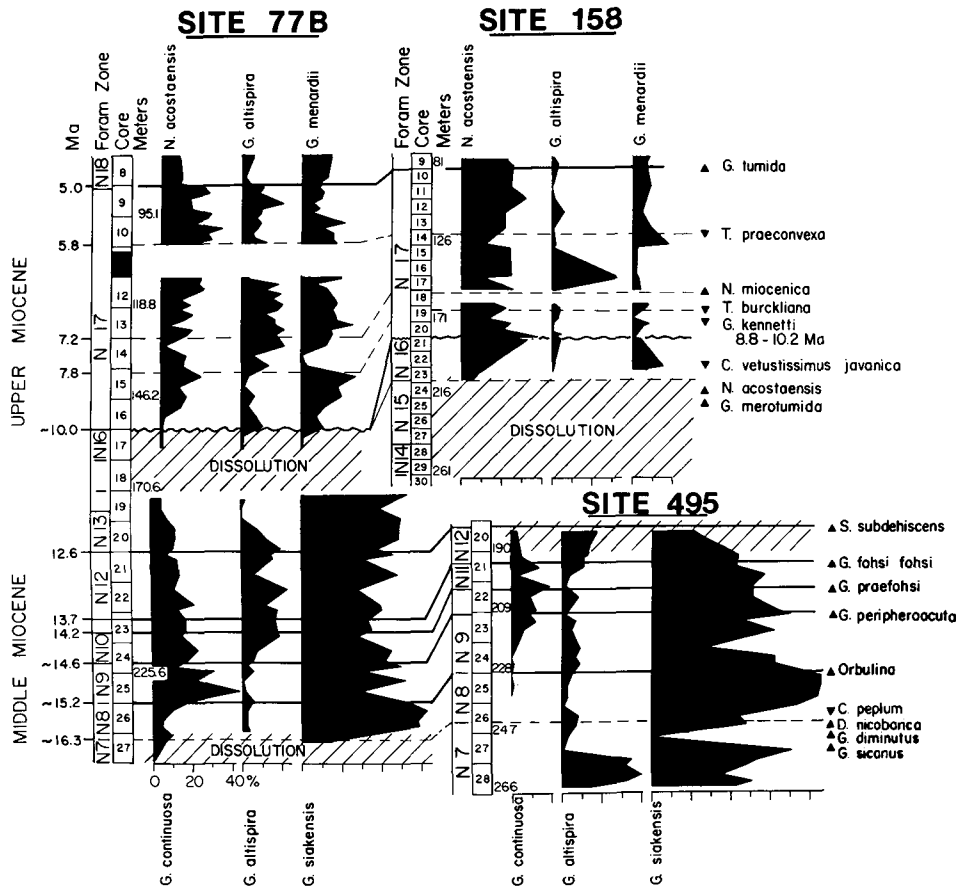
Figure 2. Correlation of the middle and upper Miocene sections, based on diatom and foraminiferal datum levels, and percent abundance of a few planktonic foraminiferal species at DSDP Sites 77B, 495 and 158. Data are from Keller (1980b), Barron (personal communication, 1983) and this study.

lana (Figure 2). The low abundance of species of the genus *Globigerinoides* reflects, in part, the effect of carbonate dissolution in the eastern equatorial Pacific during early and middle Miocene time. In the upper Miocene section at Site 77B, warm-water species such as *Dentoglobigerina altispira* and *Globorotalia menardii* are more abundant than at Site 158. The high abundances of the warm/temperate-water species *Neogloboquadrina acostaensis* and *Globigerinita glutinata* at Site 158 suggest the presence of colder near-surface water at this more easterly site during late Miocene time. The mid-latitude planktonic foraminiferal assemblages at Site 470 differ considerably from the tropical assemblages at Sites 495 and 158 (Figure 3). However, the presence of warm-water species in the middle Miocene section at Site 470 and their absence in the upper Miocene section suggest that middle Miocene surface waters were warmer than those of the late Miocene at that site (Barron and Keller, 1983).

ISOTOPIC RESULTS

$^{18}O/^{16}O$ ratios of foraminifera from DSDP Sites 495, 173, 470 and the onshore section at Newport Beach are listed in Appendix II. Results from Newport Beach are not discussed further because isotopic ratios indicate that the samples have undergone diagenetic alteration.

Benthonic Foraminiferal Isotopic Records

Composite benthonic foraminiferal isotopic records for *Cibicidoides* from Sites 173, 470 and 495 are shown in Figure 4. (Site 173 is represented by only two points.) The general appearance of the oxygen isotopic curves of the benthonic foraminifera is similar to that of other Miocene deep sea benthonic curves published by Savin et al. (1981). Early Miocene $\delta^{18}O$ values are low (indicative of high deep water temperatures and minimal ice volume), and are followed by a rapid increase in early middle Miocene time. This increase in $\delta^{18}O$ is interpreted as reflecting a combination of deep water cooling and a major growth phase of the Antarctic ice sheet (and a concomitant change in the $\delta^{18}O$ value of sea water). Middle Miocene (14 to 12 Ma) $\delta^{18}O$ values at Site 470 are more negative (i.e. warmer or indicative of less continental ice) than early late Miocene (12 to 10 Ma) $\delta^{18}O$ values.
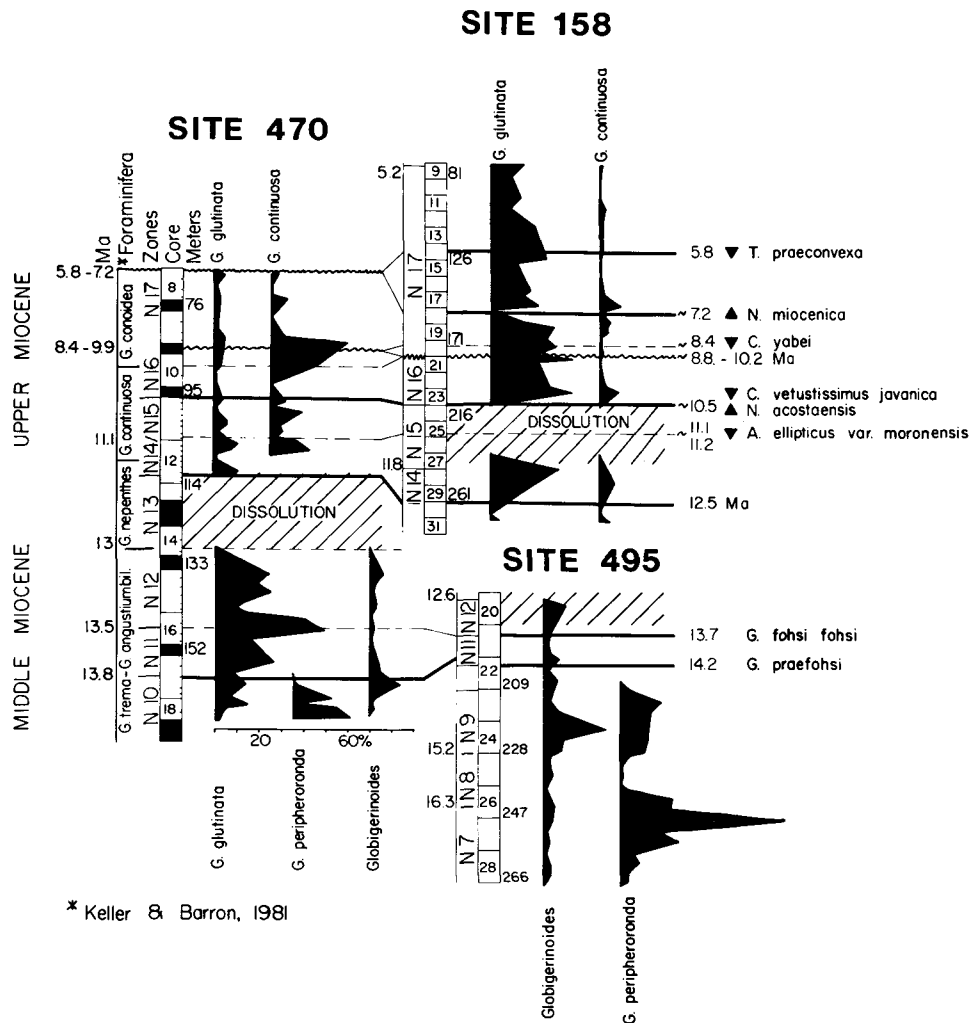
Figure 3. Correlation of the middle and upper Miocene sections and percent abundance of a few planktonic foraminiferal species at DSDP Sites 470, 495 and 158. Data are from Keller and Barron (1981), Barron and Keller (1983), Barron (personal communication, 1983) and this study.

Most of the major features of the carbon isotopic variations of the composite benthonic curve also resemble those of the benthonic deep sea curves published by Savin et al. (1981). There are some differences, however. The benthonic carbon isotopic record for the 13 to 11 Ma interval at Site 470 is especially variable. We have chosen not to correlate the eastern Pacific sites studied here with the "carbon isotopic events" defined by Loutit et al. (1983) because the eastern Pacific records did not, for the most part, have sufficiently high resolution or span sufficiently long time intervals to permit such correlations to be attempted with confidence.

Site 495

The oxygen and carbon isotopic records of foraminifera plotted in Figure 5 provide information on the depth stratification

of the planktonic species. We infer, on the basis of the $\delta^{18}O$ values, that G. venezuelana was a relatively deep-dwelling planktonic species, and that the $\delta^{18}O$ values of D. altispira, G. siakensis and Globigerinoides sacculifer reflect near-surface water conditions. This is consistent with the conclusions derived from consideration of a large number of early and middle Miocene sites by Savin et al. (this volume). With the exception of G. siakensis, depth stratification of taxa inferred from $\delta^{13}C$ records is similar to that inferred from $\delta^{18}O$ records. The $\delta^{13}C$ record of G. siakensis resembles that of the deeper dwelling G. venezuelana. Assuming that the carbon isotopic systematics of G. sacculifer have not changed markedly over the past 20 m.y., it is likely that G. sacculifer and, by inference, D. altispira have $\delta^{13}C$ values close to that of the total dissolved CO_2 in the water column (Williams et al., 1977). G. siakensis is probably also a shallow-dwelling species but with quite different carbon isotopic systemat-
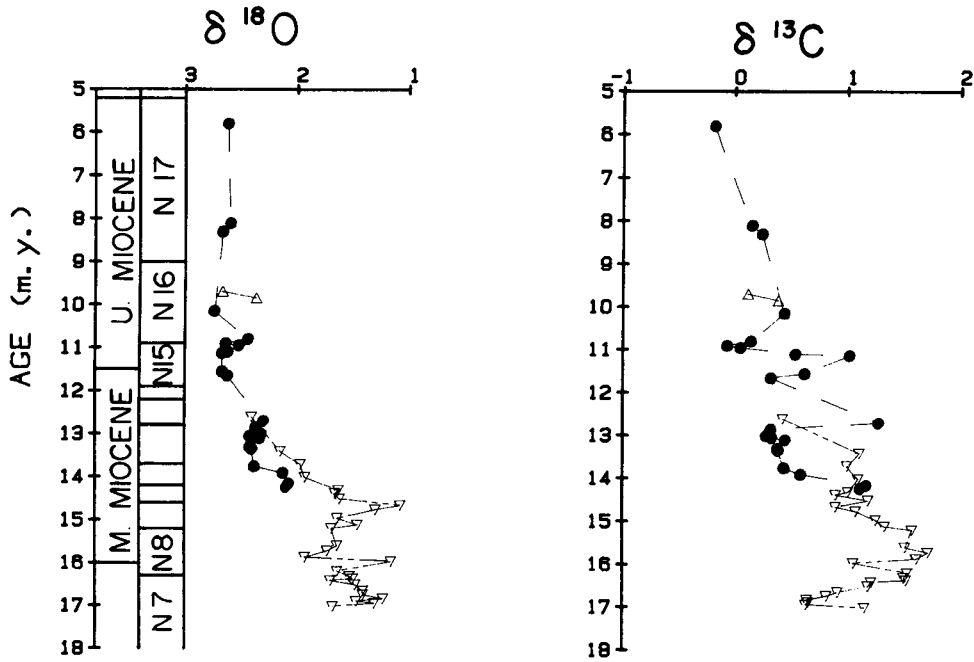
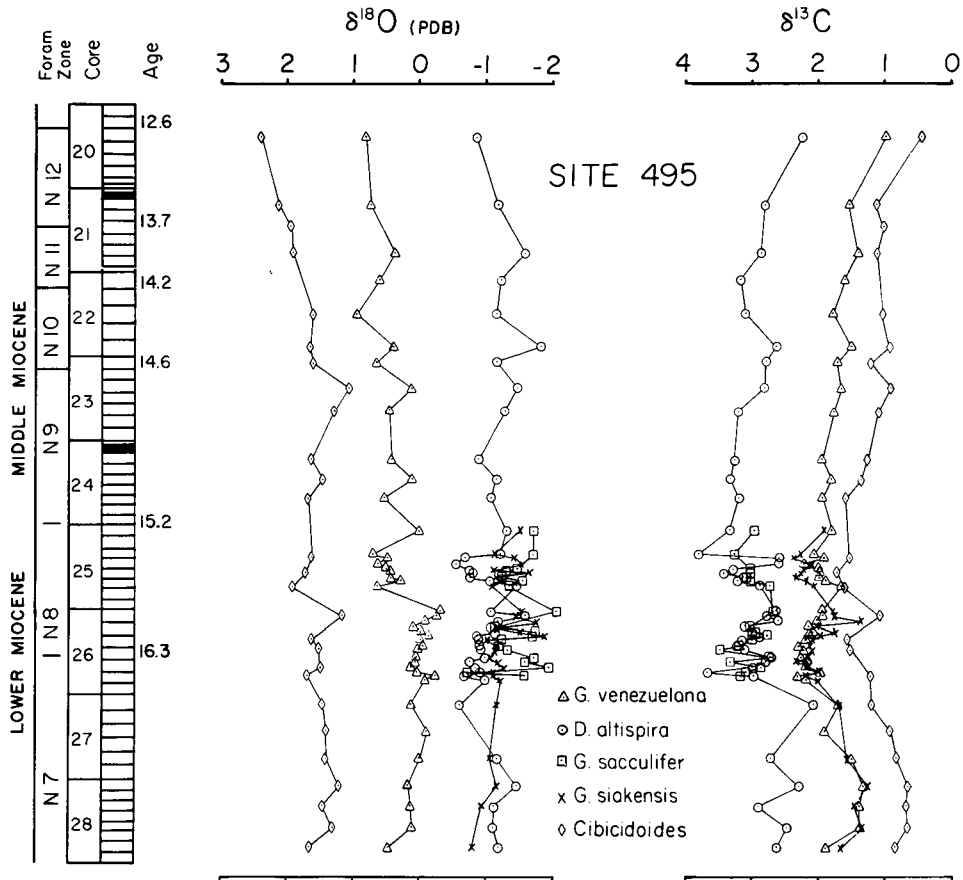Figure 4. Oxygen and carbon isotopic records for *Cibicidoides* from Sites 173 (△), 470 (●) and 495 (▽) plotted as a function of time.

Figure 5. $\delta^{18}O$ and $\delta^{13}C$ values of selected foraminiferal species plotted as a function of depth in the sediment at Site 495.

ics than *G. sacculifer* and *D. altispira*. It is possible, but less likely, that *G. siakensis* is a deeper dweller and that it does not calcify in oxygen isotopic equilibrium with ambient sea water.

Insight into the early and middle Miocene thermal structure of the water column at Site 495 and its stability with time can be gained by comparing the total range of Miocene $\delta^{18}O$ values, adjusted to account for changes in the isotopic composition of sea water as discussed above, with $\delta^{18}O$ values of calcite precipitated in isotopic equilibrium with modern sea water (referred to in the discussions below as *equilibrium* $\delta^{18}O$ *values*) at several hydrographic stations near the early and middle Miocene locations of Site 495 (2 to 7°N; 99 to 108°W according to Sclater et al., this volume) (Figure 6).

Early and middle $\delta^{18}O$ values of shallow-dwelling species, adjusted for ice volume effects, vary between approximately +0.36 and −1.33 per mil. This is a small range compared to the range of equilibrium $\delta^{18}O$ values in the upper 150 meters of the modern water column (+1.1 to −2.7 per mil), and falls within the range of calculated equilibrium values within the thermocline, between 50 and 120 meters (Figure 6). The small range of $\delta^{18}O$ values of shallow-dwelling Miocene species relative to the calculated modern equilibrium $\delta^{18}O$ values suggests relatively little variation in the temperature structure of the early and early middle Miocene Oceans at Site 495. The range of measured $\delta^{18}O$ values for *G. venezuelana* is also small and falls within the range of equilibrium values calculated at or below the thermocline at depths between 100 and 300 meters.

Holocene planktonic $\delta^{18}O$ values of *G. sacculifer* in the vicinity of backtracked Site 495 are mostly around −1 per mil (Savin and Douglas, 1973; Shackleton, 1977), and hence indicate Holocene temperatures approximately 0 to 6°C higher than those indicated by the adjusted Miocene shallow-dwelling planktonic $\delta^{18}O$ values at Site 495. Evidence for warming at Site 495 during middle Miocene time comes from comparison of the benthonic and shallow-dwelling planktonic $\delta^{18}O$ values in Figures 5 and 7. $\delta^{18}O$ values of middle Miocene planktonic foraminifera show no secular change while those of benthonic foraminifera increase, reflecting both deep water cooling and increase in the $\delta^{18}O$ value of sea water as the result of growth of the Antarctic ice sheet. This implies that surface and near-surface waters warmed by an amount sufficient to balance the increase in the $^{18}O/^{16}O$ ratio of sea water. While it would be desirable to extend this argument by analyzing younger samples from Site 495, the virtually complete dissolution of the section above Core 20 prevented this. The inferred warming of surface waters at this site is consistent with the conclusion of Savin et al. (this volume), based on time-slice studies of Miocene planktonic foraminifera, that surface waters in the eastern tropical Pacific warmed between the early Miocene (N4B) and the present.

The oxygen isotopic data do reveal some variations with time in the thermal structure of the Miocene oceans at Site 495. Differences between $\delta^{18}O$ values of planktonic and benthonic species, are independent of global changes in the $\delta^{18}O$ value of the oceans and are indicative of the intensity of vertical thermal
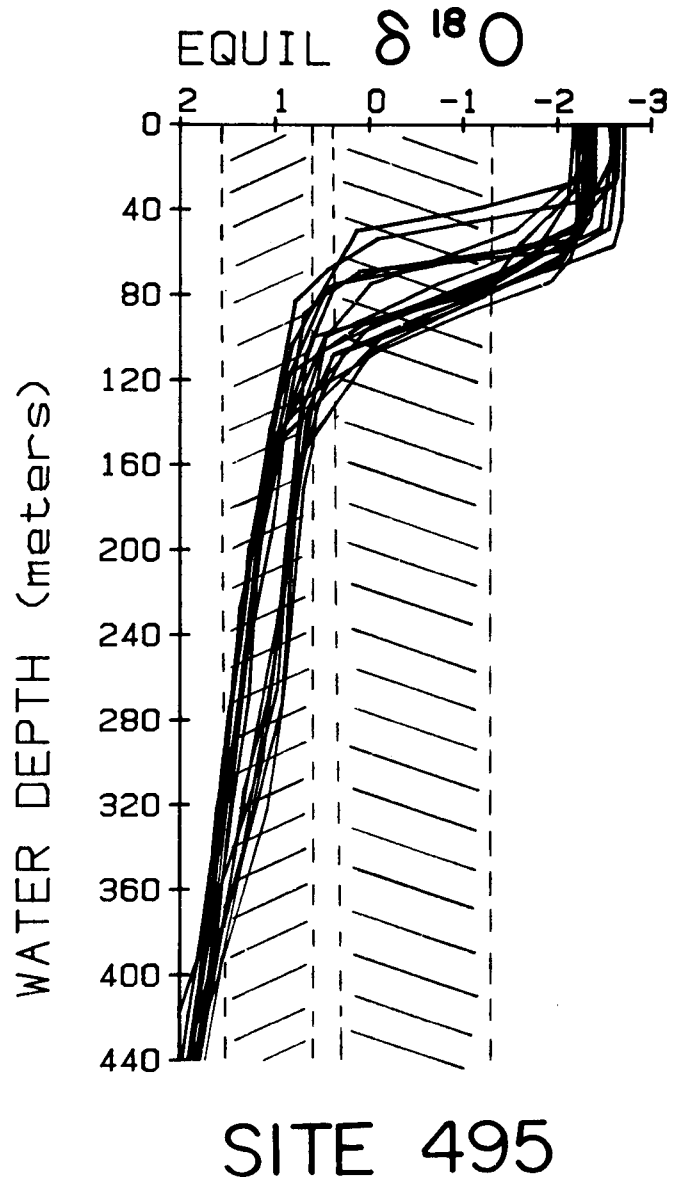
SITE 495

Figure 6. Comparison of calculated modern equilibrium $\delta^{18}O$ values for hydrographic stations near the Miocene location of Site 495 with the ranges of adjusted Miocene $\delta^{18}O$ values for *G. venezuelana* (shading sloping to the left) and for the shallow-dwelling foraminiferal species, *G. sacculifer, D. altispira* and *G. siakensis* (shading sloping to the right) from Site 495. The range of $\delta^{18}O$ values of the shallow-dwelling species falls within the range of calculated equilibrium values at depths between 50 and 120 meters, while that of the deeper-dwelling species, *G. venezuelana* falls within the range of calculated equilibrium values between 100 and 300 meters.

stratification of the water column. In Figure 7 the differences, $\delta^{18}O_{Cibicidoides}$ minus $\delta^{18}O_{D. altispira}$ and $\delta^{18}O_{Cibicidoides}$ minus $\delta^{18}O_{G. venezuelana}$ are plotted. Variations in these differences in the lower portion of the section, deposited between approximately 17 and 14.6 Ma (foraminiferal zones N7 through N9) are for the most part small and unsystematic. In the upper part of the section, however, as characterized by the uppermost four or five
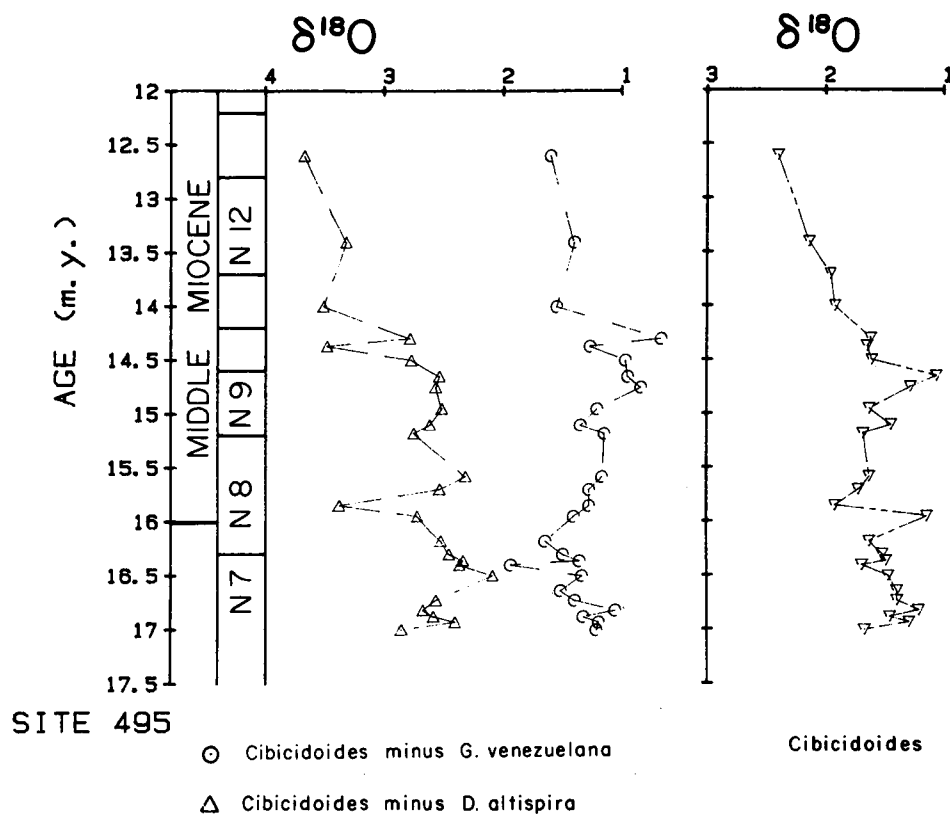
Figure 7. Difference between $\delta^{18}O$ values of *Cibicidoides* and *D. altispira* and between $\delta^{18}O$ values of *Cibicidoides* and *G. venezuelana* from Site 495 plotted as a function of age. $\delta^{18}O$ values of *Cibicidoides* are plotted on the right side of the figure.

samples representing the time period 14.6–12.5 Ma (foraminiferal zones N10 through N12), the difference between $\delta^{18}O_{Cibicidoides}$ and $\delta^{18}O_{D.\ altispira}$ is clearly greater than in the lower portion of the section (with the exception of one sample). This implies that the vertical thermal stratification of the water column became sharply intensified beginning about 14.6 Ma. The time of intensification of the vertical thermal gradient corresponds to the time of marked middle Miocene increase in benthonic foraminiferal $\delta^{18}O$ values. No significant corresponding increase is noted in $\delta^{18}O_{Cibicidoides}$ minus $\delta^{18}O_{G.\ venezuelana}$, probably because *G. venezuelana* grows below the thermocline in waters whose temperatures vary sympathetically with those of the deep waters at Site 495.

The general appearance, although not every detail, of the $\delta^{13}C$ time series curves of *D. altispira* and *G. venezuelana*, as well as *Cibicidoides* from Site 495, is similar to the pattern of $\delta^{13}C$ values of *Cibicidoides* from Site 289, as shown in Figure 8 (as well as other benthonic carbon isotopic curves shown by Savin et al., 1981). The increase in $\delta^{13}C$ values reaching a maximum between 16 and 15 Ma and the decrease in $\delta^{13}C$ values up to about 12 Ma are clear. These similarities suggest that a large part of the observed variability of both planktonic and benthonic $\delta^{13}C$ values at Site 495 reflects fluctuations in the average carbon isotopic composition of ocean waters. Furthermore, temporal var-

iations in the productivity of near-surface waters should affect $\delta^{13}C$ values of planktonic foraminifera in complex ways, perhaps causing them to increase under some circumstances and to decrease under others. The similarities in the pattern of fluctuations of the planktonic and benthonic records at Site 495 suggest that either changes in the intensity of upwelling at that site were minor or that they occurred but fortuitously produced no effect on the planktonic $\delta^{13}C$ records.

Site 173 and Site 470

Sites 173 and 470 lie within the modern California Current system (Figure 1). The Miocene planktonic and benthonic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ values for those sites are plotted in Figure 9.

It is likely that at least some of the foraminifera from the lowermost four samples of Site 470 has been diagenetically altered. These samples, from Cores 17 and 18, lie within about 3 m of basalt basement. Foraminifera from Core 18 were separated from chalk. *G. bulloides* from Core 17, Section 3 has an unusually low $\delta^{18}O$ value and *G. bulloides* from Core 18, Section 1 has an unusually high $\delta^{13}C$ value. It is likely that these unusual isotopic compositions reflect diagenetic alteration of the test
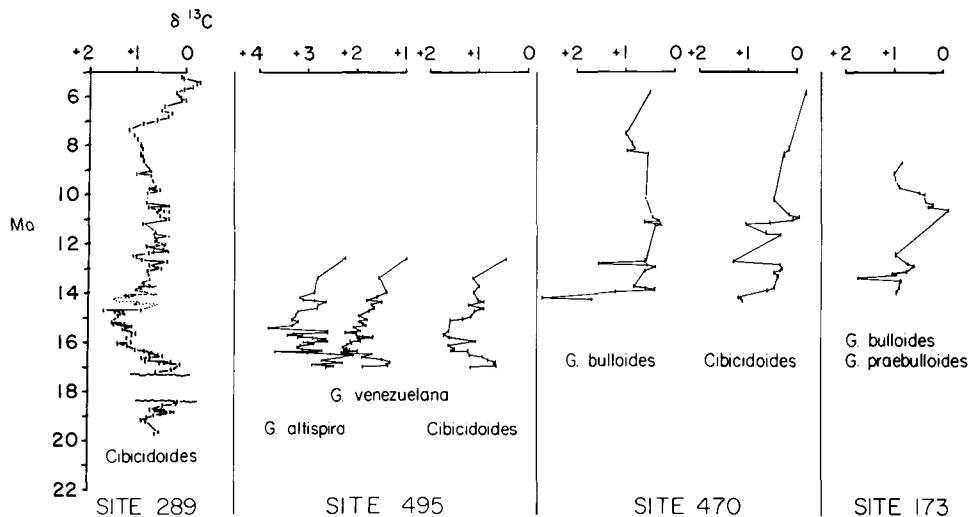
Figure 8. $\delta^{13}C$ values of *Cibicidoides* from Site 289, *Cibicidoides, G. venezuelana* and *D. altispira* from Site 495, *Cibicidoides* and *G. bulloides* from Site 470 and *G. bulloides/praebulloides* from Site 173 plotted as a function of time.

material. Therefore, little paleoenvironmental significance is attributed to the isotopic results of the lowermost four samples.

The isotopic evidence suggests that the middle/late Miocene interval sampled at Site 470 was one of stable oceanographic conditions. It is possible, however, that conditions were more variable on a short time scale than is suggested by the relatively small sample-to-sample variations in $\delta^{18}O$, since the sediments of this site were deformed, and perhaps mixed, by the drilling process (Yeats et al., 1981).

$\delta^{18}O$ values for *G. bulloides* and *G. praebulloides* from Site 173 are more positive than those of Site 470, reflecting the more northerly position of this site (Figure 9). Sample-to-sample variability of $\delta^{18}O$ values is greater in the upper Miocene section than the middle Miocene at Site 173, and the late Miocene sequence contains a number of samples that yield $\delta^{18}O$ values significantly more positive (i.e., cooler) than any middle Miocene values.

To gain insight into the oceanographic processes which could have produced the observed range of Miocene $\delta^{18}O$ values at Sites 470 and 173, adjusted $\delta^{18}O$ values of *G. bulloides* have been compared with calculated equilibrium $\delta^{18}O$ values for calcite precipitated in the upper 220 meters at several hydrographic stations (NODC) near each of the sites (Figures 10 and 11).

The range of adjusted Miocene isotopic data for *Globigerina bulloides* at Site 470, shown in Figure 10, is small (+0.52 to –0.22 per mil) in contrast to the range of equilibrium $\delta^{18}O$ values in the upper 100 meters of the water column (+1.1 to –1.6 per mil). The range of variability of the Miocene *G. bulloides* at this site is even smaller than the seasonal range of equilibrium $\delta^{18}O$ values at the surface. Thus, if the shapes (although not necessarily the absolute values) of modern bathythermograms and profiles of equilibrium $\delta^{18}O$ vs. depth approximate those of the middle and late Miocene oceans in this area, it can be concluded from the isotopic record of *G. bulloides* that there were only small variations in surface and near-surface water temperature and/or upwelling during the

middle and late Miocene interval at Site 470. (It is possible that changes in the intensity of upwelling or the water temperature were compensated by changes in the seasonality of growth. This is unlikely, however, especially in view of the conclusions of Gannsen and Sarnthein (1983) that modern *G. bulloides* records conditions during the season of upwelling.)

While water temperatures were relatively stable at Site 470 during middle and late Miocene time, they were apparently cooler than modern temperatures at the same site. All of the adjusted $\delta^{18}O$ values of *G. bulloides* from Site 470 are more positive (i.e., cooler) than any of the equilibrium $\delta^{18}O$ values for surface waters in months of significant upwelling (summer). In fact, virtually all of the differences between $\delta^{18}O$ of Miocene *G. bulloides* and modern surface water equilibrium $\delta^{18}O$ at Site 470 exceed the differences found in the modern Indian Ocean data set of Curry and Matthews (1981a). Thus, if the depth habitat of Miocene *G. bulloides* was the same as that of the modern species, it can be concluded that surface waters at Site 470 are probably warmer now than 5.8 Ma.

In a similar examination of the data from Site 173 (Figure 11), the range of adjusted Miocene *G. bulloides* and *G. praebulloides* $\delta^{18}O$ values is large (+1.15 to –0.01 per mil) relative to the range of present-day equilibrium $\delta^{18}O$ values in the upper 100 meters of the water column (+1.56 to –0.8 per mil). Thus, the observed range of Miocene oxygen isotopic values was probably produced by large fluctuations in surface or near-surface water temperatures perhaps related, at least in part, to variations in the intensity of upwelling or depth of the seasonal thermocline.

Huyer (1983) has shown that seasonal variability of upwelling in the modern ocean is greater in the region of Site 173 than in the region of Site 470. Since the seasonal variability of winds in this region is responsible for the seasonal variability in upwelling, it is likely that longer term variability of winds might also cause long-term variations in the intensity of upwelling to be great at
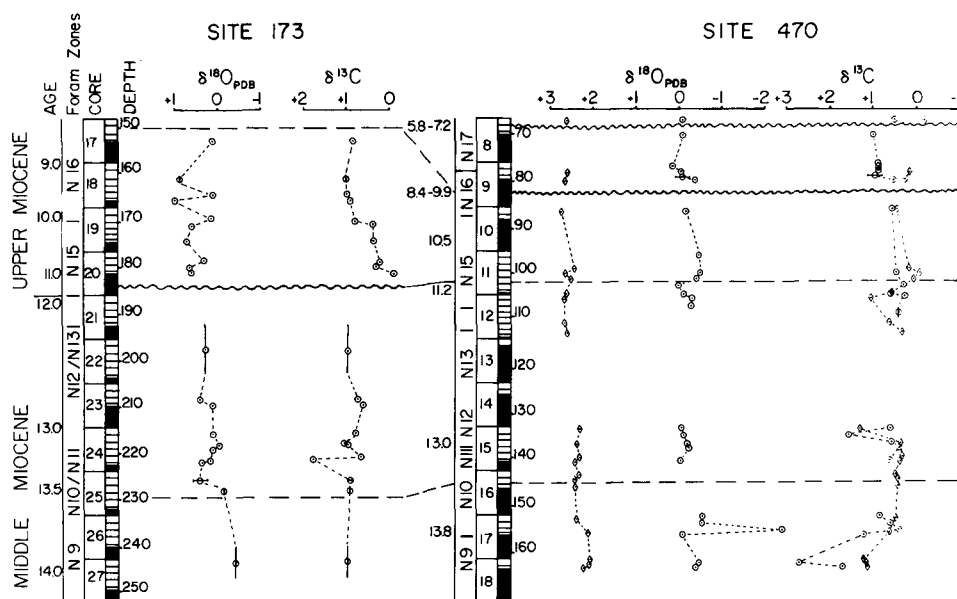
Figure 9. $\delta^{18}O$ and $\delta^{13}C$ values of *G. bulloides/praebulloides* from Site 173 and *G. bulloides* and *Cibicidoides* from Site 470 plotted versus depth in the sediment. Planktonic foraminiferal isotopic values are indicated by circles and isotopic values of *Cibicidoides* are indicated by diamonds. Biostratigraphy is from Keller and Barron (1981).

Site 173, consistent with the observed large range of measured $\delta^{18}O$ values at the site.

The adjusted $\delta^{18}O$ values of middle and late Miocene *G. bulloides/praebulloides* at Site 173 largely coincide with modern surface and mixed-layer equilibrium values at the same site and are lower by only a few per mil than modern surface equilibrium $\delta^{18}O$ values during periods of intense upwelling. There is therefore no evidence for any major change in surface temperatures at this site during the past 7.5 m.y.

Disregarding the four lowermost samples from Site 470 (because of suspected diagenetic alteration), the carbon isotopic time series curve for *G. bulloides* from Site 470 bears some resemblance to the $\delta^{13}C$ records of *Cibicidoides* from Site 289 (Figure 8) and other Pacific sites (i.e., decreasing $\delta^{13}C$ values between 14 and 11 Ma, increasing values from 11 Ma to approximately 7 Ma, and decreasing values after 7 Ma). While it is possible that this resemblance is fortuitous, it suggests that the major features of the isotopic record of *G. bulloides* at Site 470 reflect ocean-wide if not global changes in the $^{13}C/^{12}C$ ratio of dissolved inorganic carbon. It is puzzling that the benthonic $\delta^{13}C$ record of Site 289 (and most other benthonic records shown by Savin et al., 1981) agree more closely with the planktonic than the benthonic record at Site 470, and that the benthonic $\delta^{13}C$ record is especially variable in the 13 to 11 Ma interval. There is nothing in the faunal composition of the benthonic foraminifera or in their oxygen isotopic record to suggest that bottom water conditions at this site were in any way out of the ordinary.

The carbon isotopic record of *G. bulloides* and *G. praebulloides* from Site 173 is much more variable than that from Site 470, especially in the section from 11 to 9.5 Ma (Figure 8). There

is some superficial resemblance between the $\delta^{13}C$ record of *Cibicidoides* from Site 470 and that of *G. bulloides/praebulloides* from Site 173, but this is apparently fortuitous. For example, the extreme positive $\delta^{13}C$ peaks in the two records at approximately 13 Ma are diachronous according to the highly resolved biostratigraphic studies of the two sites (Keller and Barron, 1981; Barron and Keller, 1983).

The dissimilarity between the $\delta^{13}C$ record of *G. bulloides/praebulloides* from Site 173 and those of benthonic foraminifera from Site 289 and other sites probably reflects local variations in the $^{13}C/^{12}C$ ratio of surface waters at Site 173 superimposed on the average $^{13}C/^{12}C$ composition of the oceans. These local variations may reflect changes in the intensity of upwelling and productivity. However, we are not able to resolve whether decreases in ^{13}C of *G. bulloides* and *G. praebulloides* correspond to increases or decreases in upwelling intensity. This is because of uncertainty as to the extent to which the mixing of upwelled waters with surface waters lowers the $\delta^{13}C$ value of surface waters and the extent to which the enhanced biological productivity, resulting from upwelling, increases the ^{13}C content of surface waters. Prell and Curry (1981) and Gannsen and Sarnthein (1983) have found $\delta^{13}C$ values of *Globigerina bulloides* in upwelling centers to be unrelated to the intensity of upwelling, although its $^{18}O/^{16}O$ ratios record surface water temperatures during times of upwelling.

COMPARISON OF ISOTOPIC AND PALEONTOLOGIC RESULTS

Major fluctuations in the abundance of planktonic forami-
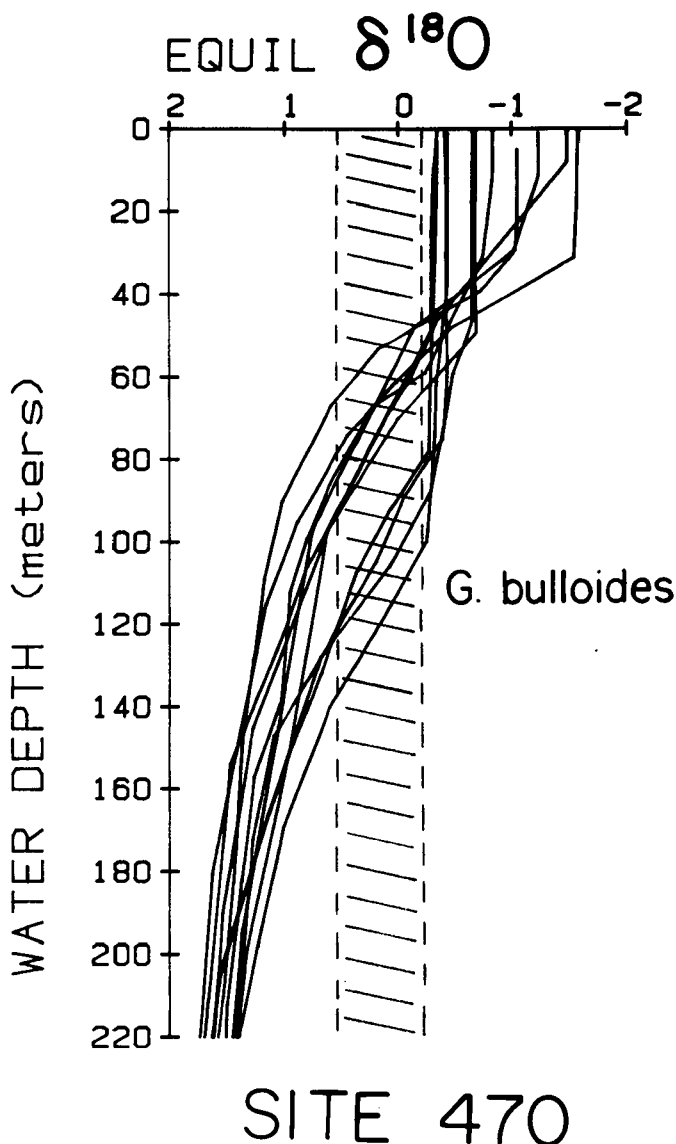
Figure 10. Comparison of calculated modern equilibrium δ¹⁸O values for hydrographic stations near Site 470 with the range of adjusted middle and late Miocene δ¹⁸O values for *G. bulloides* at Site 470 (shaded region). The range of δ¹⁸O values of *G. bulloides* is small (+0.52 to -0.22 per mil) in contrast to the range of equilibrium δ¹⁸O values in the upper 100 meters of the water column.

Figure 11. Comparison of calculated modern equilibrium δ¹⁸ values for hydrographic stations near Site 173 with the range of adjusted middle and late Miocene δ¹⁸O values for *G. bulloides/praebulloides* at Site 173 (shaded region). The range of *G. bulloides/praebulloides* δ¹⁸O values is large (+1.15 to -0.01 per mil) relative to the range of equilibrium δ¹⁸O values in the upper 100 meters of the water column.

nifera inferred to be temperature-sensitive have been used by Ingle (1967, 1973a, b), Bandy and Ingle (1970), Keller (1978) and Barron and Keller (1983) to reconstruct the climatic and oceanographic history of the eastern North Pacific. Interpretations of the faunal data from these studies have been based on the assumption that in periods when high latitudes cooled or the latitudinal thermal gradient increased, the cool California Current intensified displacing cold-water faunas and floras to the south. Hence, according to this approach, paleoclimatic oscillations can be recognized by fluctuations in the relative abundances of cold to cool-water species and temperate to subtropical-water species in sediment assemblages.

The availability of foraminiferal abundance data (Barron and Keller, 1983) for exactly the same samples analyzed isotopically from Sites 173 and 470 led us to investigate whether small-scale fluctuations in the abundance of cold-water foraminiferal species (Barron and Keller, 1983) at these sites could be correlated with changes in water temperature inferred from the isotopic data. Moreover, the oxygen isotopic data were also compared with the abundance of *Globigerina bulloides* which has been identified in other studies as thriving in zones of upwelling (Zobel, 1971; Thiede, 1972; Diester-Haass et al., 1973; and Prell and Curry, 1981). Hence, if we assume that *G. bulloides* thrived during upwelling episodes in Miocene time as it does today, we might consider fluctuations in the abundance of *G. bulloides*, or perhaps species of the *bulloides* group (*Globigerina bulloides, G.*
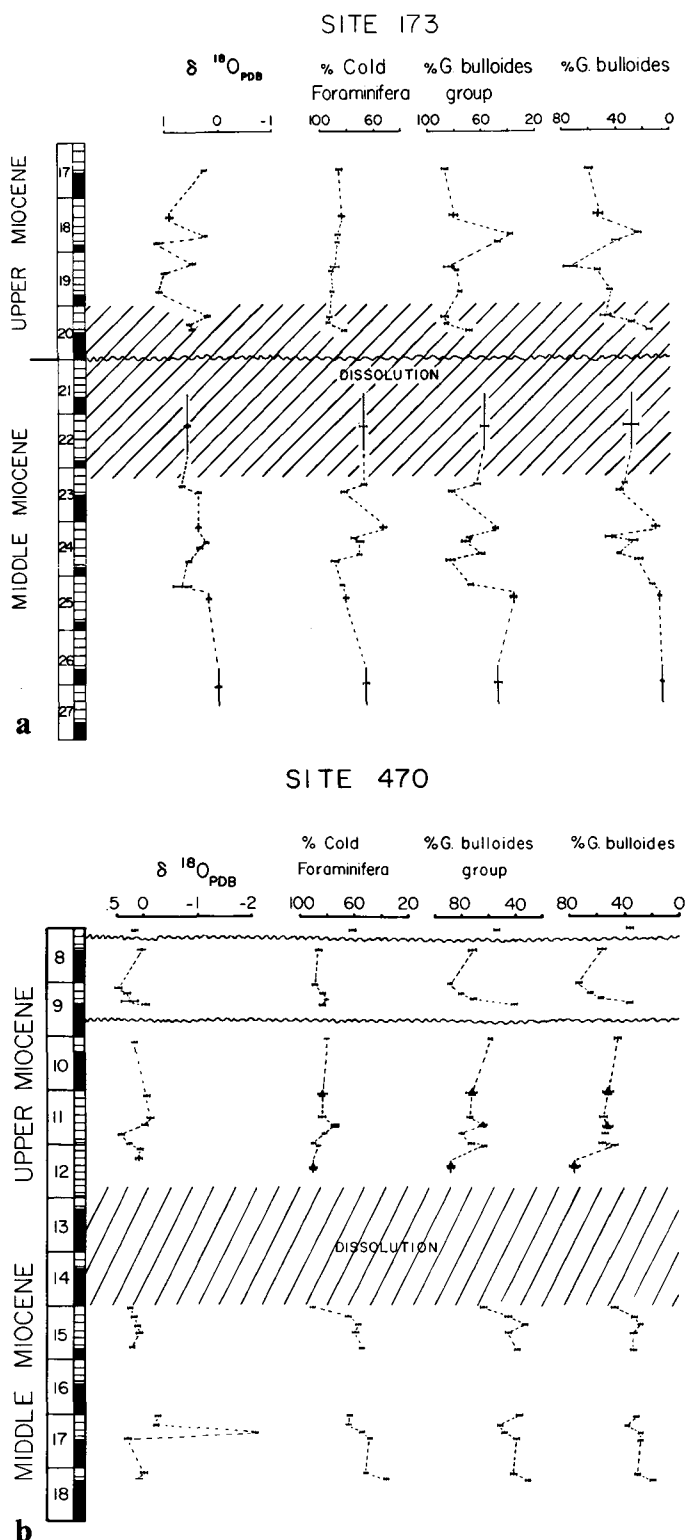
Figures 12a and 12b. The adjusted $\delta^{18}O$ time series curves of *G. bulloides/praebulloides* from Site 173 and *G. bulloides* from Site 470 are plotted versus depth in the sediments and alongside their respective foraminiferal abundance curves.

praebulloides and *G. quadrilatera*) to correspond with variations in the intensity of upwelling at the sites within the California Current system.

In Figures 12a and 12b, the oxygen isotopic time series curves for Sites 173 and 470 have been plotted alongside the foraminiferal abundance curves. In both figures, all data sets are plotted so that inferred warm conditions lie to the right and inferred cold conditions to the left. While there are some superficial resemblances between isotopic and faunal curves, at neither site can episodes of warming or cooling inferred from the isotopic data be consistently correlated with episodes of warming or cooling inferred from the faunal curves. A valid test of the relationship between the two types of records would require both faunal and isotopic analyses of larger numbers of more closely spaced samples than were examined in this study.

CONCLUSIONS

DSDP Site 495 provides a record of early and middle Miocene oceanographic conditions in the eastern equatorial Pacific. Oxygen isotopic evidence indicates that *G. sacculifer, D. altispira* and *G. siakensis* were shallow-dwelling tropical planktonic species. *G. venezuelana* deposited its test at greater depths, probably below the thermocline. With the exception of *G. siakensis*, the depth stratification of species inferred from $\delta^{18}O$ values is similar to that inferred from $\delta^{13}C$ records. $\delta^{13}C$ values of *G. siakensis* differ significantly from those of the other shallow-dwelling species and are similar to those of *G. venezuelana*.

The time series curves of the planktonic species and that of *Cibicidoides* show that temperature variability at Site 495 during early and middle Miocene time was relatively small. However $\delta^{18}O$ values of *Cibicidoides* indicate that deep waters at this site cooled while those of *D. altispira* indicate that surface and near-surface waters warmed.

Middle and late Miocene surface temperatures at Site 470 were relatively stable, but were probably lower than modern surface temperatures. At Site 173, middle and late Miocene surface temperatures were consistently lower than those at the more southerly Site 470, and were also significantly more variable. Surface temperatures at Site 173 have probably not changed significantly since late Miocene time. The inferred greater variability of surface temperatures at Site 173 may reflect greater variability of the intensity of upwelling at that site than at Site 470 during Miocene time.

The planktonic and benthonic foraminiferal carbon isotopic records at Site 495 vary sympathetically with published benthonic foraminiferal isotopic records from the Atlantic and Pacific Oceans, indicating that the carbon isotopic ratios at that site largely reflect global fluctuations in the isotopic composition of dissolved inorganic carbon.

The planktonic carbon isotopic record of Site 470 fluctuates sympathetically with published benthonic records, indicating that the middle and late Miocene $^{13}C/^{12}C$ ratio of dissolved inorganic

carbon in surface waters at this site reflected carbon isotopic variations in deep waters. The planktonic carbon isotopic record at Site 173 could not be correlated with global carbon isotopic fluctuations, indicating that, in part, local effects controlled the $^{13}C/^{12}C$ ratio of dissolved inorganic carbon in surface waters at that site.

ACKNOWLEDGMENTS

APPENDIX I. PERCENT ABUNDANCE OF PLANKTONIC FORAMINIFERA IN THE MIDDLE TO UPPER MIOCENE SECTIONS OF SITE 158
(Parentheses indicate raw counts)

DSDP SITE 158

Species list (row labels):

X=<2
Globigerina
G. angustiumbilicata
G. apertura
G. bulloides
G. ciperoensis
G. decoraperta
G. druryi
G. falconensis
G. foliata
G. nepenthes
G. pseudociperoensis
G. praebulloides
G. quadrilatera
G. siphonifera
G. woodi
Globigerinita glutinata
G. uvula
Globigerinoides bollii
G. bulloideus
G. conglobatus
G. kennetti
G. obliquus obliquus
G. obliquus extremus
G. sacculifer
G. trilobus
Dentoglobigerina altispira
Globoquadrina dehiscens
G. venezuelana
Globorotalia archeomenardii
G. cibaoensis
G. continuosa
G. humerosa
G. menardii
G. merotumida
G. plesiotumida
G. obesa
G. praemenardii
G. tumida
G. scitula
G. siakensis
Globorotaloides hexagona
G. trema
Candeina nitida
Hastigerina aequilateralis
Neogloboquadrina acostaensis
N. pachyderma
Orbulina universa
O. suturalis
Pulleniatina primalis
Sphaeroidinella seminulina
S. subdehiscens
Unknown

No. specimens counted

APPENDIX 1. PERCENT ABUNDANCE OF PLANKTONIC FORAMINIFERA IN THE LOWER TO MIDDLE MIOCENE SECTIONS OF SITE 495
(Parentheses indicate raw counts)

The following is a rotated data matrix. Column headers (read as Core / Sect. / Upper cm / Lower cm) and an "X = <2" presence marker fill the species rows. Row labels (species) and the final counts row are transcribed below.

DSDP SITE 495
Core / Sect. / Upper cm / Lower cm

X=<2

Globigerina
G. angustiumbilicata
G. bulloides
G. ciperoensis
G. sp.
G. druryi
G. falconensis
G. foliata
G. praebulloides
G. praedehiscens
G. praedigitata
G. siphonifera
G. umbilicata
G. woodi
Globigerinita glutinata
G. uvula
Globigerinoides bolli
G. bulloideus
G. diminutus
G. obliquus
G. quadrilobatus
G. sacculifer
G. sicanus
G. subquadratus
G. transitoria
G. trilobus
Dentoglobigerina altispira
Globoquadrina dehiscens
G. sellii
G. sp.
G. venezuelana
Globorotalia archeomenardii
G. continuosa
G. fohsi fohsi
G. fohsi lobata
G. menardii
G. merotumida
G. minutissima
G. peripheroacuta
G. peripheroronda
G. praefohsi
G. praemenardii
G. scitula
G. siakensis
Globorotaloides hexagona
Hastigerina aequilateralis
Neogloboq. acostaensis
cf. acostaensis
Orbulina universa
O. saturalis
Praeorbulina sp.
Sphaeroidinella disjuncta
S. seminulina
S. subdehiscens
Globigerinatella insueta
Catapsydrax cf. stainforthi
Cat. variabilis
Unknown

No. specimens counted: 226 285 6 371 298 376 314 347 442 450 338 369 374 493 306 353 653 369 441 394 363 548 379 432 300 427 408 382 418 709 372 618 554 384 404 737 345 543 431 802 494 1118 298 588 763 422

APPENDIX II

OXYGEN AND CARBON ISOTOPIC COMPOSITION OF SELECTED SPECIES OF FORAMINIFERA AT SITE 173

Core/sect	Depth (cm)	Estimated Age (m.y.)	G. bulloides / G. praebulloides $\delta^{18}O$	$\delta^{13}C$	Uvigerina $\delta^{18}O$	$\delta^{13}C$	Cibicidoides kullenbergi $\delta^{18}O$	$\delta^{13}C$	Ice Effect* Adjustment
17-2 & 3	52-54	8.60			3.59	-1.00			0.14
17	CC	8.70	0.12	0.84					0.14
18-2 & 3	52-54	9.10-9.20	0.88	1.01					0.04
18-3 & 4	52-54	9.30			3.49	-1.06			0.10
18-5	52-54	9.40	0.11	0.98					0.14
18-4 & 18	52-54 / CC	9.60-9.70					2.67	0.12	0.15
18	CC	9.70	0.99	0.92					0.16
19-2	52-54	9.85					2.37	0.39	0.32
19-2 & 19-3	131-133 / 52-54	9.90-10.0	0.48	0.49					0.32
19-3	52-54	10.00	0.59	0.38					0.43
19-4	122-124	10.20			3.90				0.43
19	CC	10.25	0.71	0.37					0.42
20-2	118-120	10.45	-0.19	0.22					0.41
20-3	50-52	10.50	0.14	0.31					0.41
20	CC	10.60	0.10	-0.10					0.40
21 & 22-5	CC / 122-124	12.30	0.28	0.97					0.32
23-3	52-54	12.80	0.42	0.74					0.31
23	CC	12.90	0.12	0.61					0.30
24-1 & 24-2	90-92 / 15-17	13.1-13.15	0.11	0.77					0.29
24-3	15-17	13.20	-0.04	1.05					0.29
24-3	52-54	13.25	0.10	0.96					0.28
24-5	15-17	13.30	0.17	0.67					0.28
24-5	52-54	13.35	0.35	1.76					0.23
25-2	52-54	13.45	0.13	0.82					0.30
25-2	52-54	13.50	0.66	0.97					0.33
25-3 & 25-4	15-17 / 52-54	13.7-13.75	-0.15	0.91					0.36
26 & 27-3	CC / 115-117	13.9-14.00	-0.41	0.97					0.40

*Described and applied as noted in text. Data in this table are not adjusted

OXYGEN AND CARBON ISOTOPIC COMPOSITION OF SELECTED SPECIES OF FORAMINIFERA AT SITE 470

Core/sect	Depth (cm)	Estimated Age (m.y.)	G. bulloides $\delta^{18}O$	$\delta^{13}C$	Cibicidoides kullenbergi $\delta^{18}O$	$\delta^{13}C$	Uvigerina hispida $\delta^{18}O$	$\delta^{13}C$	Ice Effect* Adjustment
8-1	35-39	5.80	-0.08	0.50	2.62	-0.18	2.79	-1.04	0.24
8-3	34-39	7.40					2.97	-0.19	0.20
8	CC	7.50	-0.08	0.98					0.32
9-1	54-59	7.90	0.11	0.87					0.32
9-1	54-59	7.90	0.20	0.87					0.32
9-2	54-59	8.10	0.01	0.78	2.60	0.16	2.51	-0.66	0.32
9-2	54-59	8.10	-0.09	0.94					0.32
9-3	54-59	8.20	0.18	0.70			3.48	-0.84	0.32
9-3	54-59	8.20	-0.32	1.22					0.32
9	CC	8.30	-0.36	0.53	2.67	0.25			0.32
10-1	54-59	10.15	-0.16	0.57	2.74	0.45			0.32
11-1	54-59	10.60	-0.47						0.42
11-3	55-60	10.80			2.44	0.15			0.40
11-4	55-60	10.90	-0.51	0.45	2.64	-0.06			0.40
11-5	55-60	10.95	-0.41		2.52	0.06			0.40
11-6	55-60	11.05	0.01	0.30					0.40
11	CC	11.10	-0.12	0.59	2.62	0.55			0.39
12-1	20-25	11.15	-0.31	0.27	2.67	1.03			0.39
12-2&3	55-60	11.25	-0.28	0.41					0.38
12-5&6	55-60	11.55			2.67	0.63			0.38
12-7	55-60	11.65			2.62	0.33			0.37
15-1	57-62	12.70	-0.07	0.59	2.30	1.29			0.31
15-2	53-58	12.80	-0.13	1.55					0.31
15-3	58-63	12.85	-0.20	0.56	2.37	0.33			0.30
15-4	60-65	12.90	-0.24	0.38					0.29
15-5	61-66	13.00			2.32	0.29			0.29
15	CC	13.05	-0.06	0.60	2.42	0.34			0.28
16-1	21-26	13.10			2.33	0.46			0.29
16-2	111-116	13.30			2.42	0.39			0.30
16-3	22-27	13.35			2.40	0.40			0.30
17-1	31-36	13.75	-0.57	0.83	2.38	0.45			0.35
17-2	31-36	13.80	-0.55	0.58					0.38
17-3	31-36	13.85	-2.43	0.40					0.40
17	CC	13.90	-0.08	1.20	2.12	0.60			0.40
18-1	107-112	14.15			2.07	1.18			0.44
18-1 & 18-1	107-112 / 139-144	14.20	-0.47	2.70					0.44
18-1	139-144	14.22					2.09	1.13	0.44
18-2	52-57	14.25	-0.39	1.69	2.21	1.11			0.45

*Described and applied as noted in text. Data in this table are not adjusted.

OXYGEN AND CARBON ISOTOPIC COMPOSITION OF SELECTED SPECIES OF FORAMINIFERA AT SITE 495

Core/ sect	Depth (cm)	Estimated Age (m.y.)	G. venezuelana $\delta^{18}O$	$\delta^{13}C$	D. altispira $\delta^{18}O$	$\delta^{13}C$	G. siakensis $\delta^{18}O$	$\delta^{13}C$	G. sacculifer $\delta^{18}O$	$\delta^{13}C$	Cibicidoides kullenbergi $\delta^{18}O$	$\delta^{13}C$	Ice Effect* Adjustment
20-3	70-72	12.60	0.80	0.99	-0.87	2.24					2.40	0.44	0.31
21-2	67-69	13.40	0.74	1.54	-1.18	2.80					2.14	1.12	0.28
21-4	67-69	13.70									1.96	1.01	0.32
21-6	67-69	14.00	0.37	1.39	-1.59	2.87					1.92	1.11	0.38
22-1	70-72	14.20	0.60	1.60	-1.23	3.17							0.42
22-3	70-72	14.30	0.95	1.78	-1.17	3.09					1.62	1.02	0.46
22-5	35-37	14.37	0.38	1.51	-1.84	2.63					1.65	0.91	0.51
23-1	75-79	14.50	0.64	1.72	-1.17	2.79					1.61	1.20	0.61
23-3	75-79	14.65	0.12	1.66	-1.47	2.80					1.07	0.91	0.65
23-5	75-79	14.75	0.45	1.77	-1.28	3.20					1.29	1.09	0.70
24-2	75-79	14.95	0.42	1.95	-0.89	3.25					1.63	1.27	0.76
24-4	75-79	15.10	0.10	1.82	-1.17	3.31					1.35	1.45	0.77
24-6	75-79	15.18	0.53	1.95	-1.08	3.19					1.68	1.59	0.79
25-1	75-79	15.25	0.00	1.81	-1.32	3.33	-1.52	1.92	-1.72	2.96			0.80
25-3	75-79	15.45	0.70	2.07	-1.22	3.80	-1.15	2.26	-1.72	3.25			0.80
25-4	98-102	15.58	0.46	1.93	-0.69	2.58	-1.41	2.36			1.63	1.53	0.81
25-4	140-144	15.62	0.63	2.22	-0.56	2.58	-1.55	2.09					0.92
25-5	75-79	15.68	0.49	2.00	-1.24	3.28	-1.12	2.21	-1.46	3.02			0.92
25-5	98-102	15.70	0.44	1.98	-0.82	3.43	-1.66	2.26	-1.30	3.02	1.72	1.73	0.92
25-2	140-144	15.72	0.42	1.98	-0.77	3.13	-1.17	2.34	-1.24	3.06			0.92
25-6	98-102	15.80	0.27	1.89	-1.07	3.22	-1.26	2.17	-1.57	3.01			0.92
25-6	140-144	15.85	0.64	1.66	-1.46	2.89	-1.11	2.07	-1.35	2.73	1.92	1.63	0.92
26-1	75-79	15.93	-0.33	1.95	-1.08	2.63	-1.54	1.79	-2.06	2.69			0.92
26-1	98-102	15.95	-0.26	1.94	-1.58	2.78	-1.45	1.75			1.15	1.07	0.92
26-1	140-144	15.98	-0.09	2.03	-1.18	2.59	-1.76	1.37					0.92
26-2	98-102	16.05	0.09	2.14	-1.08	3.09	-1.18	2.02	-1.17	3.03			0.92
26-2	140-144	16.10	-0.01	2.09	-1.14	2.99	-1.52	1.74	-1.75	2.95			0.92
26-3	75-79	16.15	-0.15	2.15	-0.87	2.87	-1.89	1.97	-1.70	2.77			0.92
26-3	92-96	16.18	-0.02	2.19	-0.90	3.14	-1.02	2.08	-1.25	2.99	1.63	1.55	0.92
26-3	140-144	16.21	-0.05	2.28	-0.91	3.21	-1.17	2.13	-1.16	3.19			0.92
26-4	98-102	16.30	0.02	2.21	-0.94	3.11	-1.15	2.09	-1.33	3.46	1.52	1.52	0.92
26-4	140-144	16.33	0.04	2.25	-0.99	2.71	-1.06	2.15	-1.73	2.71			0.92
26-5	75-79	16.35	0.07	2.16	-0.76	2.79	-1.19	2.23	-1.58	3.32			0.92
26-5	98-102	16.36	0.13	2.19	-0.85	2.99	-1.27	2.14	-1.94	2.85	1.49	1.54	0.92
26-5	136-140	16.38	0.04	1.97	-0.91	3.66	-1.12	1.98	-0.73	3.07			0.92
26-6	52-56	16.40	-0.25	2.30	-0.68	2.97	-1.12	2.15	-1.58	3.16	1.69	1.23	0.92
26-6	103-107	16.43	-0.09	2.17	-0.99		-1.22	2.00					0.92
27-1	75-79	16.50	0.13	1.70	-0.62	2.06	-1.16	1.69			1.47	1.20	0.92
27-3	75-79	16.64	-0.12	1.90							1.40	0.93	0.92
27-5	75-79	16.73	0.00	1.48	-1.17	2.17	-1.06	1.57			1.40	0.83	0.92
28-1	75-79	16.82	0.16	1.32	-1.46	2.28	-1.17	1.26			1.22	0.66	0.92
28-3	75-79	16.88	0.13	1.38	-1.13	2.90	-0.94	1.45			1.46	0.67	0.92
28-5	64-68	16.93	0.10	1.37	-1.11	2.47	-1.05	1.35			1.30	0.65	0.92
28-7	44.48	17.00	0.45	1.89	-1.19	2.63	-0.08	1.67			1.67	1.17	0.92

*Described and applied as noted in text. Data in this table are not adjusted.

OXYGEN AND CARBON ISOTOPIC COMPOSITION OF SELECTED SPECIES OF FORAMINIFERA AT NEWPORT BEACH

Sample*	G. bulloides $\delta^{18}O$	$\delta^{13}C$	Uvigerina $\delta^{18}O$	$\delta^{13}C$
N7A	0.25	0.38	1.62	-0.41
N7	-0.29	0.68	1.95	-0.59
WNPB 13	0.22	0.50		
N6	-0.03	0.05	-0.30	
N5	-0.62	-0.19		
N4A	0.27	0.24	-1.42	-0.69
N4	-0.13	0.27	1.35	-0.09
N3	-0.38	-0.23	0.92	-0.42
N2A			0.98	-0.73
NE 19	0.42	-0.21	2.33	-0.22
TM17	0.19	-0.31	-0.79	-0.49
TM14			0.37	-0.49

*For the stratigraphic position of these samples, see Barron and Keller (1983).

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