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# *Depth stratification of planktonic foraminifers in the Miocene ocean*

*Gerta Keller**
*U.S. Geological Survey*
*345 Middlefield Road*
*Menlo Park, California 94025*
*and*
*Department of Geology*
*Stanford University*
*Stanford, California 94305*

## ABSTRACT

**A depth stratification of planktonic foraminifers based on oxygen isotopic ranking is proposed for the Miocene. Species are grouped into surface, intermediate, and deep dwellers based upon oxygen isotopic composition of individual species. The depth stratification is applied to planktonic foraminiferal populations in three Miocene time-slices (21 Ma, 16 Ma, and 8 Ma) in the equatorial, north, west, and east Pacific. The late Miocene time-slice is compared with modern Pacific GEOSECS transect water-mass profiles of temperature and salinity in order to illustrate the similarities between the depth ranking of planktonic foraminifers and temperature and salinity conditions. The geographic distribution of inferred surface, intermediate, and deep water dwellers was found to be very similar to modern temperature profiles: surface dwellers appear to be associated with warmest temperatures (>20°C), upper intermediate water dwellers with temperatures between 10 and 20°C, and lower intermediate and deep water dwellers with temperatures below 10°C. Tropical high-salinity water appears to be associated with the upper intermediate *Globorotalia menardii* group in the modern ocean.**

**Depth stratification applied to two Miocene time-series analyses in the equatorial Pacific (Sites 77B and 289) indicates increased vertical and latitudinal provincialism between early, middle, and late Miocene time. The early and middle Miocene equatorial Pacific was dominated by the warm surface water group, which shows distinct east-west provincialism. This provincialism is interpreted as the periodic strengthening of the equatorial surface circulation during polar cooling phases. During the late Miocene the upper intermediate group increased and the surface group declines. At the same time the east-west provincialism disappeared. This faunal change may have been associated with the major Antarctic glaciation and resultant strengthening of the general gyral circulation and the strengthening of the Equatorial Countercurrent due to the closing of the Indonesian Seaway at that time.**

*Present address: Department of Geological and Geophysical Science, Princeton University, Princeton, New Jersey 08544

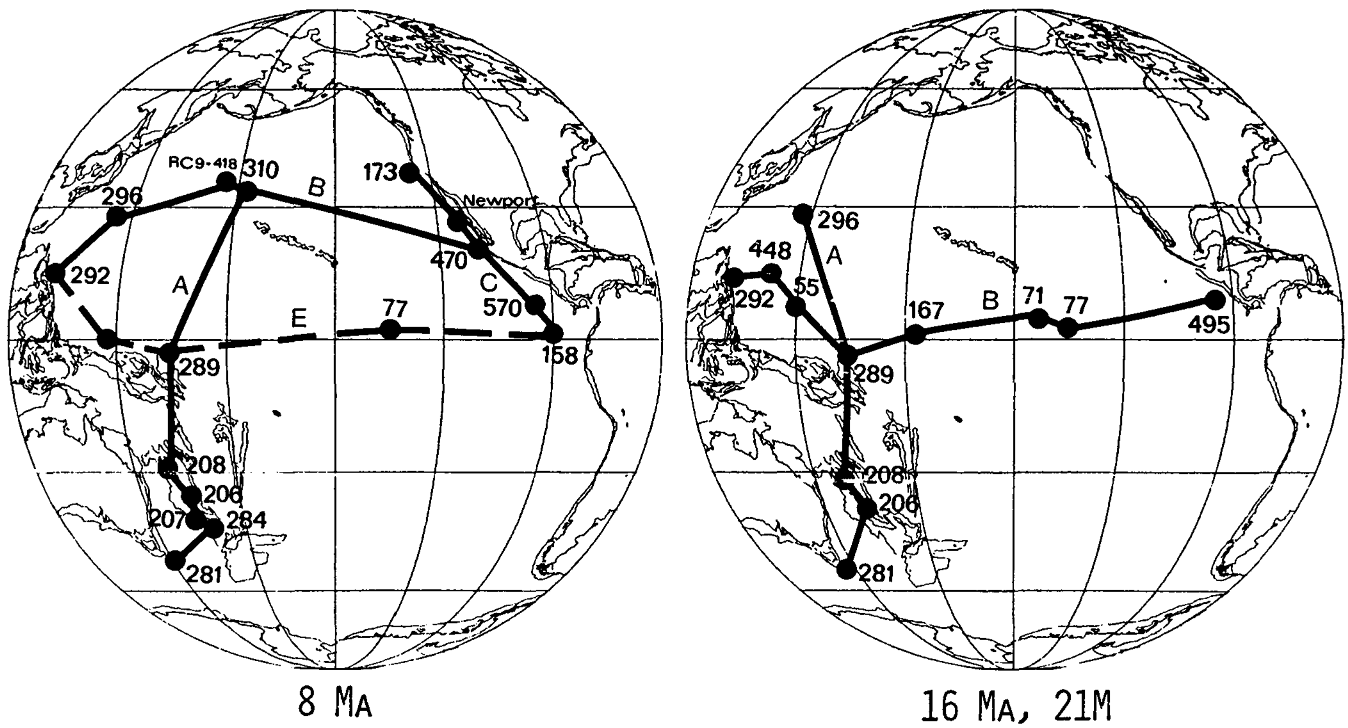



Figure 1. a. Miocene data points in the Pacific Ocean. Figure 1a, late Miocene (8 Ma) data points: (A) West Pacific, (B) North Pacific, (C) Northeast Pacific, (D) Equatorial Pacific. b. Early Miocene data points (21 Ma, 16 Ma): (A) West Pacific, (B) Equatorial Pacific.

## INTRODUCTION

The stable isotope composition of planktonic foraminifers has become an increasingly valuable tool for paleoclimatic and paleoceanographic studies. Many workers have reported a good agreement between depth stratification of species from plankton tows (Williams et al. 1979; Bé et al. 1971) and inferred depth from oxygen isotopic data although some species appear to be in disequilibrium (Emiliani 1954; Shackleton and Vincent 1978; Douglas and Savin 1978; Boersma and Shackleton 1978; Williams and Williams 1980; Vincent et al. 1981; Keller 1983; Savin et al. 1985; Poore and Matthews 1984, a,b). Although the species-specific differences in the $^{18}O/^{16}O$ ratio of the calcite shells of planktonic foraminifers from deep-sea cores is still debated, the calcite shells of many ecologically important species appear to calcify in equilibrium with seawater (Williams and Williams 1980; Fairbanks et al. 1980, 1982). Fairbanks et al. (1980) noted that non-spinose species appear to calcify in oxygen isotope equilibrium whereas spinose species appear to calcify out of equilibrium by –0.3 to –0.4 ‰ in $\delta^{18}O$ values. They also observed that in the Gulf Stream species appear to calcify in significantly narrower depth zones than their actual vertical distribution would imply. Specifically, they found that species appear to calcify in the photic zone, or upper 100 m of the water column, and that they are stratified within this zone. This implies that species calcify at specific temperature and density conditions within the photic zone and then migrate to greater depths, as opposed to calcifying within the upper 400 m of the water column as previously assumed. Poore and Matthews (1984b) suggest that the two hypotheses can be reconciled, if we consider that in most oceanographic situations the temperature and salinity conditions of the upper 400 m of the water column can be found at times in the photic zone. In either case, depth stratified planktonic foraminiferal data should provide information of the temperature conditions in the surface water-masses.

The purpose of this report is to discuss and illustrate the Miocene quantitative foraminiferal data of three time-slice intervals (21 Ma, 16 Ma, and 8 Ma) and two time-series analyses (Sites 77B and 289) in terms of (1) groups inferred to dwell in relative surface, intermediate, and deep waters based on oxygen isotope ranking of individual species, (2) the relationships of planktonic foraminifers to water-mass properties such as temperature and salinity, based on comparison of late Miocene faunal transects with modern water-mass profiles of the Pacific GEOSECS transect profiles (Craig et al. 1981) and (3) water-mass stratification changes in the Miocene ocean and inferred paleoclimatic changes.

Four late Miocene (8 Ma) faunal transects have been chosen to illustrate faunal depth stratification in various regions of the Pacific: West Pacific, North Pacific, Equatorial Pacific, and northeast Pacific (California Current province) (Figure 1). In addition, West Pacific and Equatorial Pacific data points are also

TABLE 1. DEPTH RANKING OF PLANKTONIC FORAMINIFERS IN THREE MIOCENE TIME-SLICES AT 21 Ma, 16 Ma, AND 8 Ma*

| | 8 Ma | 16 Ma | 21 Ma |
|---|---|---|---|
| Surface | Globigerinoides mixed spp.<br>G. trilobus-G. sacculifer<br>Globoquadrina altispira<br>+Pulleniatina obliquiloculata<br>*Orbulina universa | Globigerinoides mixed spp.<br>G. trilobus-G. sacculifer<br>G. subquadratus<br>Gl. siakensis-G. mayeri<br>Globoquadrina altispira | Globorotalia kugleri<br>Globigerinoides mixed spp.<br>G. trilobus-G. sacculifer<br>Gl. siakensis-Gl. mayeri<br>Globigerina angustiumbilicata<br>Globoquadrina altispira |
| Upper Intermediate | Globorotalia menardii group<br>Sphaeroidinella seminulina<br>+Globigerina nephenthes-G. drury<br>+Globorotalia continuosa<br>+Globorotalia acostaensis<br>+Globoquadrina dehiscens | Globorotalia peripheroronda<br>Gl. fohsi group<br>+Globorotalia continuosa<br>*Globoquadrina dehiscens | *Globoquadrina dehiscens |
| Lower Intermediate | Globorotalia conoidea<br>+Globigerina woodi<br>Globigerina bulloides<br>Neogloboquadrina pachyderma | Globorotalia miozea<br>+Globigerina woodi<br>Globigerina bulloides | Globorotalia miozea<br>+Globigerina woodi<br>Globigerina bulloides |
| Deep | Globoquadrina venezuelana | Globoquadrina venezuelana | Globoquadrina venezuelana<br>Catapsydrax ssp.<br>Globoquadrina tripartita |

*Note: Taxa are grouped into surface, upper and lower intermediate, and deep dwellers based on $\delta^{18}O$ ranking. Asterisk marks species with variable $\delta^{18}O$ values. Species needing further study to rank them confidently are marked with +.

illustrated for late early Miocene (16 Ma) and early Miocene (21 Ma) time-slices in order to illustrate changes in depth stratification and relative abundances of species during the Miocene (Figure 1). Changes in Miocene depth stratification are also illustrated in two time-series analyses (Sites 77B and 289) and climatic oscillations are interpreted from abundance fluctuations of temperature sensitive species. The three time-slice intervals and age determinations are discussed in Barron et al. (1985).

## DATA ANALYSIS

The relative depth stratification of planktonic foraminifers is based on isotopic analyses of various species in three Miocene time-slices at 21 Ma, 16 Ma, and 8 Ma. Isotopic ranking of species is based on Deep Sea Drilling Project (DSDP) sites with multiple species analyses for each time-slice interval. Isotopic data are published in Tables 1–4 of Savin et al. (1985). Quantitative data on Miocene planktonic foraminifers have been generated by CENOP workers and are published in Keller (1980a, b; 1981a, b), Srinivasan and Kennett (1981a, b; Kennett and Srinivasan, 1985), Barron and Keller (1983), and Barrera et al. (1985). Relative abundance data of species is based on representative sample splits (using an Otto microsplitter) of 300–500 specimens per sample in the size fraction greater than 150 microns. Three to eight samples were analyzed for each time-slice interval in each deep-sea core, and samples were averaged to obtain a representative faunal assemblage.

## ISOTOPIC RANKING

To establish isotopic depth ranking of taxa, oxygen isotope values have been plotted against latitudes for each site analyzed in the three time-slice intervals (see Figures 2–4). Consistency in the relative isotopic ranking among the various taxa is interpreted to reflect depth ranking in the water column. Table 1 suggests the relative depth ranking of Miocene species for each time-slice, and Plates 1 and 2 illustrate the depth ranking of species in the early and middle to late Miocene. No absolute oxygen isotope values are proposed in Table 1 because isotopic values change across latitudes and are related to water-mass conditions at each locality.

### *Late Miocene: 8 Ma*

A variety of planktonic foraminiferal taxa have been analyzed in the late Miocene time-slice interval in 18 DSDP sites across latitudes, as illustrated in Figure 2. In low to middle latitudes, *Globoquadrina venezuelana* consistently has the heaviest oxygen isotope values and is interpreted as a deep dweller living near the lower part of the thermocline.

*Globigerinoides trilobus-G. sacculifer* appear to be the shallowest, or lightest species in the Pacific and equally light, or slightly heavier than *Globoquadrina altispira* in the Indian Ocean and South Pacific (Figure 2). Mixed species of *Globigerinoides* retain very light oxygen isotope values. This suggests that species of the genus *Globigerinoides* are shallow, or surface dwellers along with *G. altispira* and *Pulleniatina obliquiloculata*. Oxygen isotope values of *Orbulina universa* are variable and may range from heavier than *Globorotalia menardii* to lighter than *Globigerinoides trilobus-G. sacculifer* (Figure 2). This species is tentatively grouped as a surface dweller.

Among isotopically intermediate taxa in low latitudes, the *Globorotalia menardii* group (includes *Globorotalia limbata*) and

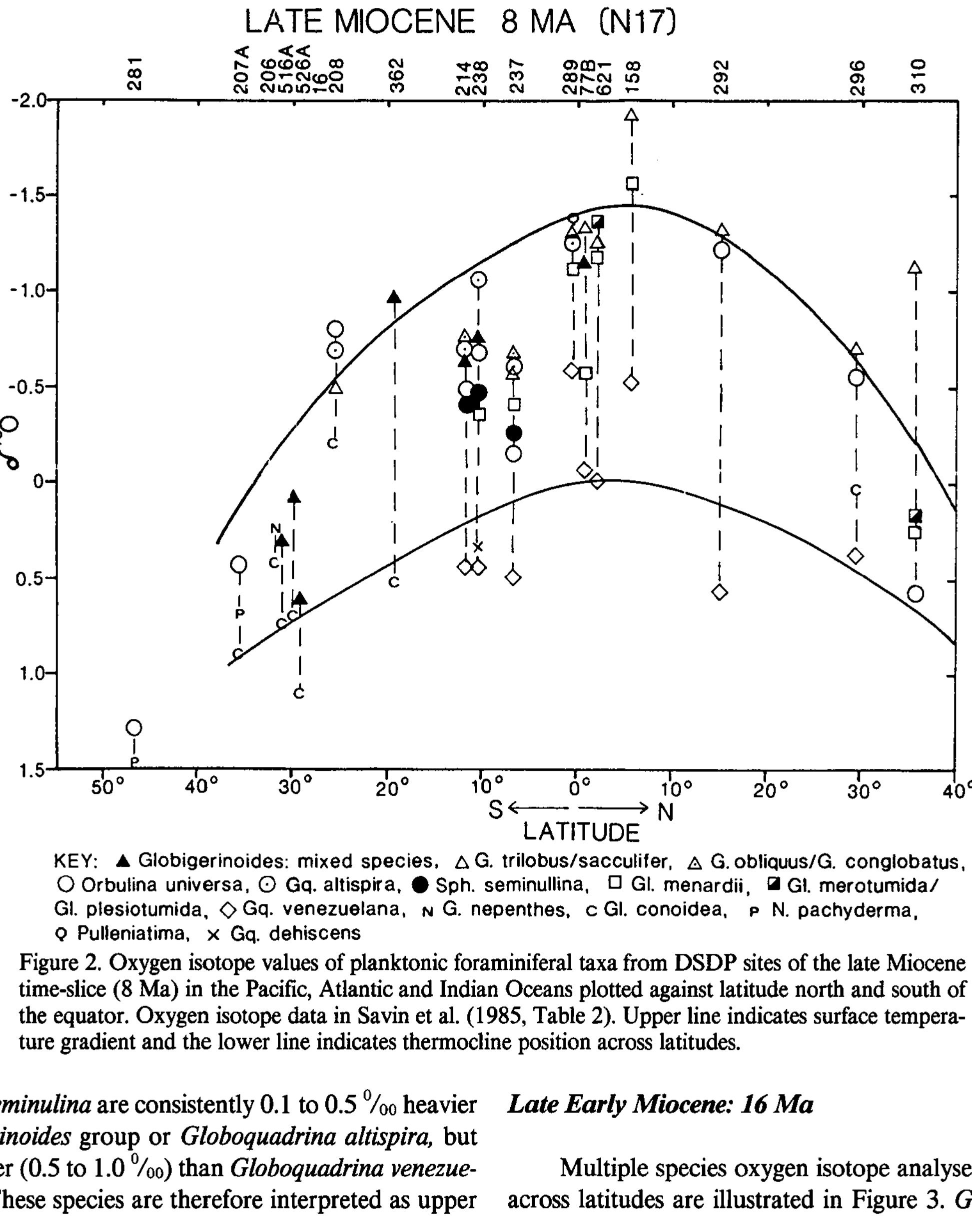



Figure 2. Oxygen isotope values of planktonic foraminiferal taxa from DSDP sites of the late Miocene time-slice (8 Ma) in the Pacific, Atlantic and Indian Oceans plotted against latitude north and south of the equator. Oxygen isotope data in Savin et al. (1985, Table 2). Upper line indicates surface temperature gradient and the lower line indicates thermocline position across latitudes.

*Sphaeroidinella seminulina* are consistently 0.1 to 0.5 ‰ heavier than the *Globigerinoides* group or *Globoquadrina altispira,* but considerably lighter (0.5 to 1.0 ‰) than *Globoquadrina venezuelana* (Figure 2). These species are therefore interpreted as upper intermediate dwellers (UIW) (Table 1). The *Globigerina nepenthes–G. druryi* group, *Globorotalia continuosa–Gl. acostaensis* group and *Globoquadrina dehiscens* have also been tentatively placed in this group, although further multiple species isotopic analyses are necessary to confirm their depth ranking.

In temperate middle latitudes *Globorotalia conoidea* consistently has heavy oxygen isotope values whereas *Neogloboquadrina pachyderma* appears lighter than *Globorotalia conoidea,* but heavier than *Orbulina.* Both *Gl. conoidea* and *N. pachyderma* are interpreted as lower intermediate (LIW) species (Table 1). *Globigerina bulloides* and *G. woodi* are also tentatively placed in this group. Figure 2 illustrates the isotopic values of species across latitudes with the upper line indicating the surface temperature gradients as inferred from the isotopically lightest species and the lower line indicating the thermocline position as inferred from the isotopically heaviest species.

### *Late Early Miocene: 16 Ma*

Multiple species oxygen isotope analyses of 24 DSDP sites across latitudes are illustrated in Figure 3. *Globoquadrina venezuelana,* analyzed in ten sites, is consistently the heaviest planktonic foraminifer. The isotopically lightest species, or surface dwellers, include *Globorotalia siakensis, Globigerinoides trilobus–G. sacculifer, G. subquadratus, Globigerinoides* mixed species, and *Globoquadrina altispira,* similar to the late Miocene time slice (Table 1).

The intermediate group is less well defined. *Globorotalia peripheroronda* is 0.2 to 0.5 ‰ heavier than *G. trilobus–G. sacculifer* and *Globigerinoides* mixed species, except at Site 366A where the oxygen isotope values are similarly light perhaps due to diagenesis (Figure 3). *Globorotalia continuosa* also appears to fall into the intermediate group, although this species has not been analyzed from the same sample as other species in Figure 3. *Globoquadrina dehiscens* analyzed in 10 sites ranks 0.4 to 1.0 ‰ heavier than the surface group and *Globorotalia peripheroronda,* except at the high latitude Site 408 where it is anomalously light

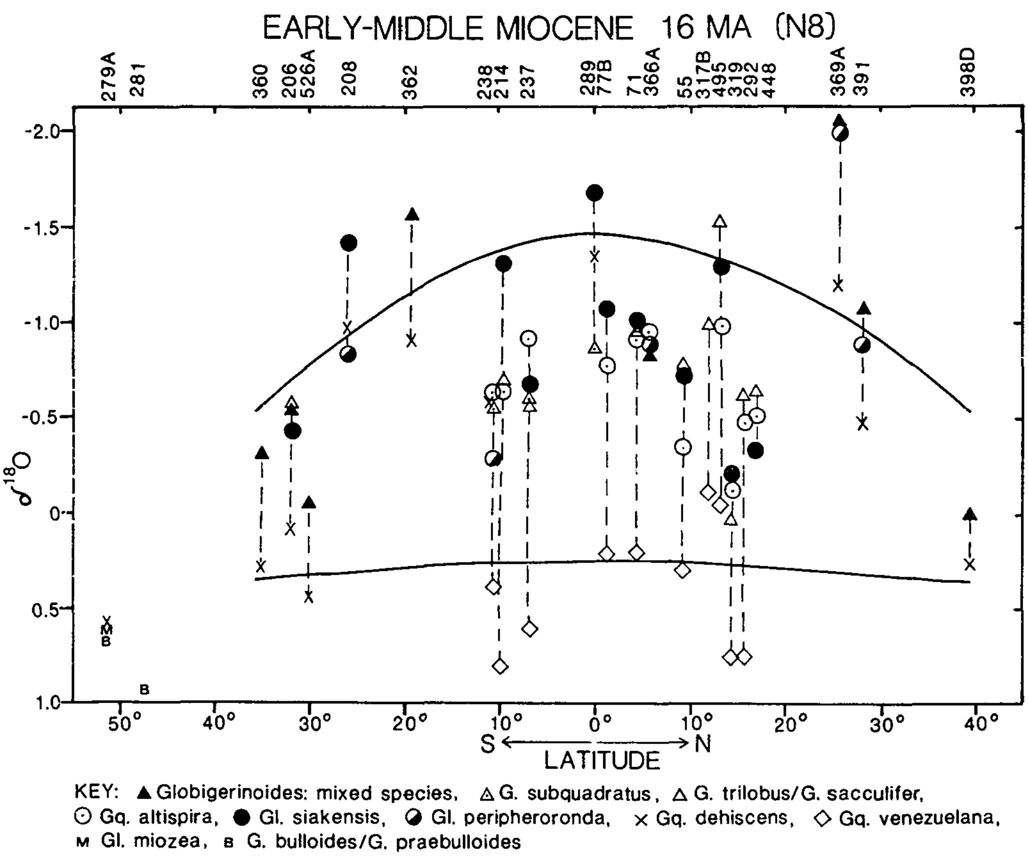



Figure 3. Oxygen isotope values of planktonic foraminiferal taxa from DSDP sites of the late early Miocene time-slice (16 Ma) in the Pacific, Atlantic, and Indian Oceans plotted against latitude north and south of the equator. Oxygen isotope data in Savin et al. (1985, Table 2). Upper line indicates surface temperature gradient and lower line indicates thermocline position across latitudes.

similar to *Globigerinoides* mixed species. This suggests that *Gq. dehiscens* ranks as intermediate species in low latitudes, but ranks as a surface dweller in higher latitudes. This may be a general problem with species which range from high to low latitudes; such species tend to occupy deeper positions in low latitudes and may become surface dwellers in high latitudes.

The lower intermediate group in middle to high latitudes comprises cool to temperate taxa and includes *Globorotalia miozea, Globigerina bulloides* and *G. woodi* (Table 1).

### *Early Miocene: 21 Ma*

Multiple species oxygen isotope analyses of 19 DSDP sites across latitudes are illustrated for the early Miocene time-slice in Figure 4. Among the heaviest taxa are *Catapsydrax* spp., *Globoquadrina tripartita*, and *Gq. venezuelana* (Table 1). *Globoquadrina venezuelana* has anomalously enriched oxygen isotope values at Sites 71 and 55 perhaps due to diagenesis.

Surface dwellers comprise the largest group in the early Miocene (Table 1) *Globorotalia kugleri* is consistently the lightest species (10 sites). *Globorotalia siakensis* (7 sites) is heavier than *Gl. kugleri* and *Globigerina angustiumbilicata* except at Site 55, and lighter than *Globigerinoides trilobus–G. sacculifer* or *Globigerinoides* mixed species (Figure 4. *Globigerinoides trilobus-G. sacculifer* has an unusually heavy oxygen isotope value at Site 292 (heavier than *Gq. venezuelana*) which may be due to dissolution. There is little change in the position of the surface temperature gradient or the thermocline across latitudes between early and middle Miocene time as inferred from isotopically lightest and heaviest species (Figures 3 and 4).

There are few isotopically intermediate species in the early Miocene time-slice. The lower intermediate group is composed of the cool to temperate species *Globorotalia miozea, Globigerina bulloides,* and *G. woodi,* similar to the middle Miocene time-slice. *Globoquadrina dehiscens* has been tentatively placed into the upper intermediate group although isotope values of this species are highly variable ranging from 0.3 to 1.2 ‰ below *Globigerinoides* species to values as low as *Globoquadrina venezuelana.* This high variability may be in part a taxonomic problem because *Gq. dehiscens* evolved from *Gq. tripartita* (a deep dweller) in the early Miocene and transitional forms may have been included in the analyses. It is also possible that *Gq. dehiscens* adapted to a different water-mass after its evolution from *Gq. tripartita.*

## MIOCENE FAUNAL TRANSECTS

In Figures 5 to 7 planktonic foraminifers have been grouped

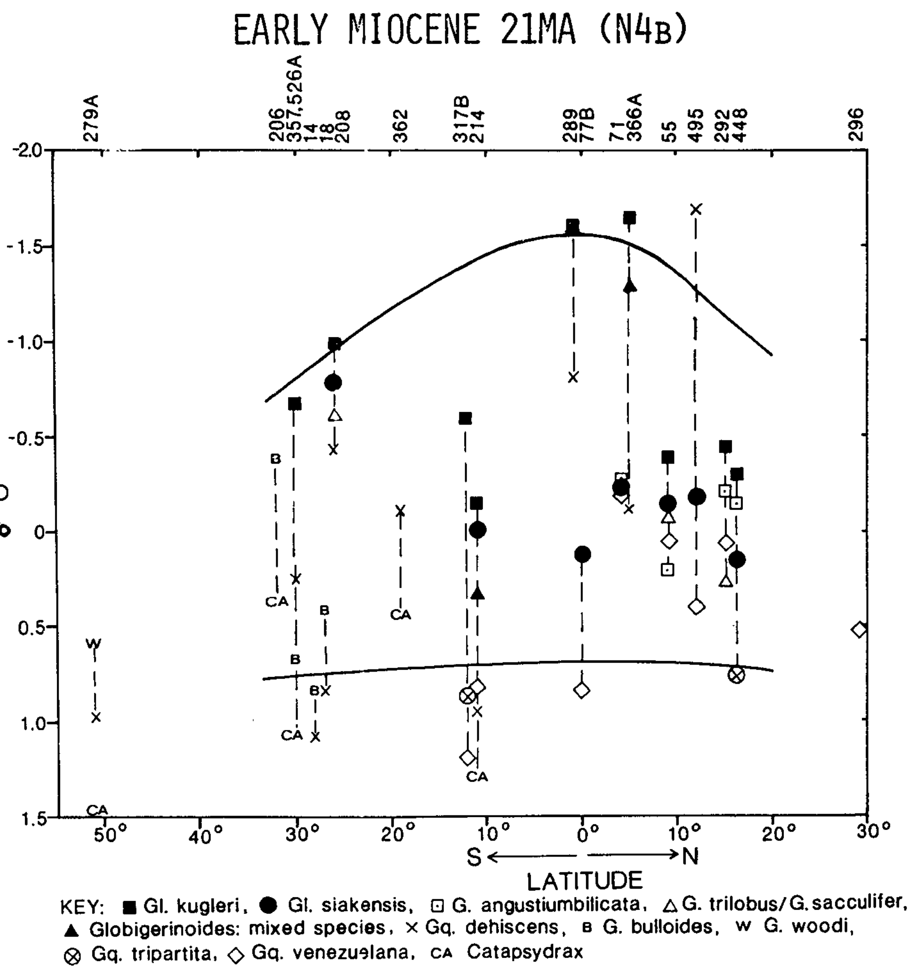



Figure 4. Oxygen isotope values of planktonic foraminiferal taxa from DSDP sites of the earliest Miocene time-slice (21 Ma) in the Pacific, Atlantic, and Indian Oceans plotted against latitude north and south of the equator. Oxygen isotope data in Savin et al. (1985, Table 2). Upper line indicates surface temperature gradient and lower line indicates thermocline position across latitudes.

into surface, upper intermediate (UIW), lower intermediate (LIW) and deep water dwellers for the three Miocene time-slices and plotted in four faunal transects (West Pacific, North Pacific, Northeast Pacific, and Equatorial Pacific) in order to illustrate faunal changes through the Miocene and across latitudes. The late Miocene (8 Ma) faunal transects are compared with modern ocean GEOSECS water-mass profiles of temperature and salinity in order to illustrate the similarities between the depth ranking of planktonic foraminifers as inferred from oxygen isotope ranking, and temperature and salinity conditions across latitudes. Ideally, modern water-mass profiles should be compared with modern faunal transect data; unfortunately, no Recent quantitative faunal data are available for the Pacific. One might argue that a comparison of modern ocean temperature and salinity profiles with late Miocene faunal data are invalid, or at least suspect, since oceanographic and paleoclimatic conditions have changed considerably over the last 8 million years. However, large scale oceanographic conditions such as the major gyral circulation in the Pacific may not have been very different from the present as indicated by faunal studies that suggest that the late Miocene marks the onset of paleoceanographic conditions similar to the present (Lohmann and Carlson 1981, Burckle et al. 1982; Barron and Keller 1983). In this study it is assumed that a consistent similarity between faunal groups and the temperature or salinity profiles in each transect implies that there may be a relationship between the faunal groups (surface, intermediate, or deep water dwellers), and temperature (or density) and salinity conditions. However, ultimately this assumption will have to be tested on modern faunal data.

### *Late Miocene: 8 Ma*

The west Pacific faunal transect (Figure 5) illustrates the bipolarity of fauna in the northern and southern hemispheres, which has also been shown for Pliocene and Pleistocene fauna (Cifelli 1969; Kennett 1978; Keller 1978). Nearly identical faunal assemblages are found at Site 310 (43°N) and Site 208 (31°S) with the exception that the UIW species *Globigerina nepenthes,*

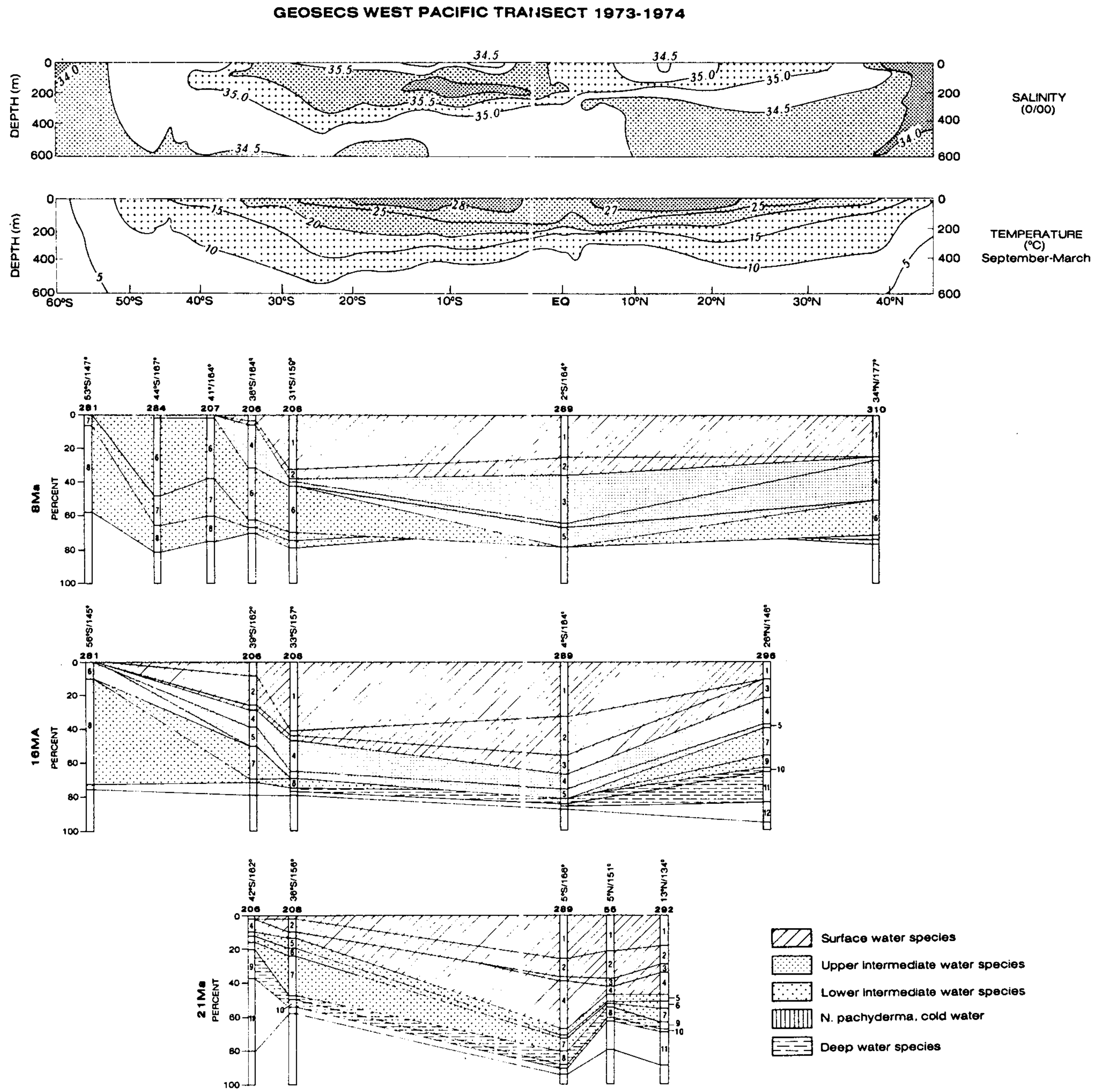



Figure 5. GEOSECS West Pacific transect profiles of temperature and salinity of the modern ocean (Craig et al., 1981) and depth stratification of planktonic foraminifers in the West Pacific transect at 8 Ma, 16 Ma and 21 Ma. Depth ranking of species is based on $\delta^{18}O$ ranking. Species are grouped into surface, upper intermediate, lower intermediate, and deep water groups. Key: 8 Ma time-slice: (1) *Globigerinoides*, (2) *Globoquadrina altispira*, (3) *Globorotalia menardii*, (4) *Globigerina nepenthes-G. druryi*, (5) *Gl. acostaensis*, (6) *Gl. conoidea*, (7) *G. woodi*, (8) *G. bulloides*, (10) *Gq. venezuelana*, (11) *Globigerinita glutinata*.

16 Ma time-slice: (1) *Globigerinoides*, (2) *Globorotalia siakensis-Gl mayeri*, (3) *Globoquadrina altispira*, (4) *Gq. dehiscens*, (5) *Globorotalia peripheroronda-Gl. fohsi*, (6) *Gl. continuosa*, (7) *Gl. miozea*, (8) *Globigerina woodi*, (9) *G. bulloides*, (10) *Globoqudrina venezuelana*, (11) *Sphaeroidinella disjuncta*, (12) *Globigerinita glutinata*.

21 Ma time-slice: (1) *Globigerina angustiumbilicata*, (2) *Globigerinoides*, (3) *Globoquadrina altispira*, (4) *Globorotalia kugleri*, (5) *Gl. siakensis-Gl. mayeri*, (6) *Globigerina woodi*, (7) *G. bulloides-G. praebulloides*, (9) *Globoquadrina venezuelana*, (10) *Catapsydrax*, (11) *Globigerinita glutinata*.

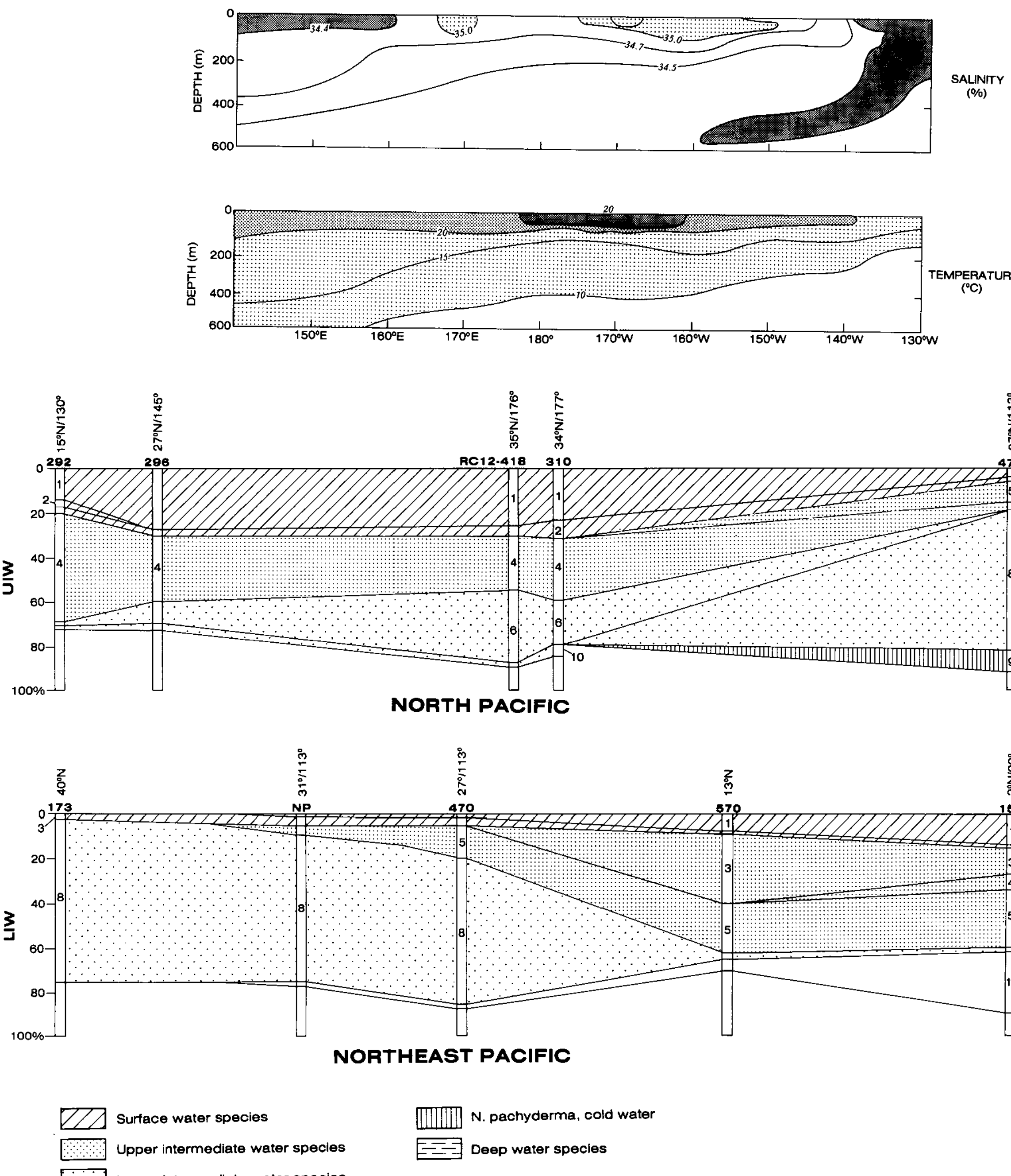



Figure 6. GEOSECS North Pacific transect profiles of temperature and salinity of the modern ocean and depth stratification of planktonic foraminifers in the north Pacific and northeast Pacific at 8 Ma. See Figure 5 caption for key to taxa.

which is abundant in Site 310 and Site 206 (36°S) but not at Site 208. The LIW group, the temperate species *Globorotalia conoidea,* and cool water species *Globigerina woodi* and *G. bulloides,* are rare or absent in equatorial water, but are common in middle latitudes and dominate in high latitudes.

Comparison of inferred late Miocene faunal depth stratification with modern GEOSECS water-mass profiles (Figure 5) reveals similarities, especially between temperature and depth stratification of species. Surface dwellers appear to be restricted to waters of greater than 20°C. In the GEOSECS west Pacific temperature profile, the 20°C isotherm outcrops at about 35°N and 35°S, similar to the latitudinal restrictions of the inferred late Miocene surface dwelling fauna in the South Pacific. The temperate UIW dweller *Globigerina nepenthes* and temperate LIW dweller *Globorotalia conoidea* disappear between 44°S and 53°S latitude near the outcrop location of the 10°C isotherm (Figure

5). The cool water component of the LIW group, *Globigerina woodi* and *G. bulloides*, dominate faunal assemblages south of 44°S, which compares to water temperatures cooler than 10°C in the modern ocean.

The similarity between temperature profiles and faunal depth stratification is also apparent in the North Pacific and northeast Pacific transects (Figure 6). The northeast Pacific transect illustrates a north-south transect through the California Current province and to the equator. Faunal changes in this region are especially pronounced and show the southward transport of a cool high latitude fauna with the California Current. Inferred faunal depth stratification suggests that the cool LIW group dominates north of 27°N latitude (Site 470) whereas the warm UIW group dominates to the south. Unfortunately, no GEOSECS temperature data are available for this region.

In the North Pacific transect the surface group comprises only 6% of the total fauna in the cool water California Current province (Site 470, 27°N lat.), but increases to 20–32 percent in the warmer central and western Pacific. The distribution of the surface group is similar to the 20°C isotherm which outcrops in the eastern Pacific and deepens westward (Figure 6). The UIW group also increases in abundance westward from 8% in the eastern Pacific to 24% and 45% in the central and western Pacific respectively. Similarly, the 10°C isotherm deepens westward.

In the equatorial Pacific the GEOSECS transect profiles illustrate east-west differences in the modern ocean near Sites 77B and 289 respectively (Figure 7). For instance, significantly higher surface water temperatures (~3°C) prevail in the west equatorial Pacific, the 20°C isotherm is at about 200 m depth as compared to 50–100 m depth in the upwelling region of the east equatorial Pacific, and the 10°C isotherm lies between 300–400 m in the west, but varies between 200–400 m in the east equatorial Pacific (Figure 7). These east-west temperature differences appear to be reflected in the faunal depth stratification. For example, the shallowing of the 20°C isotherm in the east equatorial Pacific is reflected in the lower abundance of surface dwelling species. The increased abundance in UIW dwellers, which coincides with temperatures between 10°C and 20°C, may be due to the increased upwelling in the eastern equatorial Pacific, but may also reflect higher salinity waters. Salinity profiles (Figures 5 and 7) show high salinity tongues between 150–200 m depth south of the equator in both west and east equatorial Pacific. *Globorotalia menardii*, which may prefer high salinity water (Poore 1981), is equally abundant in both regions (Sites 77B and 289).

The similarities between both the outcroppings of the 10°C and 20°C isotherms, and the general deepening of the isotherms, to the abundance distribution of the inferred surface, UIW and LIW groups suggests that the surface group may occupy waters warmer than 20°C, the UIW may occupy waters between 10°C and 20°C, and the LIW group waters cooler than 10°C. However, since late Miocene faunal groups are compared with modern temperature profiles, it can only be assumed that the temperature gradients of the late Miocene and the modern ocean were similar.

There is some evidence to support an interpretation of late Miocene faunal stratification based on Recent water-mass profiles from a study by Bé et al. (1971) based on plankton tow data (between 0–200 m) and the temperature profile (upper 700 m) in the Atlantic. This study shows a close correlation in both the geographic distribution and abundance of *Globigerinoides* (inferred surface dweller) with surface water temperatures greater than 20°C. The greatest abundance of cool water species *Globigerina bulloides* and *Neogloboquadrina pachyderma* (inferred LIW group) is found in temperatures of less than 10°C. However, many species occupying the intermediate temperature range, between 10–20°C in the modern ocean (*Globorotalia inflata, Gl. crassaformis, Gl. truncatulinoides*) evolved during Pliocene–Pleistocene times.

### *Early Miocene: 21 Ma, 16 Ma*

Inferred depth stratification of planktonic foraminifers of the earliest Miocene (21 Ma) and late early Miocene (16 Ma) time-slices are also illustrated for the equatorial and west Pacific transects (Figures 5, 7). Comparison of the early, late early, and late Miocene time-slices reveals marked changes in the depth stratification of species through the Miocene.

In the southwest Pacific the surface group increases from 12% in the earliest Miocene (Site 208) to 45% in the late early Miocene and decreases to 30% in the late Miocene. A sharp drop to lower surface values occurs between 31° and 36°S latitude (Sites 208, 206) in the late Miocene. At these latitudes the earliest and late Miocene are dominated by the cool LIW group, whereas in the late early Miocene the warmer surface and UIW group dominates (Figure 5).

In the equatorial Pacific the surface group gradually decreases from a high of 65–80% in the earliest Miocene, to 55–70% in the late early Miocene and to 25–35% in the late Miocene. At the same time there is a decrease in the deep dwelling group (extinction of *Catapsydrax*) and near disappearance of cold water species *Globigerina bulloides* and *G. woodi* between the earliest and late early Miocene (Figure 7). In the late early Miocene, species which inhabit the UIW appear in the equatorial Pacific and in the mid-latitude west Pacific (*Globorotalia peripheroronda–Gl. fohsi* group, *Gl. continuosa*). This group becomes dominant in the late Miocene with the evolution of *Gl menardii* in the tropics and *Gl. acostaensis* in tropical to subtropical waters. Hence, major changes in the depth stratification are the two-thirds decrease in the late Miocene surface group associated with an expansion of the UIW group and differentiation into tropical and temperate components.

The changing depth stratification in the three Miocene time-slices implies that the upper water-mass (0–500 m) has gradually evolved from a relatively simple to a highly complex stratified ocean by late Miocene time associated with an increased faunal provincialism and steepening of the thermal gradients between equator and poles as observed by many previous workers (Kennett 1978; Lohmann and Carlson 1981; Keller 1981a; Moore and

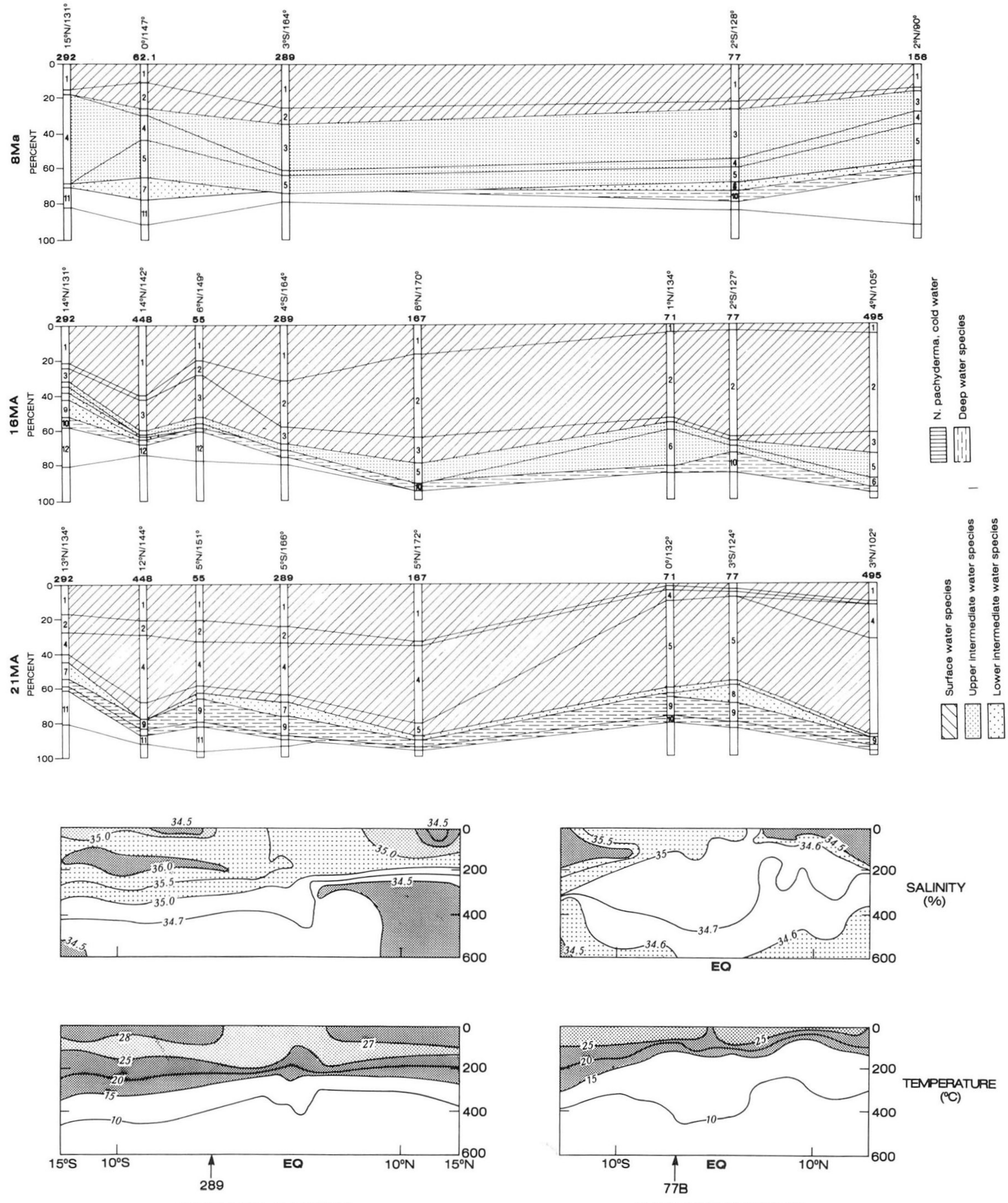



Figure 7. Depth stratification of planktonic foraminifers in equatorial Pacific at 8 Ma, 16 Ma and 21 Ma. (See Figure 5 caption for key to taxa) and GEOSECS west and east equatorial Pacific transects of temperature and salinity. Relative location of the GEOSECS transects near Sites 289 and 77B.

Lombari 1981; Thunell and Belyea 1982; Barron and Keller 1983). This faunal provincialism implies generally cooler surface water temperatures in middle latitudes during early and late Miocene, whereas surface water temperatures increased or remained unchanged in the tropics throughout the Miocene (suggested by the presence of long ranging forms, such as *Globigerinoides*). A general warming of surface waters in the tropics between the early and late Miocene is also observed in the oxygen isotope data as discussed by Savin et al. (1985).

## DEPTH STRATIFICATION: TIME—SERIES ANALYSIS

Depth stratification of planktonic foraminifers during the Miocene is illustrated from the west and east equatorial Pacific (Sites 289 and 77B, Figures 8 and 9) in order to: (a) analyze the nature of water-mass stratification through the Miocene as implied by relative abundances of surface, intermediate, and deep dwelling species; (b) identify water-mass changes that may have caused or contributed to the major faunal changes in the early, middle, and late Miocene; and (c) identify species abundance changes that correlate with cold-warm oscillations in the oxygen isotope record. Quantitative faunal analysis of Site 289 was done by Srinivasan and Kennett (1981a, b; Kennett and Srinivasan 1985). They also provided the data for this study. Faunal data for Site 77B were reported earlier in Keller (1980a, 1981b).

Depth stratification of planktonic foraminifers at Site 77B and 289 imply major changes in water-mass stratification through the Miocene. The earliest Miocene ocean (Zones N4–N5) was dominated by the warm water surface group (70–80%) marked by pronounced east-west faunal provincialism and minor intermediate and deep water groups (Figures 8 and 9). This suggests that water temperatures remained warm (>20°C?) through most of the living habitat of planktonic foraminifers at this time. It is noteworthy that the N4/N5 Zone boundary is characterized by a major faunal turnover, primarily in the surface group, resulting in the decline and eventual extinction of the Paleogene fauna and evolution of the Neogene fauna (Kennett 1978; Keller 1981a). A gradual change in the water-mass stratification is also implied at this time by a permanent decline in the deep water group (extinction of *Catapsydrax*), associated with a major cool event in the $\delta^{18}O$ record (Boersma and Shackleton 1978; Savin et al. 1985), widespread deep-sea unconformity and sea level lowstand (Vail and Hardenbol 1979; Keller and Barron 1983).

The surface group dominates through the late early and middle Miocene with *Globorotalia siakensis–Gl. mayeri* dominant in Site 77B and *Globigerinoides* dominant in Site 289 (Figures 8 and 9). The early middle Miocene is marked by an increase followed by a gradual decline in the intermediate group associated with generally cooler $\delta^{18}O$ temperatures. The evolution and range of the intermediate dwelling *G. fohsi* plexus characterizes this interval. Deep-water dwellers are nearly absent. The continued dominance of the surface group suggests that in the tropics the living habitat of this group remained essentially unchanged during the major phase of polar glaciation in the Neogene. However, cooling is indicated by the increasing abundance of the cooler intermediate group, indicating increased stratification of the upper water-mass.

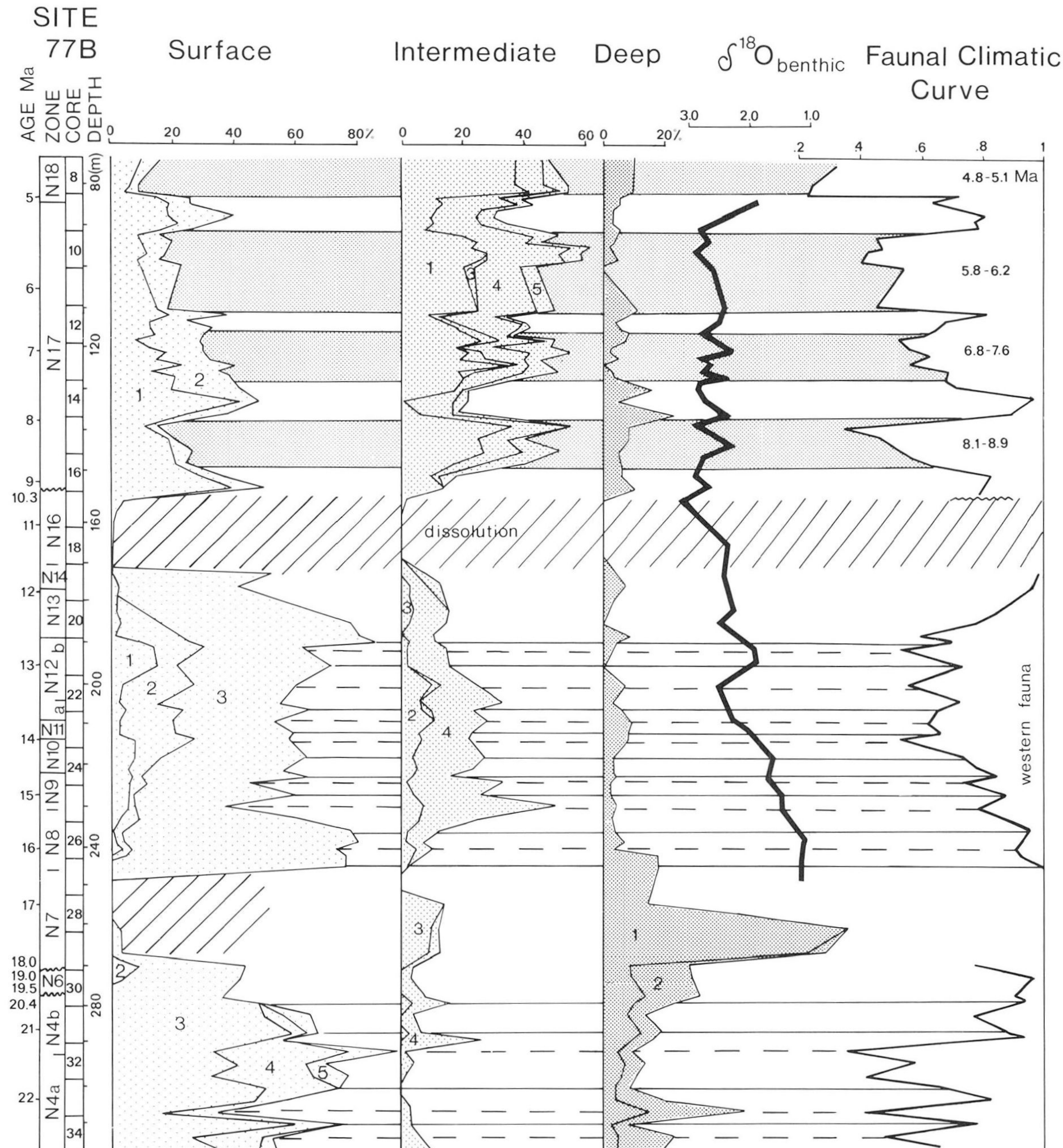
The most dramatic change in water-mass stratification is implied during the late Miocene. Beginning at the middle/late Miocene boundary (~12 Ma) there is an abrupt decline in the surface group (extinction of *Gl. siakensis–Gl. mayeri*) and increase in the intermediate group (evolution of *Gl. menardii–Gl. tumida, G. nepenthes–G. druryi* groups), coincident with significantly lower $\delta^{18}O$ temperatures. No east-west faunal provincialism is apparent at this time. This faunal change suggests the establishment of a distinct broad intermediate water layer at the expense of a reduced surface water layer (Figures 8 and 9). Lower abundances in the surface group and presence of a deep water group at Site 77B suggests that in the eastern equatorial Pacific water was significantly cooler, perhaps due to increased upwelling, and more stratified than in the west equatorial region.

## FAUNAL CLIMATIC CURVE

### *Early and Middle Miocene*

The early and middle Miocene equatorial Pacific is dominated by a surface group that exhibits definite east-west faunal provinces. This provincialism is expressed in a western equatorial fauna (Site 289) dominated by *Globigerinoides* spp. *Globoquadrina altispira, G. angustiumbilicata,* and *Gl. kugleri,* and an east equatorial fauna (Site 77B) dominated by the *Gl. siakensis–Gl. mayeri* group. Such faunal differences are presumably related to water-mass properties and therefore may reveal oscillating climatic conditions and fluctuations in the intensity of the equatorial current circulation. A faunal climatic curve has been constructed based on this east-west provincialism. In this curve the western fauna is represented as the proportion of the total eastern (E) and western (W) fauna W/W+E, whereas in the east equatorial Pacific the eastern fauna is proportional E/E+W. Hence, the faunal climatic curves in Figures 8 and 9 illustrate incursions of the migrating eastern and western faunal components during cool-warm oscillations.

In the west Pacific Site 289 examination of the surface dwelling group, the faunal climatic curve and the benthic $\delta^{18}O$ curve suggest a close relationship between these groups during the early and middle Miocene. For paired samples, there is a one-to-one correspondence (solid lines, Figure 9) between high abundance peaks in the surface fauna, high proportion of the west equatorial faunal component (climatic curve), and lighter $\delta^{18}O$ values, or climatic warming. (No isotope data are available for the lower part of the early Miocene at Sites 289 and 77B). Incursions of the east equatorial faunal component generally correlate with heavier $\delta^{18}O$ values, or climatic cooling. Exceptions to this correlation are one point in the faunal climatic curve at 15.9 Ma and two points in the $\delta^{18}O$ curve at 12.3 Ma and 12.4 Ma that correlate with heavier $\delta^{18}O$ values indicating cooling, not warm-




SURFACE: 1 Globigerinoides, 2 D. altispira, 3 Gl.siakensis-Gl. mayeri, 4 Gl. kugleri, 5 G. angustiumbilicata

INTERMEDIATE: 1 Gl. menardii-Gl. tumida, 2 Gl. peripheroronda-Gl. fohsi, 3 Gq. dehiscens, 4 Gl. continuosa-Gl. acostaensis, 5 G. nepenthes-G. druryi

DEEP: 1 Gq. venezuelana, 2 Catapsydrax

Figure 8. Planktonic foraminiferal fauna of Site 77B grouped into surface, intermediate, and deep water dwellers, benthic oxygen isotope curve of Savin et al. (1981), and faunal climatic curve based on east-west provincialism in surface dwellers in the early and late early Miocene, and based on surface dwellers versus *Globorotalia menardii* in the late Miocene. The time scale is after Berggren et al. (in press) and ages for faunal climatic events have been extrapolated from sediment rate curves. Solid lines in early and middle Miocene mark correlation between high percent surface dwellers and high percent eastern faunal component, dashed lines correlate low percent surface dwellers with high western faunal components indicating global cooling and warming respectively. Late Miocene gray intervals show correlation between low percent surface dwellers and high percent *Gl menardii* assumed to indicate polar cooling. Zig-zag lines mark hiatuses.

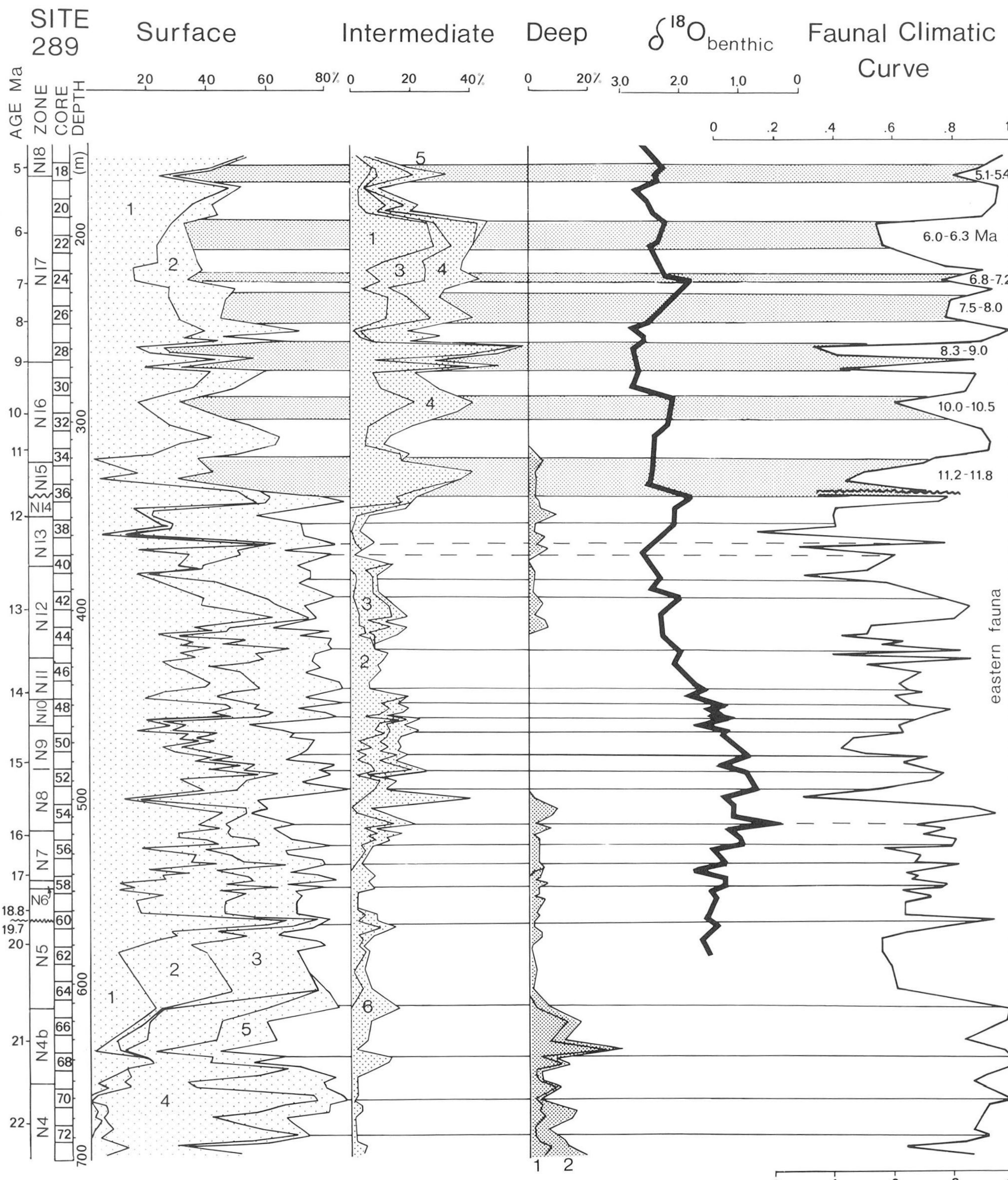



Figure 9. Planktonic foraminiferal fauna of Site 289 grouped into surface, intermediate, and deep water dwellers, benthic oxygen isotope curve of Woodruff et al. (1981), and faunal climatic curve. Solid lines in early and middle Miocene show correlation between high peaks in surface dwellers, high peaks in western faunal components, and polar warming as indicated by light $\delta^{18}O$ values. For complete explanation see Figure 8 caption.

ing (dashed lines, Figure 9). Nevertheless, this excellent correlation indicates that in the west equatorial Pacific high percent abundance in the surface group and dominance of the west equatorial fauna record warm climatic events.

The polar cooling trend observed in the $\delta^{18}O$ curve between 16 and 13 Ma (Woodruff et al., 1981) is not reflected in the surface group (Figure 9), except for an increase in the cooler intermediate group. This suggests that overall surface conditions in the west equatorial Pacific remained warm. There is, however, a slight increase in the eastern faunal component at Site 289 at this time suggesting intensified circulation and equatorial upwelling, as would be expected during periods of polar cooling and ice build-up.

Figure 10 illustrates the early and middle Miocene benthic isotope record and faunal climatic curve at Site 289. Cool climatic phases predicted from the faunal curve and benthic isotope data are shaded. In the faunal climatic curve, cooling episodes are identified by incursions of the eastern faunal component into the west equatorial Pacific, presumably due to intensified equatorial current circulation. Ages for cooling events have been calculated from sediment accumulation curves based on datum levels of planktonic foraminifers, nannofossils, diatoms, and radiolarians tied to the revised time scale of Berggren et al. (in press; also see Barron et al. 1985).

In the east equatorial Pacific Site 77B there is a good correlation between high abundance peaks in the surface group and high proportion of the eastern faunal component (solid lines, Figure 8), and low abundance of surface dwellers with incursions of the western faunal component (dashed lines, Figure 8).

However, there is only a general correspondence between faunal fluctuations and the benthic isotope curve (Savin et al. 1981; 1985). The disparity is partly due to fewer data points and because the benthic isotope values record bottom water temperatures. No continuous isotope record of planktonic foraminifers is available at this time. Nevertheless, there appears to be a general correlation between heavier isotope values, or cooling, and increased eastern faunal component. By analogy with the west equatorial Pacific Site 289, it is assumed that the high eastern faunal component indicates climatic cooling, whereas incursions of the western faunal component at Site 77B indicate climatic warming.

The warm western faunal component generally increases in Site 77B between 16 and 13 Ma, correlating with the polar cooling trend (Figure 8). This suggests that at the time of middle Miocene high latitude cooling, there is climatic warming of surface waters in the equatorial Pacific. Planktonic isotope data of the time-slice intervals corroborate this observation (Savin et al. 1985). Similar observations based on $\delta^{18}O$ data have been made by earlier workers (Savin et al. 1975; Shackleton and Kennett 1975).

### *Late Miocene*

During the late Miocene the faunal differences between the east and west equatorial Pacific disappeared (Figures 8 and 9) along with the extinction of the surface *Globorotalia siakensis–Gl. mayeri* group and the *Gl. fohsi* group of the intermediate water dwellers. No significant new surface dwelling species evolved to replace the *Gl. siakensis–Gl. mayeri* group. The western surface dwellers (primarily *Globigerinoides* spp.) established themselves in the east equatorial Pacific instead (Figure 8). A major expansion occurred in the intermediate group with the evolution of the *Globorotalia menardii–Gl. tumida* groups. The expansion appears to be associated with the high salinity, high density Equatorial Countercurrent, and the more temperate *Globigerina nepenthes–G. druryi* group. In addition, *Gl. acostaensis* evolved from the early and middle Miocene *Gl continuosa.* The deep water group remained an insignificant part of the faunal assemblage in Site 77B (<10%) and is nearly absent in Site 289.

A reciprocal relationship exists between warm surface water dwellers (S) and the cooler intermediate dweller *Gl. menardii–Gl. tumida* group (Im) and this relationship S/S+Im has been used to

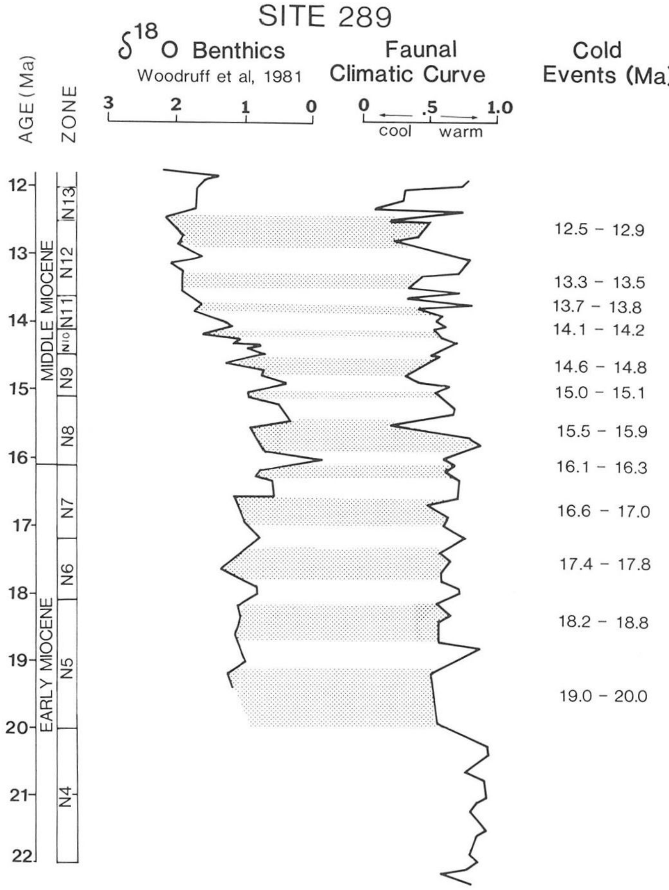



Figure 10. Early and middle Miocene benthic oxygen isotope curve and faunal climatic curve based on east-west faunal provincialism at Site 289, plotted against time. Time scale of Berggren et al. (in press) and Barron et al. (1985). Dotted intervals mark cold events observed in both benthic $\delta^{18}O$ data and the faunal climatic curve (incursions of eastern faunal component). Ages of cold events extrapolated from sediment accumulation curve.

develop the late Miocene faunal climatic curve (Figures 8 and 9). Early and middle Miocene correlations between abundance peaks in the surface group and light $\delta^{18}O$ values have indicated that the surface group expands during climatic warming. I assume here that the *Gl. menardii–Gl. tumida* group expands during polar cooling phases. Based on this assumption, cooling phases are identified in Site 289 at 11.2–11.8 Ma, and 10.0–10.5 Ma; sediments of these intervals are removed by a hiatus in Site 77B. The Site 289 cool event at 8.3–9.0 Ma is present in Site 77B at about 8.1–8.9 Ma; cool events 7.5–8.0 Ma and 6.8–7.2 Ma appear to be combined into one cooling phase between 6.8–7.6 Ma in Site 77B. Latest Miocene cool events are present in Site 289 at 6.0–6.3 Ma and in Site 77B at 5.8–6.2 Ma, whereas the cool event at 5.1–5.4 Ma is not present in Site 77B, probably due to a short hiatus. However, there is only a general correlation between inferred faunal cooling phases and the benthic isotope curve, and no time-series isotope data are available for planktonic foraminifers at this time. Isotope analyses of planktonic foraminifers will be necessary to corroborate the cooling phases predicted from faunal data.

## PALEOCLIMATIC IMPLICATIONS

Most of the faunal parameters discussed, the major evolutionary assemblage changes, and the increasing vertical and latitudinal stratification between early, middle, and late Miocene as well as east-west equatorial provincialism can be explained by paleoclimatic and paleoceanographic changes. Both oxygen isotope studies (Shackleton and Kennett 1975; Savin et al. 1975, 1985) and faunal climatic indices indicate a successive warming in the equatorial Pacific between early, middle, and late Miocene that correlates with increased polar cooling and hence resulted in increased thermal gradients between equator and poles. Many of the faunal assemblage changes appear to be related to these paleoclimatic fluctuations. For instance, the major faunal change in the early Miocene surface and deep water groups at about 21 Ma that marks the extinction of the late Oligocene fauna (e.g. *Gl kugleri, Catapsydrax* spp.) and evolution of the Neogene fauna may be linked to both a major cooling phase and the development of a deep circum-Antarctic circulation (Kennett et al. 1975; Keller 1981a). East-west faunal provincialism during the early and late early Miocene may be due to intensified equatorial surface circulation during polar cooling (transport of eastern fauna westward) and more sluggish surface circulation during warm events. The most significant faunal change during the middle Miocene is the evolution of the *Globorotalia fohsi* group, an intermediate dwelling species group that indicates increased stratification of the water column in the tropics. This group became extinct at the end of the middle Miocene and was replaced by the late Miocene *Globorotalia menardii* group which appears to prefer high salinity water.

Equatorial warming continued into the late Miocene, as indicated by the increased abundance of surface dwellers in the east equatorial Pacific and abundance of the intermediate water *Gl. menardii–Gl. tumida* group. However, the abrupt faunal change between middle and late Miocene, the disappearance of significant east-west provincialism, and most of all, the evolution and dominance of the intermediate water group are difficult to explain by paleoclimatic changes alone. These faunal changes are interpreted to reflect the development or strengthening of the Equatorial Countercurrent system during the middle Miocene when the Indonesian Seaway effectively closed, and the general strengthening of the gyral circulation that resulted from increased Antarctic glaciation at that time (see also Kennett et al. 1985).

## SUMMARY AND CONCLUSIONS

Planktonic foraminifers have been grouped into surface, intermediate, and deep dwellers based on oxygen isotope ranking of individual species. This depth ranking should be considered as preliminary because (a) relatively few oxygen isotope analyses have been done on individual species and unusual values due to diagenesis and dissolution often can not be recognized and (b) the depth habitat of planktonic foraminifers is still not well understood in modern assemblages.

The Miocene depth stratification inferred from oxygen isotope ranking of species has been compared with Pacific GEOSECS water-mass profiles and a consistent relationship is observed between temperature and the faunal groups. The distribution of the surface group (lightest oxygen isotope values) corresponds to water temperatures greater than 20°C, the distribution of the upper intermediate group (intermediate oxygen isotope values) corresponds to water temperatures between 10°–20°C, and the distribution of the lower intermediate and deep water groups (heavy oxygen isotope values) correspond to waters cooler than 10°C. However, since modern ocean temperature profiles are compared with late Miocene faunal assemblages the actual temperature values are suspect. Quantitative faunal analyses of Recent assemblages will be necessary to corroborate these observations. Nonetheless, the consistent correlation of these temperatures with the depth ranked faunal groups makes depth stratification of species a potentially useful tool in paleoceanographic interpretations.

Miocene depth stratification of species indicates increasing vertical as well as latitudinal stratification between the early, middle, and late Miocene. The increasing latitudinal stratification is well known from the geographic distribution of several microfossil groups (foraminifers, diatoms, nannofossils) and lends support to the isotopic depth ranking of species. The vertical water-mass stratification information provides a potentially new tool to study changes in the surface waters (0–500 m). This study indicates that the early Miocene equatorial Pacific has a dominant surface water group and very minor deep and intermediate water groups. During the middle Miocene a significant upper intermediate water fauna develops and during the late Miocene the upper intermediate group expands and dominates the faunal assemblages during warm climatic intervals whereas surface dwellers dominate during cool events. Hence, the Miocene surface ocean evolved from a relatively simple, uniform, warm early Miocene ocean dominated by isotopically light species (surface) to a more stratified middle Miocene ocean with the development of an intermediate surface water layer (represented by isotopically heavier species), and to a complex stratified late Miocene ocean with a decreasing warm surface layer and increasing intermediate layer.

Depth stratification of species has been applied to two time-series analyses of Miocene sequences in the east and west equatorial Pacific (Sites 289 and 77B). These time-series analyses show the dominance of the surface group during the early and middle Miocene and their decline during the late middle Miocene (extinction of *Globorotalia siakensis*) and increase in the intermediate group (evolution of *Globorotalia menardii-Gl. tumida* group). A distinct east-west faunal provincialism is apparent in the surface water group during the early and middle Miocene with the *Globigerinoides* group dominant in the western region and the *Gl. siakensis-Gl. mayeri* dominant in the eastern region. During the late Miocene this provincialism disappears. This provincialism is interpreted as the result of intensified equatorial surface circulation during polar cooling phases and more sluggish circulation during warm events. The disappearance of the provincialism during the late middle Miocene and development of the upper intermediate faunal group may be associated with the major Antarctic glaciation and resultant strengthening of the general gyral circulation and the strengthening of the Equatorial Countercurrent due to the closing of the Indonesian Seaway at that time.

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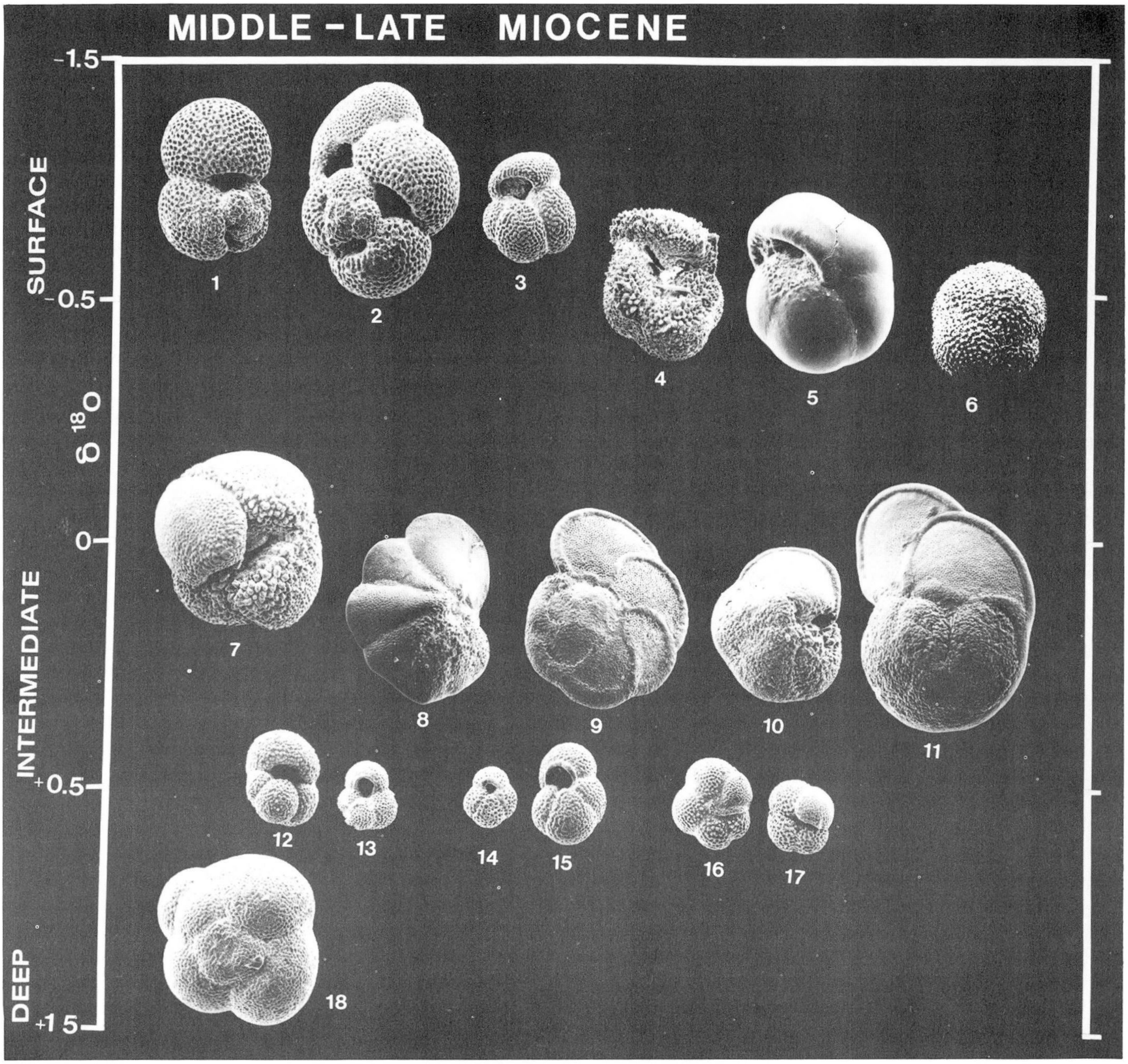


Plate I. Isotopic ranking of middle to late Miocene planktonic foraminifers illustrated in relation to general low latitude $\delta^{18}O$ values. All species are illustrated at the same magnification to show relative size differences. Key to taxa: Surface: (1) *Globigerinoides trilobus;* (2) *G. sacculifer;* (3) *G. obliquus;* (4) *Globoquadrina altispira;* (5) *Pulleniatina primalis;* (6) *Orbulina.* Intermediate: (7) *Globoquadrina dehiscens;* (8) *Globorotalia fohsi;* (9) *Gl. menardii;* (10) *Gl conomiozea;* (11) *Gl. tumida;* (12) *Globigerina bulloides;* (13) *G. woodi;* (14) *G. druryi;* (15) *G. nepenthes;* (16) *Gl. acostaensis.* Deep: (17) *Globoquadrina venezuelana.*

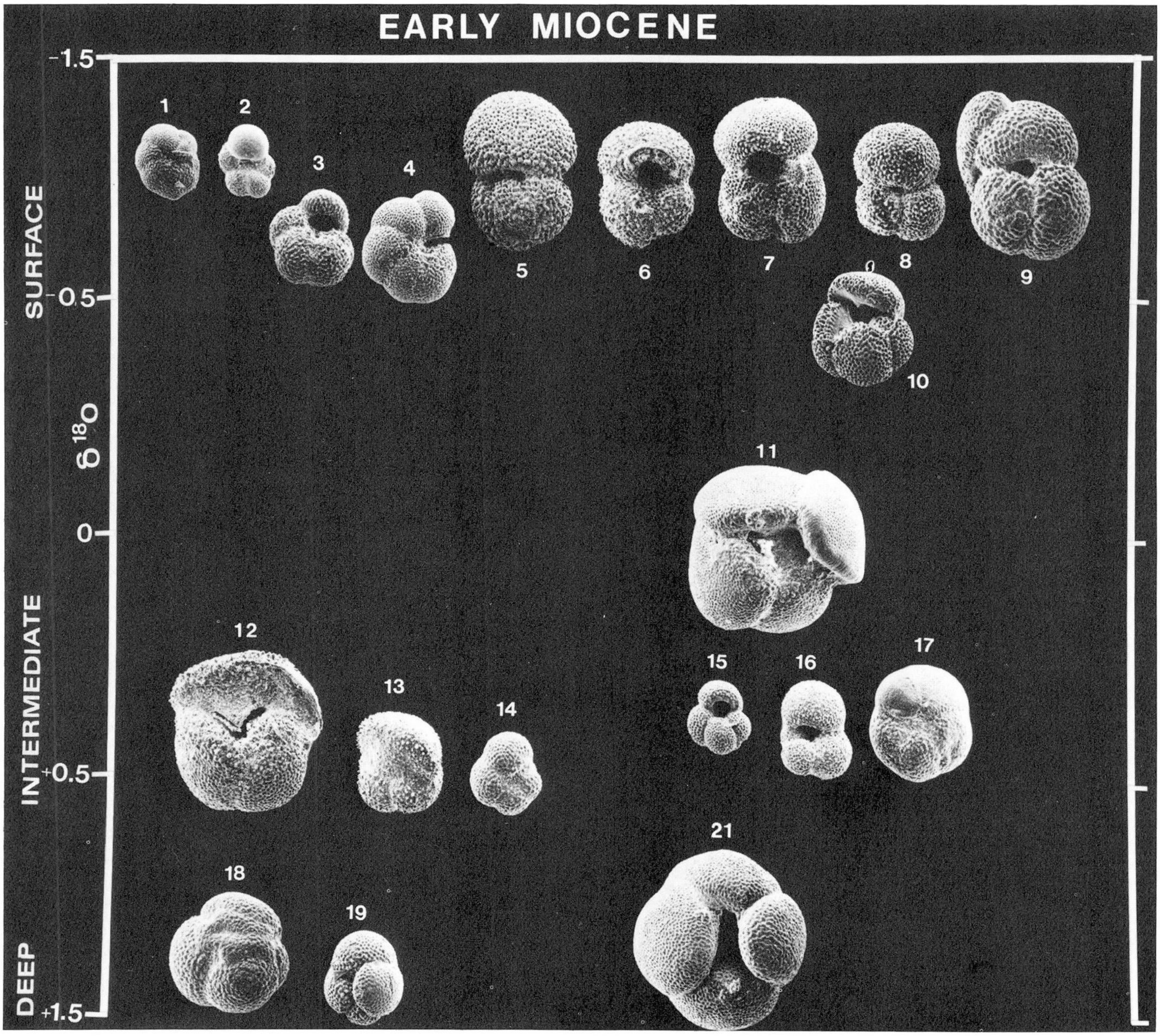


Plate II. Isotopic ranking of early Miocene planktonic foraminifers illustrated in relation to general low latitude $\delta^{18}$ values. All species are illustrated at the same magnification to show relative size differences. Key to taxa: Surface: (1) *Globorotalia kugleri;* (2) *Globigerina angustiumbilicata;* (3) *G. ciperoensis;* (4) *Gl. siakensis;* (5) *Globigerinoides trilobus;* (6) *G. subquadratus;* (7) *G. altiaperturus;* (8) *Globigerinoides parawoodi;* (9) *G. sacculifer;* (10) *Globoqudrina altispira.* Intermediate: (11) *Globoquadrina dehiscens;* (12) *Gq. praedehiscens;* (13) *Globigerina binaiensis;* (14) *Globorotalia continuosa;* (15) *Globigerina woodi;* (16) *G. bulloides praebulloides;* (17) *Gl miozea.* Deep: (18) *Catapsydrax dissimilis;* (19) *C. unicava;* (20) *Globoquadrina tripartita;* (21) *Gq. venezuelana.*

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