Neogene planktonic foraminiferal biogeography and paleoceanography of the Indian Ocean

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ABSTRACT: Indian Ocean planktonic foraminiferal biogeography has been examined for 5 Neogene time-slices and used to reconstruct surface circulation patterns. The major changes in biogeographic patterns were associated with regional tectonic and global climatic events. The closure of the Indo-Pacific passage at the end of the early Miocene strengthened low-latitude circulation in the Indian Ocean and led to the development of distinct tropical and subtropical faunal provinces. Global climatic cooling during the middle and late Miocene resulted in steeper latitudinal temperature gradients and enhanced faunal provincialization. Planktonic foraminiferal distributions indicate the presence of an Agulhas Current, Subtropical Convergence and seasonal monsoon system by the late Miocene. A polar faunal province is first recognized in the Indian Ocean by the late Pliocene and attributed to further high-latitude cooling.

INTRODUCTION

The modern distribution of planktonic foraminifera has been extensively studied using plankton tow, surface sediment and sediment trap data, and the results of such studies have greatly improved our understanding of the ecology of planktonic foraminifera (Bé and Tolderlund 1971; Tolderlund and Bé 1971; Bé, 1977; Bé and Hutson 1977; Fairbanks and Wiebe 1980; Fairbanks et al. 1980, 1982; Thunell and Reynolds 1984). Of particular importance to paleoceanographers is the relationship between planktonic foraminiferal distributions and water mass properties, such as temperature, salinity and nutrient content. Previous studies by Thunell and Belyea (1982) in the Atlantic and Kennett et al. (1985) in the Pacific have documented how the geographic distribution of different planktonic foraminiferal assemblages responded to the major global climatic changes of the Neogene.

The purpose of this study is to evaluate the response of the Indian Ocean planktonic foraminifera to global and regional changes in climate and oceanography during the Neogene. The regional setting of the Indian Ocean provides a unique environment to monitor these biogeographic responses. The continental configuration around the Indian Ocean has a greater effect on surface circulation than the configuration around the other oceans. The presence of a seasonally reversing monsoon system, a tropical surface water connection with the Pacific Ocean, the relative absence of an eastern boundary current, and the virtual lack of a Northern Hemisphere circulation system all provide potential differences in Neogene surface circulation patterns between the Indian Ocean and the Atlantic and Pacific Oceans. As a result, the biogeographic changes in planktonic foraminifera during this time period in the Indian Ocean may exhibit a regional as well as a global signal.

PREVIOUS WORK

Biogeographic studies of the Tertiary oceans have delineated the temporal and spatial distribution patterns of various mi-

crofossil groups (Haq 1980; Sancetta 1978, 1979; Berggren 1981; Thunell and Belyea 1982; Kennett et al. 1985). Using the present day biogeographic provinces and their associated faunas, inferences can be made about the biogeographic significance of fossil assemblages. Two assumptions are generally made in such studies. First, surface water temperature is the primary factor controlling the latitudinal distribution of the various groups of plankton. Second, a constant ecologic preference is assumed for each of the taxa (Haq and Lohmann 1976). The latter assumption implies that observed migrations were due to oceanographic changes and not changes in the ecological preferences of a taxon.

Cenozoic global oceanographic and climatic changes have been summarized by Kennett (1977) and Berger et al. (1981). The development of a psychrospheric ocean near the Eocene/Oligocene boundary set in motion climatic processes which continue to affect the present oceans (Kennett and Shackleton 1976). Opening of the Drake Passage in the late Oligocene allowed unrestricted circum-polar circulation and thermal isolation of Antarctica (Kennett 1977). Low-latitude circum-global circulation was disrupted by the closing of the Indo-Pacific passage (Hamilton 1979; Kennett et al. 1985) and the Paratethys (Hsu 1977; Rogl and Steininger 1984) at the end of the early Miocene and by the uplift of the isthmus of Panama in the middle Pliocene (Keigwin 1978). Neogene climates further deteriorated with high-latitude cooling accompanied by an expansion of the Antarctic ice sheet in the middle Miocene culminating in the late Miocene (Shackleton and Kennett 1975a; Savin 1977; Woodruff et al. 1981; Miller and Fairbanks 1983; Hodell and Kennett 1986). Early Pliocene climates were marked by a return to warmer marine conditions (Kennett 1977; Keigwin 1979). The final major Neogene climatic event occurred with the major phase of Northern Hemisphere ice growth in the late Pliocene (Berggren 1972; Shackleton and Kennett 1975b; Shackleton and Opdyke 1977; Keigwin 1979; Thunell and Williams 1983; Shackleton et al. 1984).

Neogene planktonic foraminiferal patterns in the world's oceans have been synthesized by Berggren (1981) utilizing the results of the first 50 legs of the Deep Sea Drilling Project. The study of Berggren (1981) clearly indicates that there has

been an increase in latitudinal provincialization of planktonic foraminifera throughout the Neogene. In addition to illustrating the biogeographical distributions of important taxa, Berggren (1981) discusses the development of key Neogene lineages and the diachrony associated with these taxa in each of the major oceans.

Tertiary Atlantic Ocean biogeography has been the subject of several studies. Haq and Lohmann (1976) used calcareous nannoplankton to characterize early Cenozoic floral biogeographic patterns. This was supplemented by a subsequent study of Haq (1980) in which he considered Neogene nannofossil biogeographic distributions. Planktonic foraminiferal biogeographic patterns have also been studied by several workers. Boersma and Premoli-Silva (1983) examined the Paleocene planktonic foraminiferal biogeography of the Atlantic. Neogene planktonic foraminiferal biogeographic changes in the Atlantic have been documented by Thunell and Belyea (1982), while Hodell and Kennett (1985) considered Miocene changes in the South Atlantic.

Tertiary biogeography of the Pacific Ocean has been examined by Sancetta (1978, 1979) and Kennett et al. (1985), with the biogeographic patterns for the Pacific being quite similar to those observed in the Atlantic. Of particular importance is Kennett's (1978, 1980) demonstration that the development of Southern Ocean biogeography during the late Cenozoic was linked to the establishment of circum-polar circulation.

MATERIALS AND METHODS

Core material from 15 DSDP (Deep Sea Drilling Project) sites (text-fig. 1) was used to reconstruct Neogene planktonic foraminiferal biogeographic provinces for the Indian Ocean. Five time-slices were chosen which represent critical times in the evolution of global Neogene climate (table 1). In addition, the periods selected represent times of net deposition instead of erosion in the oceans (Keller and Barron 1983). The early Miocene time-slice, planktonic foraminiferal Zone N4 of Blow (1969), establishes the biogeography of the Indian Ocean prior to the middle Miocene increase of ice on Antarctica (Shackleton and Kennett 1975a; Savin 1977; Woodruff et al. 1981; Miller and Fairbanks 1983; Kennett et al. 1985). The middle and late Miocene time-slices document changes in the biogeographic patterns of the Indian Ocean after the middle Miocene (Zone N14) increase of the Antarctic ice cap and its continued growth through the late Miocene (Zone N17) (Shackleton and Kennett 1975a; Savin et al. 1975; Savin 1977; Woodruff et al. 1981; Miller and Fairbanks 1983). The Pliocene time-slices, Zones N19 and N21, continue the transition into the "glacial" world with the Northern Hemisphere ice growth in the late Pliocene (Berggren 1972; Shackleton and Opdyke 1977; Keigwin 1979; Thunell and Williams 1983; Shackleton et al. 1984).

Samples were dried at 50°C, soaked in a warm dispersant and washed through a 63 μm sieve. The >63 μm fraction was reweighed and dry sieved using a 150 μm screen. The larger size fraction was split into aliquots of approximately 300 planktonic foraminiferal specimens using a microsplitter and all individuals were identified and counted.

At least three samples were counted per site for each time-slice. The faunal counts for each time-slice were then averaged for each site to dampen possible anomalies and provide a representative fauna (Lohmann and Carlson 1981). Species abundances were plotted for each time-slice using calculated paleopositions (text-fig. 1 and table 2) (Sclater et al. 1977).

Core coverage in the Indian Ocean decreases back through the Neogene (table 1). The late Miocene and early and late Pliocene time-slices each have very good coverage represented by 14, 13, and 15 sites, respectively. Middle Miocene coverage is adequate with 10 sites, while good core material is available for only 7 early Miocene sites. The sites used in the study are all located above the lysocline and foraminiferal tests are well preserved. As a result, the observed distributions of planktonic foraminifera have not been significantly affected by dissolution.

STRATIGRAPHY

The early Miocene time-slice, Zone N4 (Blow 1969), was defined by the presence of *Globorotalia kugleri* (Bolli 1957) and *Globigerinoides primordius* (Blow and Banner 1962) and given the approximate age of 23 Ma (Berggren et al. 1985). *Globoquadrina dehiscens* (Chapman, Parr and Collins 1934) was also used to constrain this time-slice to the later part of Zone N4 to avoid the glacial period associated with the early part of this zone (Miller and Fairbanks 1983). The high-latitude biostratigraphy (Sites 254 and 281) is much less certain since the zonal scheme used is based on low-latitude taxa.

The middle Miocene time-slice, Zone N14 (Blow 1969), was identified by the presence of both *Globigerina nepenthes* (Todd 1957) and *Globorotalia mayeri* (Cushman and Ellisor 1939) /*siakensis* (LeRoy 1939). This zone is given the approximate age of 11 Ma following Berggren et al. (1985). Calcareous nannofossil stratigraphy from Roth (1974) was used for Site 231 because planktonic foraminiferal biostratigraphy was inadequate for this time-slice.

The late Miocene time-slice, Zone N17 (Blow 1969), was distinguished by the presence of *Globorotalia plesiotumida* (Blow and Banner 1962). The early part of this zone was selected in an attempt to avoid the Messinian salinity crisis. Taxa used to narrow this time-slice were *Globorotalia conoidea* (Walters 1965) and the absence of *Globorotalia conomiozea* (Kennett 1966) which evolved in the mid to latter part of Zone N17 (Blow 1969).

The early Pliocene time-slice, Zone N19 (Blow 1969), was defined by the presence of both *Globorotalia puncticulata* (Deshayes 1832) and *Globorotalia margaritae* (Bolli and Bermudez 1965). The approximate age for this time slice is 4.0 Ma (Berggren et al. 1985).

The presence of *Globorotalia inflata* (d'Orbigny 1839) and *Globorotalia tosaensis* (Takayanagi and Saito 1962) were used to delineate the late Pliocene time-slice, Zone N21. Based on these two taxa, the late Pliocene time-slice is centered around 2.4 Ma (Berggren et al. 1985).
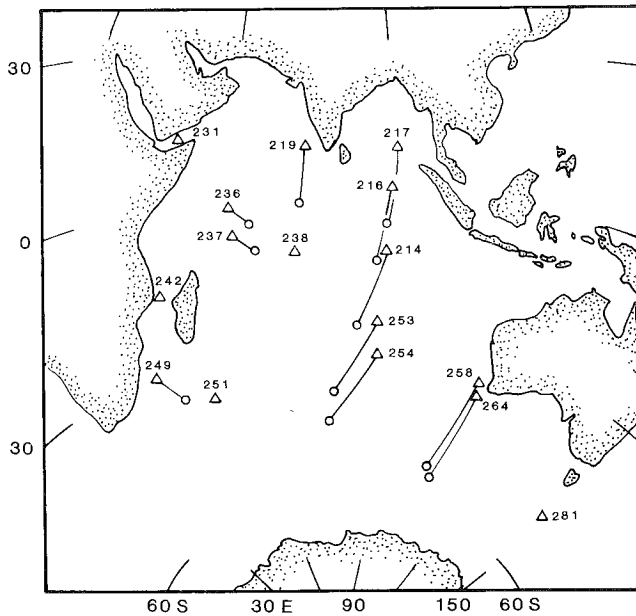
TEXT-FIGURE 1
Backtrack curves for the past 36 million years for the DSDP sites used in this study. Circles represent the paleolocations of the sites at 36 Ma, as reconstructed by Sclater et al. (1977). Triangles indicate the present day locations of the sites.

MODERN INDIAN OCEAN

Surface Circulation Patterns

According to Wyrtki (1973), surface water circulation in the Indian Ocean can be divided into three major components: *1)* the reversing monsoonal gyre, *2)* the Southern Hemispheric anticyclonic subtropical gyre, and *3)* the Antarctic waters.

The reversing monsoonal gyre alternates between the weaker NE monsoon which occurs from November through April, and the SW monsoon which develops in May and continues through October with stronger and deeper currents. The NE monsoonal circulation consists of the westward flowing NEC (North Equatorial Current), a southward flow off the coast of Somalia, and the Equatorial Counter Current (ECC) (text-fig. 2a). At the eastern end of the counter current only some of the water is recycled into the monsoonal gyre with the SEC (South Equatorial Current) and the Java Coastal Current receiving the largest portion of the counter current.

During the SW monsoon the circulation of the northern Indian Ocean gyre reverses (text-fig. 2b). This gyre consists of the northern part of the SEC, the northward flowing Somali Current, and the expanded counter current or SWMC (Southwest Monsoon Current). Net surface circulation in the northern Indian Ocean is to the east at this time. The stronger currents associated with this gyre allow the development of seasonal upwelling off the coasts of the Arabian Peninsula, Somalia and western India.

The anticyclonic flow of the subtropical gyre is similar to that of the subtropical gyres present in other oceans. The main components of this gyre are the SEC, the AC (Agulhas Current) and the part of the WWD (West Wind Drift) which is north of the STC (Subtropical Convergence) (text-fig. 2a). The subtropical gyre is separated from the monsoonal gyre by a hydrochemical front along 10°S. A distinct salinity minimum exists at this latitude, particularly in the subsurface waters from Timor to Madagascar. As the subtropical circulation turns to the south, the AC develops along the African coast and carries warm subtropical water into the Agulhas Retroflection (Gordon 1985). This current turns back on itself and flows to the east along the STC. The lack of a well-developed eastern boundary current distinguishes the Indian subtropical gyre from the other major ocean gyres.

The Antarctic waters of the Indian Ocean are similar to those of the Atlantic and Pacific Oceans. Two important features of the circulation in this region are the surfacing of the thermocline between 40 and 50°S and the Circum-Polar Current (text-fig. 2a). The Antarctic waters are bounded by the STC (40°S) and Antarctica. Two distinguishing characteristics of Antarctic surface waters are low salinities created by excessive precipitation and ice melting, and cold temperatures. The inclination of the boundary between the subtropical waters and the Antarctic waters is very steep creating a strong geostrophic flow (Wyrtki 1973). This flow coupled with the prevailing west winds cause the water to form an eastward current.

### Surface Temperature Distributions

Surface temperature distributions in the modern Indian Ocean reflect the amount of solar heat absorbed by the ocean and

TABLE 1
Time-slices and DSDP sites used in this study.

Time-Slice	Age* (Ma)	Bio-stratigraphic Zone	Sites
Early Miocene	23.7–21.8	N4	214, 216, 217, 238, 253, 254, 281
Middle Miocene	11.3–10.5	N14	214, 216, 217, 231, 237, 238, 251A, 253, 254, 281
Late Miocene	7.1–5.3	N17	214, 216, 219, 231, 237, 238, 242, 249, 251A, 253, 254, 258A, 264, 281
Early Pliocene	5.0–3.0	N19	214, 216, 217, 219, 231, 237, 238, 242, 249, 253, 254, 264, 281
Late Pliocene	3.0–1.8	N21	214, 216, 217, 219, 231, 237, 238, 242, 249, 251A, 253, 254, 258A, 264, 281

*Ages taken from Berggren et al. (1985)
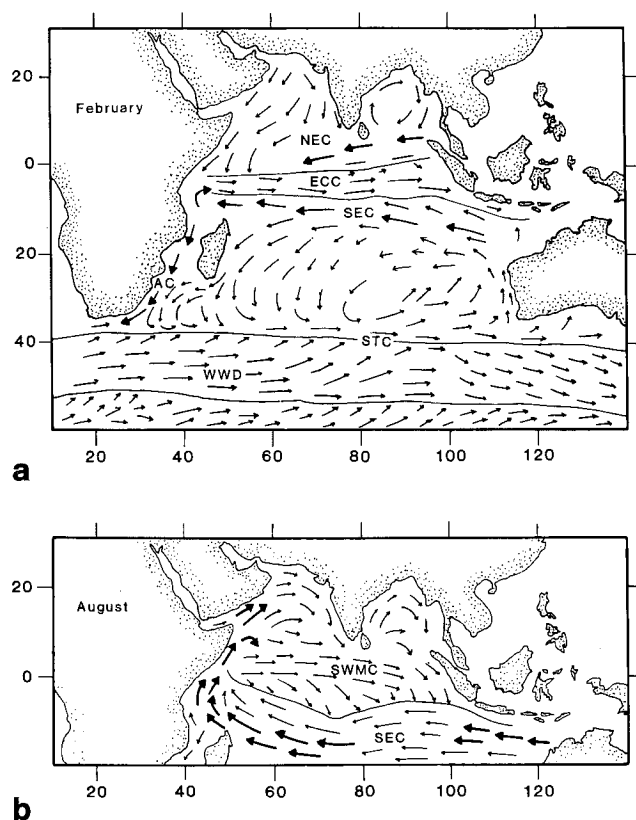
TEXT-FIGURE 2
Modern surface circulation patterns in the Indian Ocean during February (northeast monsoon) and August (southwest monsoon) (modified from Bé and Hutson (1977) and Cullen and Prell (1984)).

its subsequent distribution by surface water circulation (text-fig. 3). The equatorial region (20°N to 20°S) is characterized by very warm surface waters (26–28°C during the summer months and 23–28°C in the winter), and is strongly influenced by the monsoonal system. The subtropical area, 20°S to 35°S, is marked by a gradual decrease in surface water temperatures from 26°C to 20°C in the summer and 23°C to 18°C in the winter. There is a sharp increase in the surface thermal gradient between 35°S and 50°S, with a 13°C drop in temperature to 7°C and 5°C in the summer and winter, respectively. The STC, which is the boundary between the subtropical gyre and the Antarctic waters, is positioned within this steep temperature gradient. During the summer, the 0°C isotherm is located south of 60°S, while in the winter the 0°C isotherm migrates to approximately 55°S. Thus, seasonal changes in Indian Ocean surface water temperatures are primarily the result of winter migration of the Polar Front which is the hydrographic boundary between the subantarctic and Antarctic surface waters and the seasonally changing monsoonal system. Equatorial areas show very little seasonal change in temperature. In contrast, the polar-subpolar regions undergo strong season changes in surface water temperature

Modern Biogeography

Bé and Hutson (1977) used both plankton tow and surface sediment samples to map the distributions of Recent plank-

tonic foraminifera in the Indian Ocean. The subsequent study of Cullen and Prell (1984) on northern Indian Ocean surface sediments elaborated on the earlier work of Bé and Hutson (1977). The results of Bé and Hutson (1977) clearly show that planktonic foraminifera are latitudinally distributed in the Indian Ocean. These faunal distributions reflect the physical and chemical properties of the various Indian Ocean surface water masses.

Bé and Hutson (1977) were able to identify five planktonic foraminiferal assemblages using surface sediment material (text-fig. 4 and table 3). The polar/subpolar province (S1) is associated with the Antarctic surface waters. Characteristic planktonic foraminifera in this province include *Neogloboquadrina pachyderma* (Ehrenberg 1861), *Globigerina bulloides* (d'Orbigny 1826) and *Globigerina quinqueloba* (Natland 1938) (table 3). The transitional province (S2) separates the warmer and cooler surface waters and is found immediately north and south of the STC. The faunal assemblage found within this province is characterized by *Globorotalia inflata* and *Globorotalia truncatulinoides* (d'Orbigny 1839) with co-occurring species associated with the warmer and cooler water masses (table 3).

The assemblage associated with the subtropical gyre (S3) is dominated by *Globigerinoides ruber* (d'Orbigny 1839), with significant abundances of *Globigerinita glutinata* (Egger 1893), *Globigerinoides sacculifer* (Brady 1877), *Globigerinella aequilateralis* (Brady 1879) and *Globigerina rubescens* (Hofker 1956) (table 3). In the equatorial regions of the Indian Ocean, the tropical assemblage (S4) is found as a mixture of warm-water species (table 3), the most notable of which are *Globorotalia menardii* (Parker, Jones and Brady 1865), *Gs. sacculifer*, *Neogloboquadrina dutertrei* (d'Orbigny 1839), *Pulleniatina obliquiloculata* (Parker and Jones 1865) and *Globorotalia tumida* (Brady 1877).

An interesting assemblage found by Bé and Hutson (1977) is the tropical-subtropical boundary current assemblage (S5).

TABLE 2
Paleolatitudes of the DSDP sites for each of the Neogene time-slices.

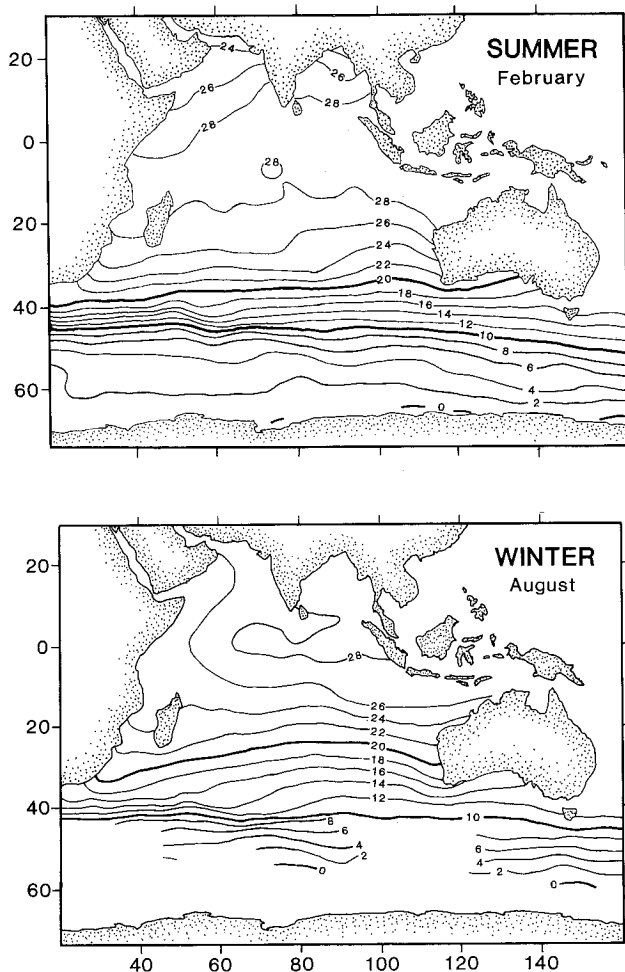| Site	Present Water Depth (m)	Longitude	Late Pliocene	Early-Pliocene	Late Miocene	Middle Miocene	Early Miocene
214	1665	88.7°E	12°S	13°S	14°S	17°S	20°S
216	2247	90.2°E	1°N	0°	1°S	4°S	8°S
217	3020	90.5°E	8°N	7°N		3°N	0°
219	1764	72.9°E	8°N	8°N	7°N		
231	2161	48.3°E	12°N	11°N	11°N	10°N	
237	1640	58.1°E	7°S	8°S	8°S	9°S	
238	2844	70.5°E	11°S	12°S	12°S	13°S	14°S
242	2275	41.8°E	16°S	16°S	17°S		
249	2088	36.1°E	30°S	30°S	31°S		
251	3489	49.5°E	37°S		37°S	38°S	
253	1962	87.4°E	26°S	26°S	27°S	30°S	32°S
254	1253	87.9°E	32°S	32°S	33°S	35°S	38°S
258	2793	112.5°E	35°S		36°S		
264	2873	112.1°E	36°S	37°S	38°S		
281	1601	147.8°E	49°S	51°S	52°S	56°S	61°S

This assemblage is dominated by *Ga. glutinata, Gr. menardii* and *G. bulloides,* the last two being strongly affiliated with warm- and cold-water masses, respectively. This boundary current assemblage is found in areas having large seasonal temperature fluctuations (e.g. the upwelling region in the northwest Indian Ocean and the area associated with the Agulhas Retroflection).

RESULTS

Individual species of planktonic foraminifera have been grouped into assemblages based on their abundance distributions (e.g. tropical bioprovince, subtropical bioprovince, transitional bioprovince, subpolar bioprovince and polar bioprovince), although the exact paleotemperature limits of each are not well known. Each of these assemblages characterizes a biogeographic province. The more important species comprising each of the assemblages for each of the time-slices are listed in table 3.
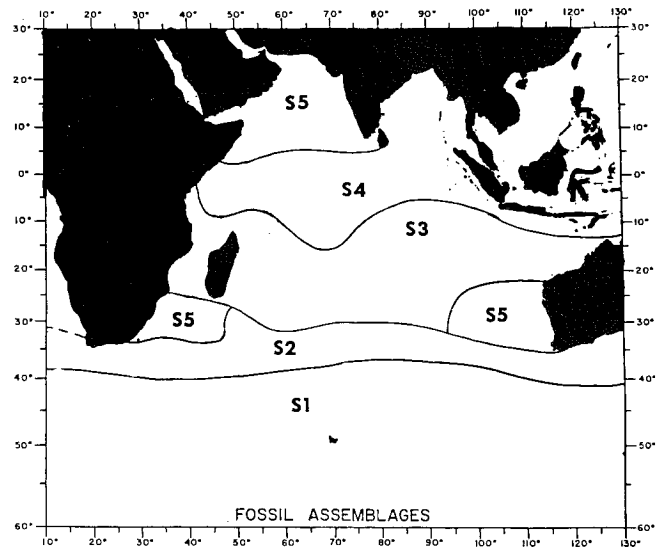
Early Miocene (23 Ma)

The early Miocene (Zone N4) planktonic foraminiferal distributions in the Indian Ocean (text-fig. 5) suggest the pres-

TEXT-FIGURE 4
Modern day Indian Ocean planktonic foraminiferal provinces determined by Bé and Hutson (1977) based on surface sediment data. S1: polar-subpolar province; S2: transitional province; S3: tropical-subtropical province; S4: tropical province; S5: tropical-subtropical boundary current province.

TEXT-FIGURE 3
Summer and winter sea surface temperature distributions for the Indian Ocean (NOAA Oceanography Report 1984, 1985).

ence of three bioprovinces. These provinces are designated as tropical, subtropical and transitional-subpolar (table 3).

The tropical province included DSDP Sites 216 and 217 which have paleolatitudes of 0 and 8°S, respectively. Two of the most abundant species of planktonic foraminifera associated with these sites were *Globigerina angustiumbilicata* (Bolli 1957) and *Globorotalia mayeri/siakensis* (text-fig. 5). Other species which show distinct equatorial or tropical distributions are *Globorotalia bella* (Jenkins 1967) and *Globoquadrina praedehiscens* (Blow and Banner 1962). These five species account for over 50% of the planktonic foraminiferal assemblage at these two sites. Also found in this province in moderate abundances (~5%) was *Globorotaloides suteri* (Bolli 1957).

Sites 214 and 238 are located within the early Miocene subtropical province at paleolatitudes of 23°S and 14°S, respectively. Although not a true subtropical province as in the modern oceans, this province served to separate the low- and high-latitude faunas. The most characteristic species of this province were *Globorotalia kugleri* and *Gt. suteri* (text-fig. 5). The transitional nature of this province resulted in the inclusion of species indigenous to other provinces. For example, *Gr. mayeri/siakensis, G. angustiumbilicata, Gr. bella* and *Globigerinita glutinata* were relatively common at Sites 214 and 238, but were more abundant in either the low- or high-latitude provinces.

The remaining sites, Sites 253, 254 and 281, which were south of the 30°S paleolatitude, were within the transitional-subpolar province. High abundances (>20%) of *Ga. glutinata, Globigerina praebulloides* (Blow 1959) and *Globigerina woodi* (Jenkins 1960) distinguished the high-latitude

TABLE 3
Dominant planktonic foraminiferal species in each biogeographic province during the Neogene.

Epoch	Age Zone	Tropical	Subtropical	Transitional	Subpolar/Polar
Early Miocene	23 Ma N4	G. angustiumbilicata* Gr. mayeri/siakensis* Gr. bella* Gt. suteri	G. kugleri Gt. suteri* G. mayeri/siakensis G. angustiumbilicata G. bella Ga. glutinata	Ga. glutinata* G. praebulloides G. woodi G. angustiumbilicata	
Middle Miocene	11 Ma N14	Gr. mayeri/siakensis Globoquadrina spp. Ss. seminulina Gr. continuosa Globigerinoides spp.	Globigerinoides spp.* Ss. seminulina* Ga. glutinata G. woodi	Gr. conoidea* Ss. disjuncta G. praebulloides Ga. glutinata	Ga. glutinata* G. bulloides Gr. conoidea G. woodi*
Late Miocene	7 Ma N17	Gr. menardii Gr. plesiotumida Globoquadrina spp. N. acostaensis Globigerinoides spp.*	Ss. seminulina* O. universa Globigerinoides spp. G. woodi Ga. glutinata	Gr. conoidea Ss. seminulina Ga. glutinata G. bulloides/falconensis G. woodi	G. bulloides/falconensis* N. pachyderma G. woodi Ga. glutinata
Early Pliocene	4.0 Ma N19	Gr. menardii Gr. tumida Globigerinoides spp. N. acostaensis* N. humerosa	Globigerinoides spp.* Ss. seminulina Ga. glutinata N. acostaensis G. woodi	Gr. puncticulata* Gr. crassaformis* G. bulloides/falconensis N. pachyderma G. woodi Ga. glutinata	G. bulloides/falconensis* N. pachyderma* G. woodi Ga. glutinata Gr. crassaformis Gr. puncticulata
Late Pliocene	2.4 Ma N21	Gr. menardii Gr. tumida N. humerosa N. dutertrei Globigerinoides spp.	Globigerinoides spp.* O. universa G. woodi	Gr. inflata* Gr. crassaformis* Ga. glutinata G. woodi	G. bulloides/falconensis N. pachyderma G. woodi Gr. inflata Ga. glutinata
Recent**		Gr. menardii N. dutertrei Gs. sacculifer Pu. obliquiloculata Gr. tumida Ga. aequilateralis	Gs. ruber Gs. conglobatus Ga. glutinata G. rubescens Gs. sacculifer Ga. aequilateralis	Gr. inflata Gr. truncatulinoides	N. pachyderma G. bulloides G. quinqueloba

*For species occurring in more than one province, the asterisk indicates the province in which the species is most abundant.
**After Bé and Hutson (1977).

province from the warm-water provinces. Moderate abundances of warm-water species such as *Gr. mayeri/siakensis* and *G. angustiumbilicata* were also found in this province.

Middle Miocene (11 Ma)

The middle Miocene (Zone N14) planktonic foraminiferal distributions in the Indian Ocean suggest the existence of four biogeographic provinces. The groupings are identified as the tropical, subtropical, transitional and subpolar provinces (table 3). Representative species distributions for each of these provinces (text-fig. 6) delineate the bioprovince boundaries.

The tropical province included Sites 216, 217, 237 and 238, and extended from approximately 10°N to 10°S. The planktonic foraminifera which dominated these populations were *Gr. mayeri/siakensis* and *Globoquadrina* spp. (*Gq. altispira* (Cushman and Jarvis 1936), *Gq. venezuelana* (Hedberg 1937) and *Gq. baroemoenensis* (LeRoy 1939)) (text-fig. 6). Another characteristic of this province was the low abundance of *Ga.*

glutinata (<5%). Other species with moderate abundances in this province were *Sphaeroidinellopsis seminulina* (Schwager 1866), *Globigerinoides* spp. and *Globorotalia continuosa* (Blow 1959).

The subtropical province included Sites 214, 231 and 238, at paleolatitudes of 18°S, 9°N, and 13°S, respectively. *Globigerinoides* spp. (*Gs. obliquus* (Bolli 1957), *Gs. quadrilobatus* (d'Orbigny 1846), and *Gs. triloba* (Reuss 1850)) and *Ss. seminulina* were the key faunal elements in this province. The low abundances of tropical species, such as *Gr. mayeri* and *Gr. siakensis,* in this province along with an increase in *Ga. glutinata* and *G. woodi* (>10%) were additional characteristics of the subtropical faunal assemblage. This province was positioned between 10°S and 30°S.

Sites 251, 253 and 254 lay within the middle Miocene transitional province. *Globorotalia conoidea* was indigenous to the transitional province (text-fig. 6), while high frequencies of *Sphaeroidinellopsis disjuncta* (Finlay 1940) and *G. praebulloides* were also associated with this province. Several
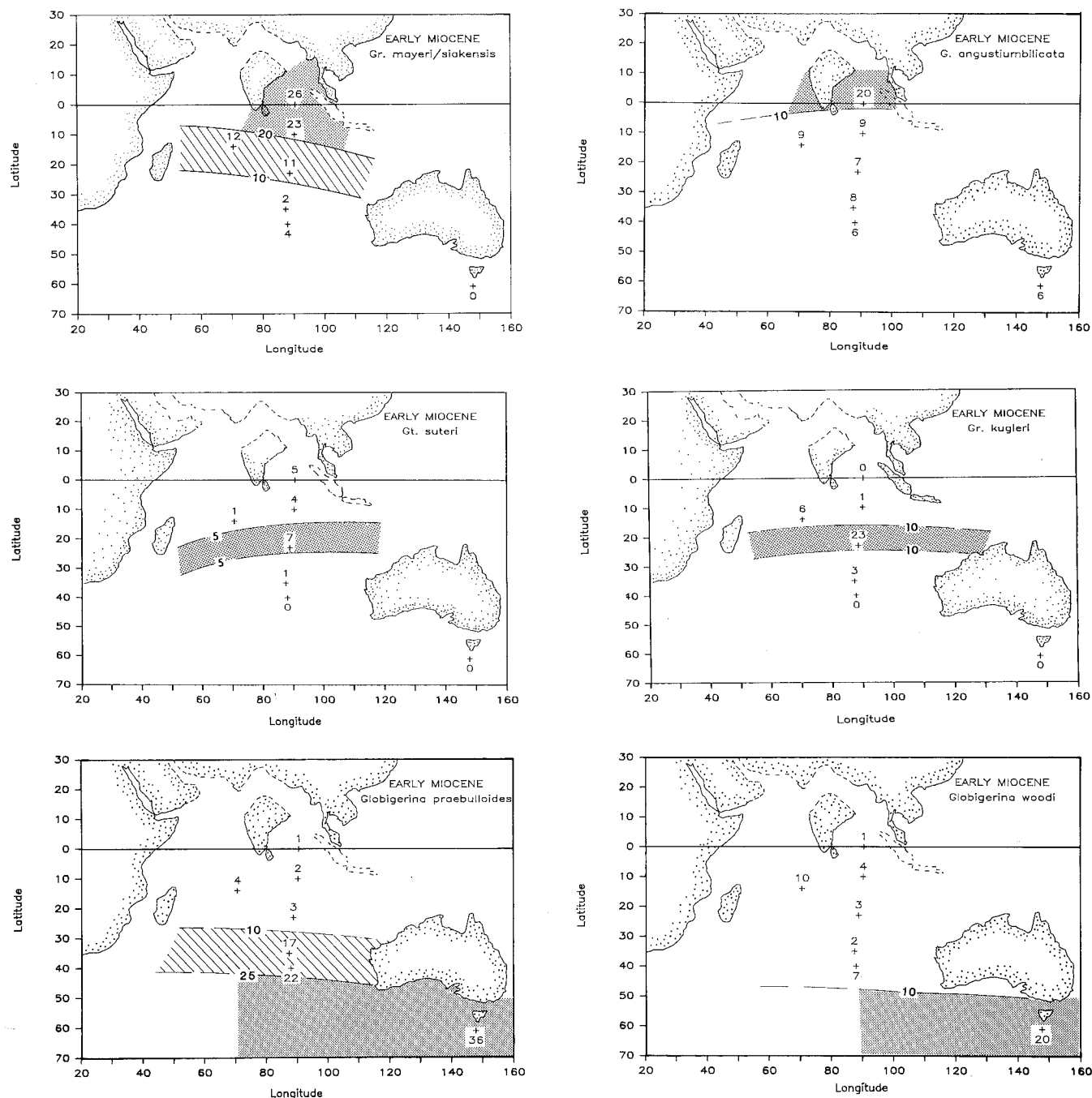
TEXT-FIGURE 5
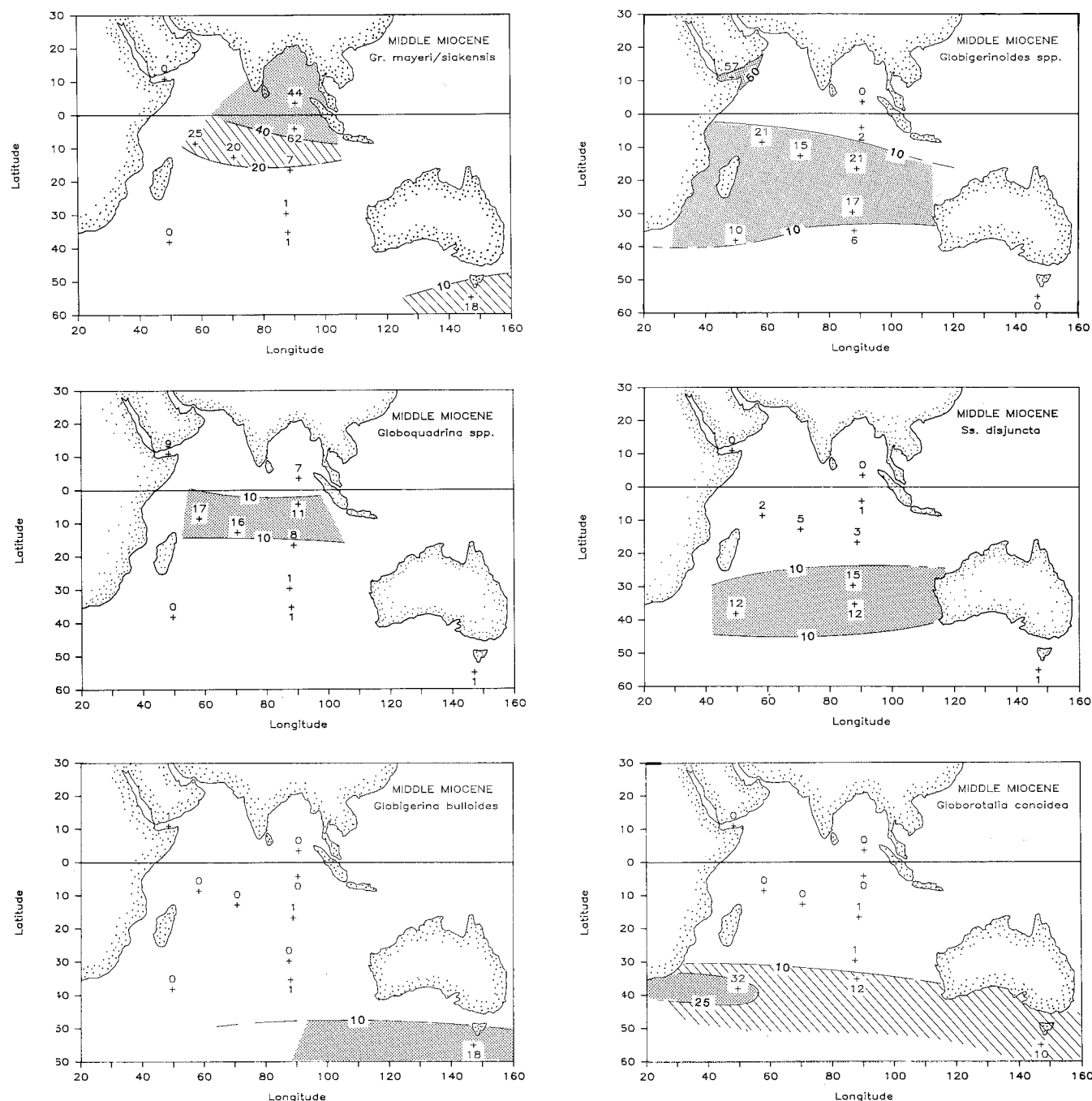Abundance distributions of selected planktonic foraminifera during the early Miocene (23 Ma).

other species from both warmer and colder biogeographic provinces were found co-occurring in this transitional province, such as *Globigerinoides* spp., *Ga. glutinata* and *G. woodi*. The geographic position of this province extended from about 30°S to 40°S during the middle Miocene.

The middle Miocene subpolar province included the region of the Indian Ocean south of Site 254 including Site 281 (40°S to 56°S). This province was marked by high abundances (>20%) of *Ga. glutinata, Globigerina bulloides* and *G. woodi*.

Globorotalia conoidea was also moderately abundant in the subpolar assemblage. The characteristic that distinguishes this province from the transitional province was the absence of all warm-water species.

Late Miocene (7 Ma)

Four distinct biogeographic provinces can also be recognized in the late Miocene and are identified as tropical, subtropical, transitional and subpolar (table 3) as shown by representative
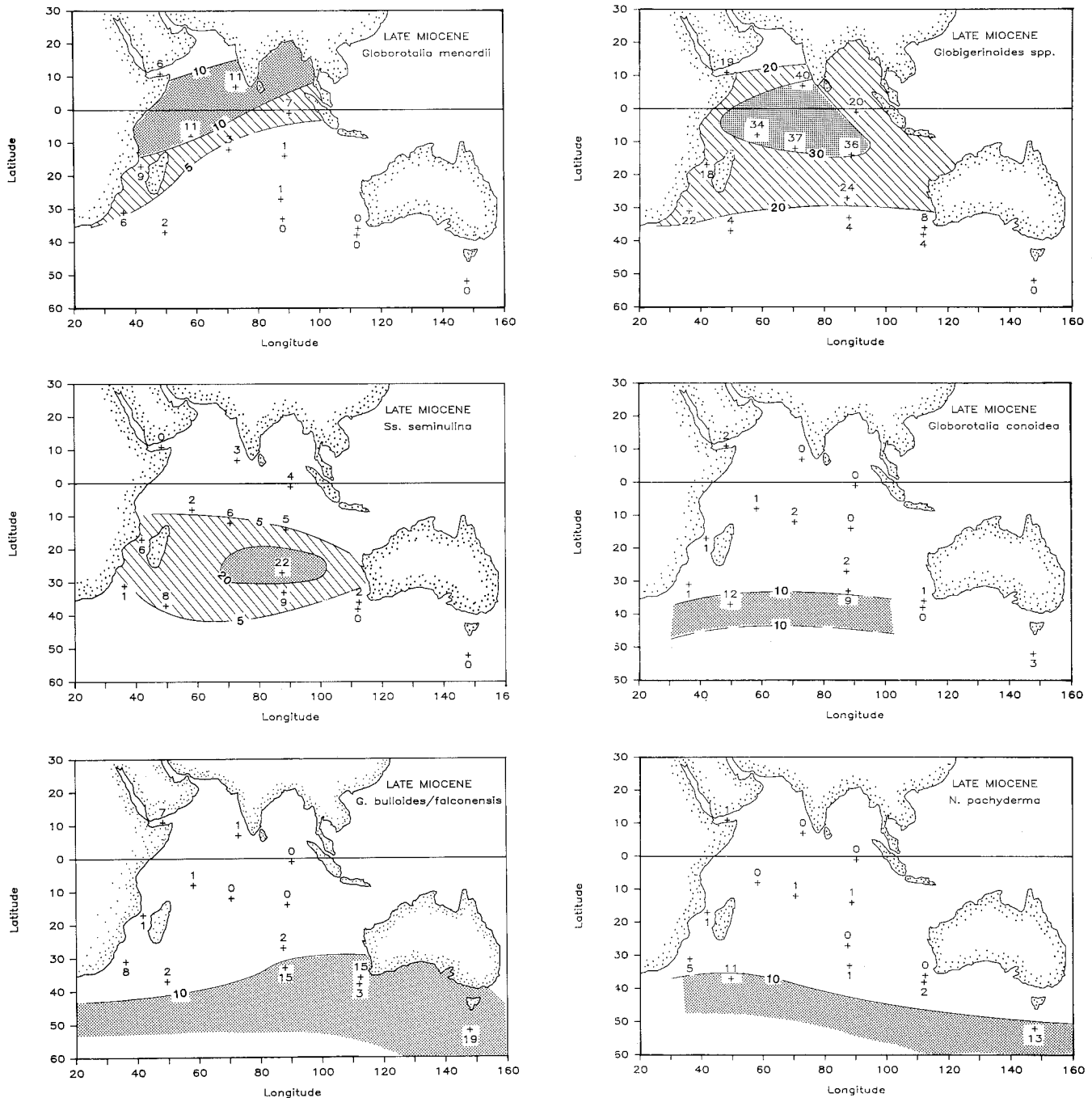
TEXT-FIGURE 6
Abundance distributions of selected planktonic foraminifera during the middle Miocene (11 Ma).

species distributions (text-fig. 7). The tropical province occupied the region including Sites 214, 216, 219, 237, 238 and 231. The late Miocene tropical province was dominated by *Globorotalia menardii, Globorotalia plesiotumida, Globoquadrina* spp. (*Gq. altispira, Gq. venezuelana,* and *Gq. baroemoenensis*) and *Neogloboquadrina acostaensis* (Blow 1959). Our identification of *Gr. menardii* in the late Miocene includes *Globorotalia cultrata* (d'Orbigny 1839) and other menardii-like forms (see Stainforth et al. 1975 for a discus-

sion). The late Miocene tropical province incorporated all of the Indian Ocean north of 15°S. A southern extension of tropical species was also found along the coast of Africa at least to 30°S.

Subtropical species included *Ss. seminulina* and *Orbulina universa* (d'Orbigny 1839) which were found most abundantly at Sites 238, 242, 249, 251 and 253 (text-fig. 7). Subtropical waters in the late Miocene covered the area from
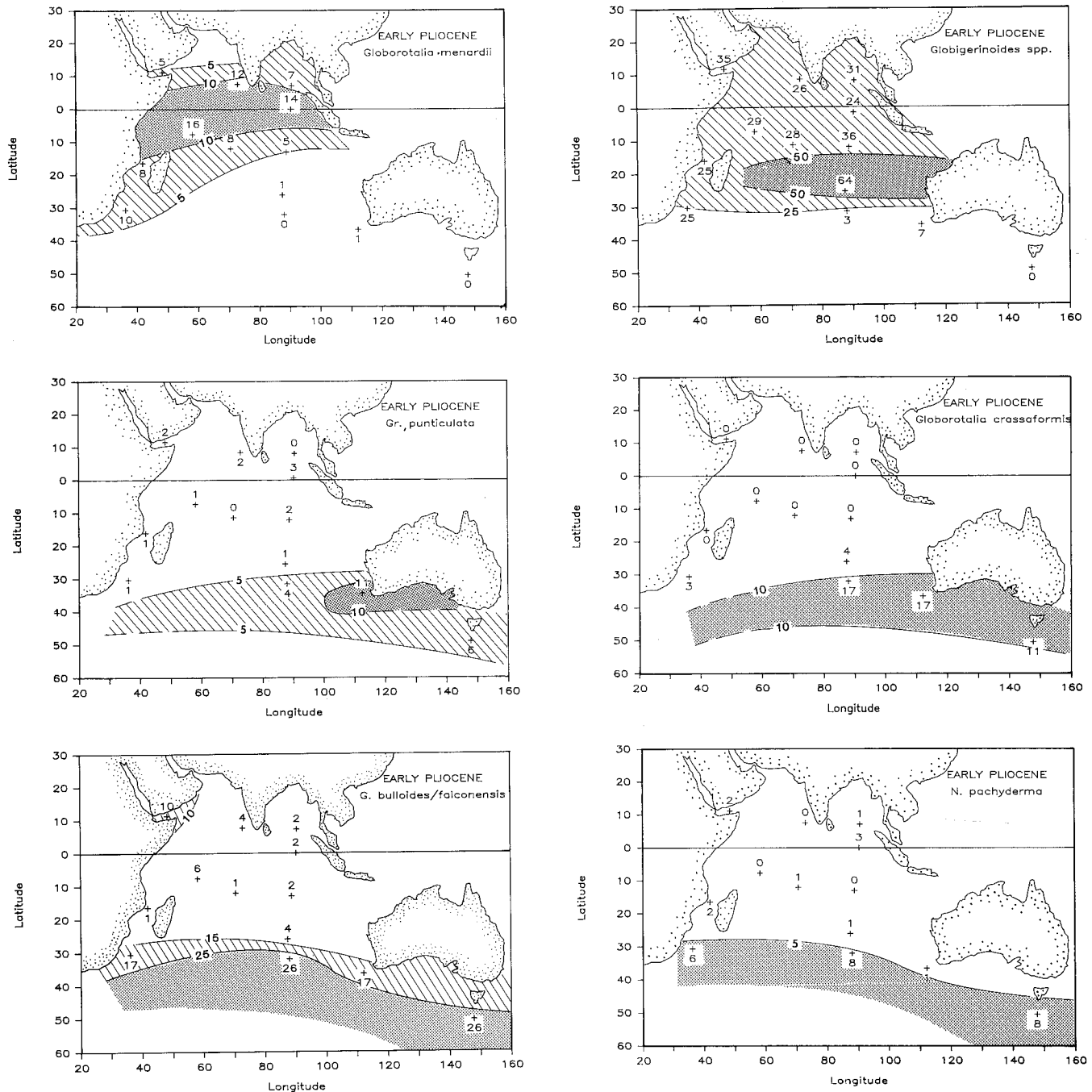
TEXT-FIGURE 7
Abundance distributions of selected planktonic foraminifera during the late Miocene (7 Ma).

approximately 15°S to 35°S. Also occurring in moderate abundances in the subtropical province were *Ga. glutinata* and *G. woodi*. *Globigerinoides* spp. had high frequencies in both tropical and subtropical regions, but seemed to be most abundant between 10°N and 10°S (text-fig. 7).

High abundances of *Gr. conoidea* continued to delineate the transitional province (text-fig. 7). Sites 251, 254 and 264 occupied paleopositions from 33°S to 40°S in the transitional

province during the late Miocene. Other species which were common in this transitional province included *Ss. seminulina, Ga. glutinata, G. bulloides/falconensis* (Blow 1959) and *G. woodi*.

The late Miocene subpolar province lay south of 40°S and included Site 281. Species indigenous to this province were *G. bulloides/falconensis* and *Neogloboquadrina pachyderma* (text-fig. 7). *Globigerinita glutinata* and *G. woodi* exhibited

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TEXT-FIGURE 8
Abundance distributions of selected planktonic foraminifera during the early Pliocene (4.0 Ma).

high abundances in this province but were not diagnostic of this water mass. The distinction of dextral and sinistral *N. pachyderma* is often used to distinguish the subpolar for the polar province (Kennett 1968, 1970). However, it was not until the late Pliocene that abundances of sinistral *N. pachyderma* were sufficient to suggest the possibility of a polar province.

Early Pliocene (4.0 Ma)

Early Pliocene faunal distributions also delineated four biogeographic provinces interpreted to be tropical, subtropical, transitional and subpolar (table 3). The latitudinal positions of these bioprovince boundaries generally migrated to the south from the late Miocene to the early Pliocene. Typical

species distributions for the early Pliocene are illustrated in text-figure 8.

Early Pliocene tropical species were abundant at Sites 214, 216, 217, 219, 231, 237, 238 and 242. The latitudinal range for this assemblage was from 10°N to 15°S. Species with clear tropical preferences were *Gr. menardii, Globorotalia tumida, N. acostaensis* and *Neogloboquadrina humerosa* (Takayanagi and Saito 1962), while *Globigerinoides* spp. (*Gs. obliquus, Gs. ruber, Gs. quadrilobatus, Gs. sacculifer* and *Gs. triloba*) also contributed significantly to the tropical assemblage.

Subtropical assemblages were dominated by *Globigerinoides* spp. (text-fig. 8). These subtropical waters in the early Pliocene occupied the region from about 10°S to 30°S including Sites 214, 238, 242, 249 and 253, along with the region north of 10°N which included Sites 217 and 231. Other species commonly found in this province were *Ss. seminulina, Ga. glutinata* and *G. woodi.*

Globorotalia puncticulata, which evolved in the early Pliocene as part of the *Globorotalia (Globoconella)* lineage, was most abundant in the transitional province (text-fig. 8). Another species indigenous to the transitional province was *Globorotalia crassaformis* (Galloway and Wissler 1927) (text-fig. 8). The position of this province in the early Pliocene was approximately 30°S to 40°S, and encompassed Sites 254 and 264. Co-occurring species included cooler subpolar forms such as *G. bulloides/falconensis, Ga. glutinata, G. woodi* and *N. pachyderma.* Warm-water species were not very abundant in the transitional province during the early Pliocene.

The subpolar province covered the area from 40°S to 55°S in the early Pliocene. Species indigenous to this province were *G. bulloides/falconensis* and *N. pachyderma* (text-fig. 8). Also, contributing to the subpolar assemblage were *G. woodi, Ga. glutinata, Gr. crassaformis* and *Gr. puncticulata.*

Late Pliocene (2.4 Ma)

Five biogeographic provinces were present in the Indian Ocean during the late Pliocene (table 3). In addition to the tropical, subtropical, transitional and subpolar provinces, a polar province was discernable by this time in the southern Indian Ocean (text-fig. 9).

The tropical province occupied all of the Indian Ocean north of 10°S. Indigenous species were similar to those of the early Pliocene tropical assemblage and included *Gr. menardii, Gr. tumida, N. dutertrei* and *N. humerosa. Globigerinoides* spp. also exhibited high abundances in the tropical province.

In the late Pliocene, the subtropical assemblage continued to be dominated by *Globigerinoides* spp. (*Gs. obliquus, Gs. ruber, Gs. triloba, Gs. quadrilobatus* and *Gs. sacculifer*) (text-fig. 9), with *G. woodi* and *O. universa* also occurring in moderate abundances in this province. The latitudinal extent of the subtropical province in the late Pliocene was 10°S to 30°S. Along the coast of Africa the subtropical and tropical provinces were deflected to the south. The tropical fauna extended as far as 20°S, while subtropical species were abundant south of 35°S.

The late Pliocene transitional assemblage was best represented by *Globorotalia inflata* and *Gr. crassaformis* (text-fig.

9). The latitudinal position of this province in the late Pliocene extended from about 35°S to 40°S. Co-occurring species in this province included *Ga. glutinata* and *G. woodi.*

The primary late Pliocene subpolar species were *G. bulloides/falconensis* and dextral *N. pachyderma* (text-fig. 9). Also contributing significantly to this assemblage were *Ga. glutinata* and *Gr. inflata.* The subpolar province was bounded to the north by Sites 251, 254 and 264 and to the south by Site 281 (35°S to 45°S).

The first polar planktonic foraminifera appearing in the Indian Ocean was sinistral *N. pachyderma* (text-fig. 9). The high abundance (44%) of this species at Site 281 was complemented by other cold-water species found in the subpolar and transitional provinces. In the modern oceans, sinistral *N. pachyderma* is primarily confined to the polar bioprovince (Kennett 1968, 1970; Bé and Tolderlund 1971; Bé 1977). This relationship is somewhat less clear for the late Neogene oceans. Keigwin (1982) documented the presence of sinistral *N. pachyderma* in late Miocene Caribbean cores and attributed these occurrences to upwelling at that time. This does not mean that *N. pachyderma* was not a polar species in the late Neogene, but rather that caution must be used in assuming that the polar bioprovinces of the late Neogene had the same exact characteristics as those found in the modern polar water masses.

DISCUSSION

The Neogene was marked by a series of distinct paleoclimatic and paleoceanographic events which profoundly affected biogeographic patterns in all of the oceans. Prior to the Neogene, the thermal structure of the oceans had begun to change with the transformation from a thermospheric to a psychrospheric ocean near the Eocene/Oligocene boundary (Kennett and Shackleton 1976). The temperature regime of the global oceans continued to change with the opening of the Drake Passage and subsequent development of the Circum-Polar Current. Along with enhanced high-latitude circulation, circum-equatorial circulation diminished during the Neogene, first, near the end of the early Miocene with low-latitude separation between the Pacific and Indian Oceans (Hamilton 1979) and closure of the Paratethys (Rogl and Steininger 1984), and secondly with separation of the Atlantic and Pacific Oceans in the middle Pliocene (Keigwin 1978). As a direct result of these changes in the circulation system, high-latitude cooling began which characterized much of the Neogene (Kennett 1977; Kennett and van der Borch 1986). Evolution of this new circulation regime changed gradients in physical and chemical properties of surface water masses, which in turn resulted in reorganization of planktonic foraminiferal bioprovinces.

Early Miocene Biogeography and Surface Circulation

Early Miocene planktonic foraminiferal faunas in the Indian Ocean exhibited gradational rather than sharp biogeographic boundaries due to the small latitudinal thermal gradient of the surface waters at this time (Loutit et al. 1983; Savin et al. 1985). Distributions of *G. angustiumbilicata* and *Gr. mayeri/siakensis* along the Ninetyeast Ridge and at Site 281 il-
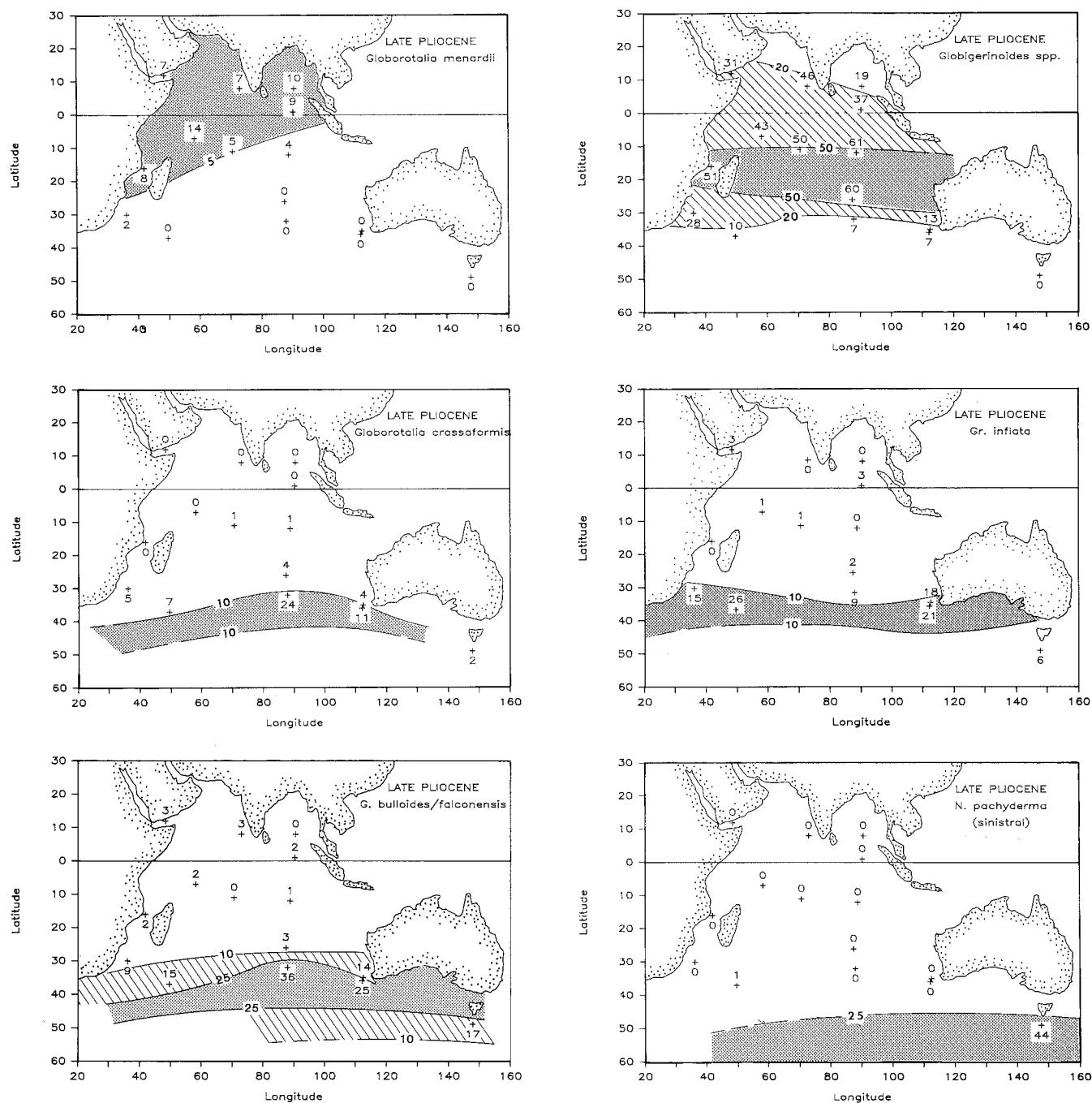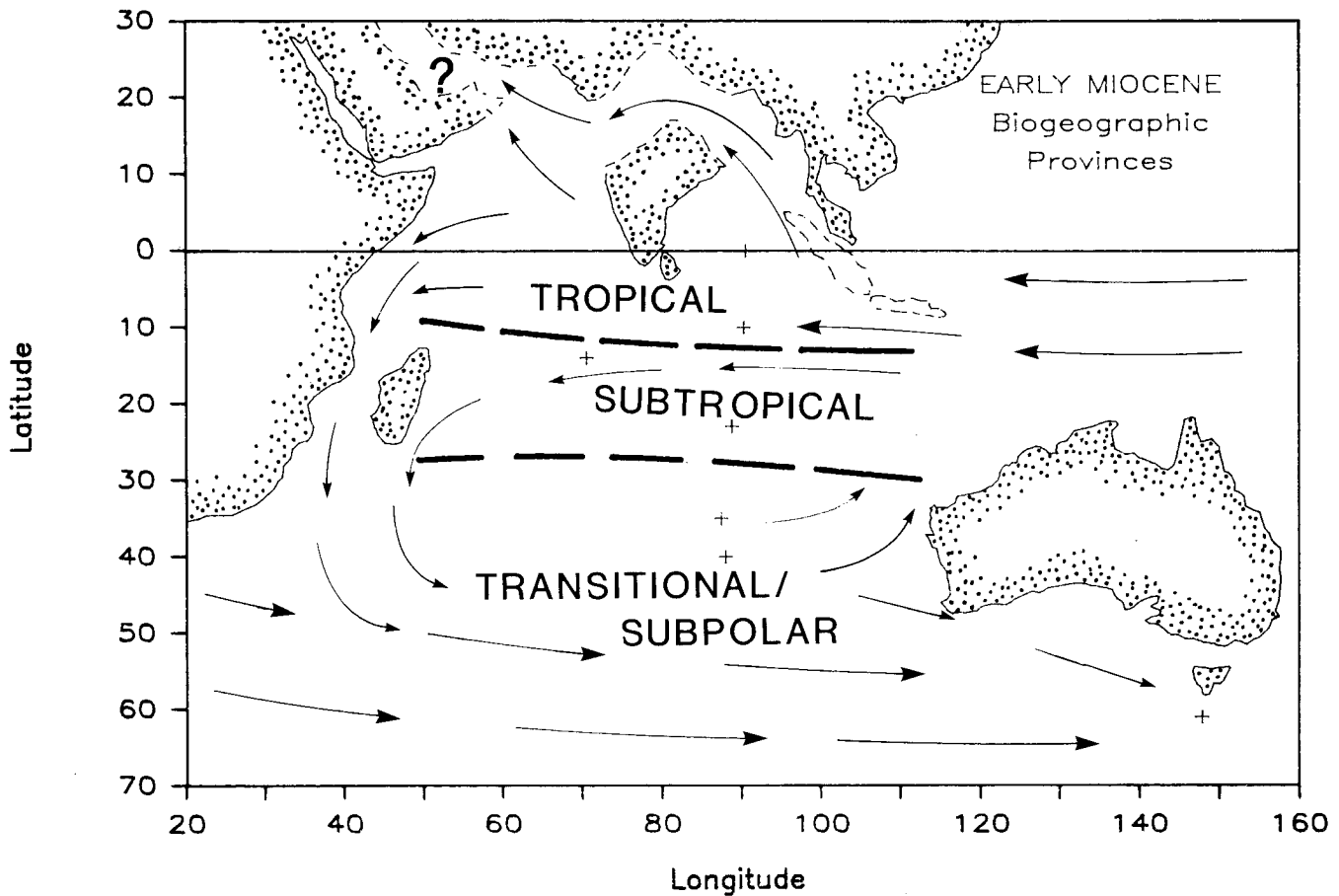
TEXT-FIGURE 9
Abundance distributions of selected planktonic foraminifera during the late Pliocene (2.4 Ma).

lustrate this lack of sharp ecological boundaries in the early Miocene (text-fig. 5). It is clear from the species distributions that *G. angustiumbilicata* and *Gr. mayeri/siakensis* had low-latitude or warm-water preferences (text-fig. 5). However, during the early Miocene warm-water species were also found in high-latitude regions (Site 281 at approximately 60°S). Likewise, species such as *Globigerina praebulloides* and *G. woodi* (text-fig. 5), which prefer colder temperatures, were also present in the low latitudes. As a result, early Miocene

planktonic foraminiferal assemblages commonly contained mixtures of warm- and cold-water species, and we attribute this to the weak latitudinal temperature gradient at this time.

Surface circulation patterns for the early Miocene can only be speculated upon due to the relatively sparse biogeographic data. However, the faunal distributions, along with the plate configuration in the early Miocene, can be used to make some inferences about surface circulation patterns. Planktonic

TEXT-FIGURE 10
Planktonic foraminiferal biogeographic and surface circulation reconstructions for the early Miocene (23 Ma).

foraminiferal distributions suggest that there was little separation between equatorial and subtropical circulation at this time. Early Miocene tropical circulation in the Indian Ocean was part of the low-latitude circum-equatorial flow which began in the Pacific Ocean and continued through the Indian Ocean and possibly into the Mediterranean Sea (Hsu 1977; Rogl and Steininger 1984). Equatorial waters probably flowed into the Mediterranean, while flow along the African coast was probably weak (text-fig. 10).

The absence of a distinct ecologic boundary between the warm- and cold-water provinces in the early Miocene is attributed to a weak latitudinal temperature gradient. The Pacific latitudinal temperature gradient is estimated to have been only 6°C at this time (Loutit et al. 1983). Wind-driven surface circulation was probably much weaker than during the later Neogene due to the weaker latitudinal temperature gradient and weaker atmospheric circulation (Leinen and Heath 1981). This weak circulation in the subtropical regions may also account for the lack of sharp provincial boundaries. Planktonic foraminiferal distributions do not indicate the presence of a STC in the early Miocene. A well-developed circulation gyre in the subtropical region would promote the separation of subtropical water from Antarctic and equatorial waters. In the modern Indian Ocean, the STC serves as a

sharp ecologic boundary for planktonic foraminifera (Bé and Hutson 1977). The lack of an adequate thermal gradient and a weak Circum-Polar Current (relative to the late Neogene) combined to inhibit the development of the STC in the early Miocene.

To maintain the weak latitudinal temperature gradient in the early Miocene, Antarctic surface water must have been significantly warmer than at present or confined to a narrow band around Antarctica. Evidence from the Southern Ocean indicates that subantarctic and Antarctic surface waters in the early Miocene were much warmer than at present with estimated temperatures of 8–11°C (Kennett 1978). In addition to warmer Antarctic waters, the position of the early Miocene Circum-Polar Current was further south as a result of a more southerly position of Australia (approximately 12° south of its present position; text-fig. 12).

Middle Miocene Biogeography and Surface Circulation

Middle Miocene surface water temperature differences between the tropics and the Antarctic region were sufficient to cause increased provincialization of planktonic foraminifera (Loutit et al. 1983). Equatorial warming occurred throughout
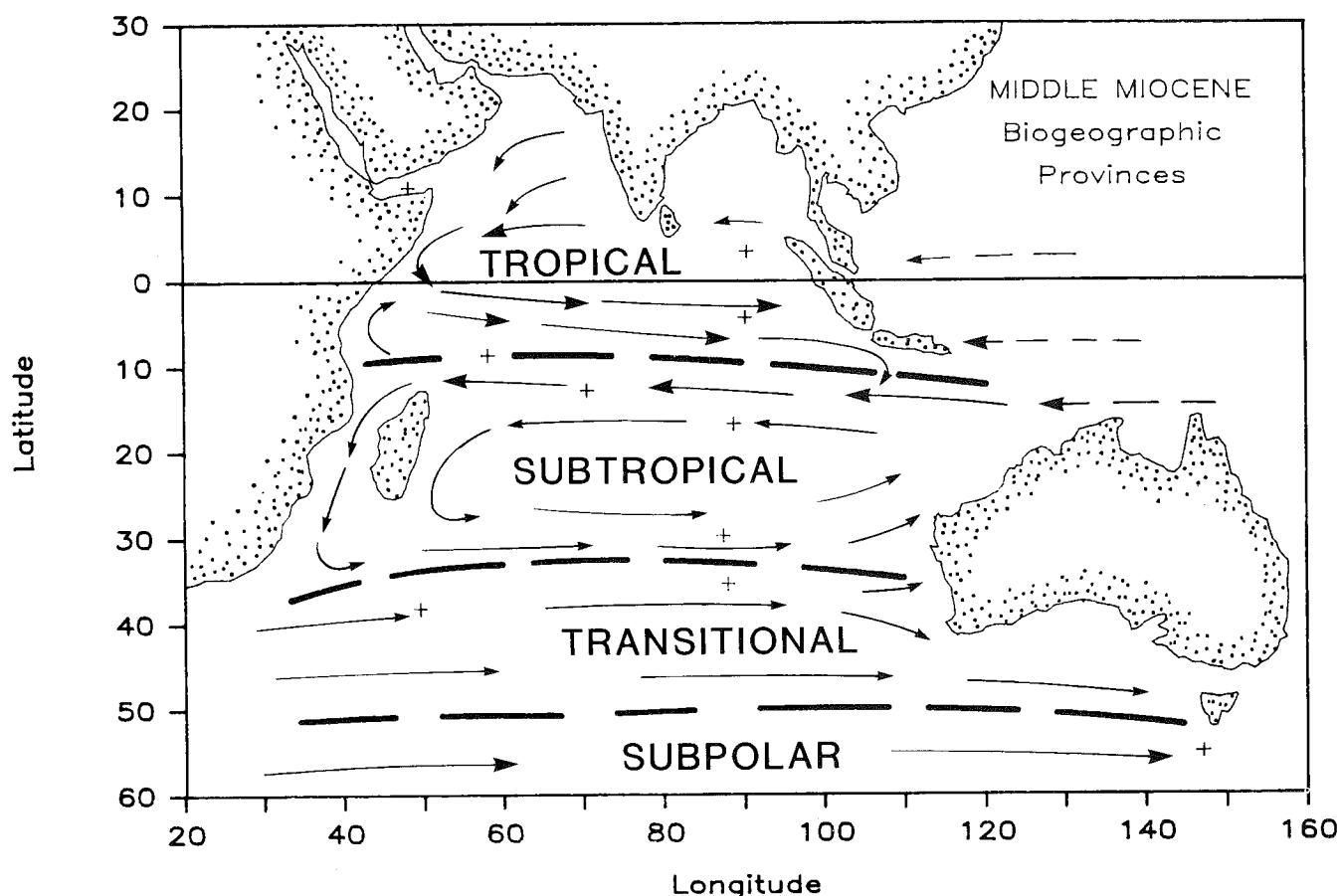
TEXT-FIGURE 11
Planktonic foraminiferal biogeographic and surface circulation reconstructions for the middle Miocene (11 Ma).

most of the Neogene and by the middle Miocene, a well-developed tropical planktonic foraminiferal province existed in the Indian Ocean (text-fig. 11). While tropical surface waters warmed, Antarctic waters cooled (Kennett 1977; Loutit et al. 1983). In contrast to the early Miocene planktonic foraminiferal distributions, middle Miocene high-latitude regions were dominated by cold-water species with only rare occurrences of warm-water forms. Planktonic foraminifera exhibited narrower latitudinal ranges during the middle Miocene due to increased latitudinal temperature differences (text-fig. 6).

The middle Miocene tropical province included all of the northern Indian Ocean to 10°S and was more readily distinguished from the subtropical province than in the early Miocene (text-fig. 11). A sharp decrease in the abundance of tropical species (text-fig. 6; *Gr. mayeri/siakensis* and *Globoquadrina* spp.) delineated the boundary between the middle Miocene tropical and subtropical provinces.

Aside from the decrease in tropical forms, the subtropical province was marked by high abundances of *Globigerinoides* spp. (text-fig. 6). Due to intensified flow of the subtropical gyre, warm surface waters were carried further south in the middle Miocene. The invigorated subtropical circulation, along with high-latitude cooling, resulted in the development

of an ecologic boundary that separated the subtropical and transitional provinces. There was a clear separation of these two provinces in the middle Miocene although this boundary was not as distinct as later in the Neogene. This is interpreted to be the early stage of development of the STC.

The high-latitude region can be subdivided into two middle Miocene bioprovinces (text-fig. 11). During the early Miocene, the high latitudes were dominated by *Ga. glutinata, G. praebulloides* and *G. woodi* (text-fig. 5), but with no differentiation of transitional and subpolar provinces (text-fig. 10). In contrast, the distributions of *Ss. disjuncta, Gr. conoidea* and *G. bulloides* in the middle Miocene (text-fig. 6) allow the identification of distinct transitional and subpolar provinces (text-fig. 11). The middle Miocene evolution of the *Globoconella* lineage was significant in that each species in the lineage was a marker for the transitional province (Kennett and Srinivasan 1983). By 11 Ma (Zone N14), *Gr. conoidea* had evolved as the major representative of this lineage with high abundances at Sites 251, 254 and 281 (text-fig. 6) marking the position of the transitional province.

Globigerina bulloides served as a good indicator for the middle Miocene subpolar province (text-fig. 6), in contrast to its early Miocene ancestor, *G. praebulloides* (text-fig. 5). The presence of a distinct subpolar province reflected the cooling
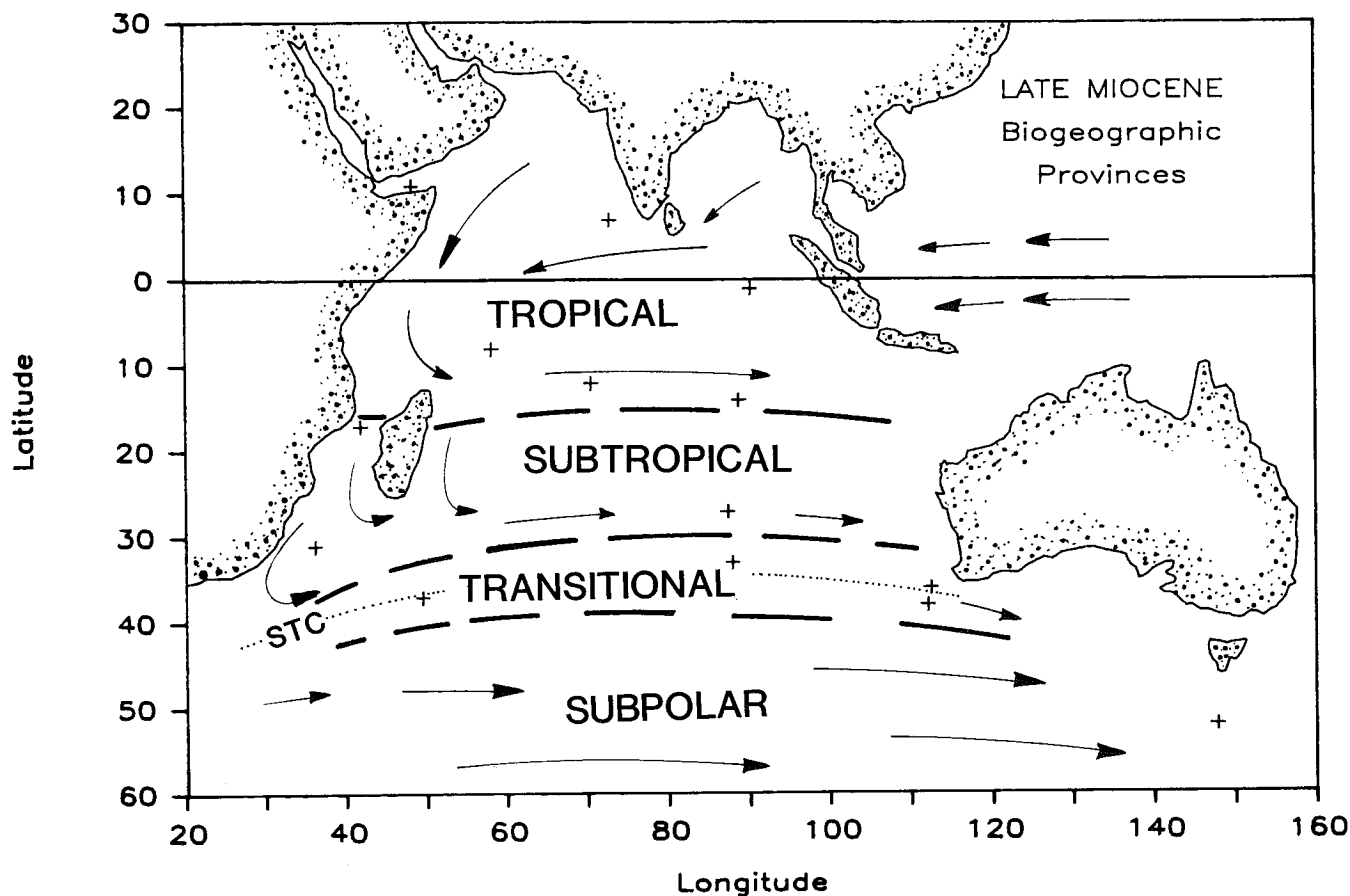
TEXT-FIGURE 12
Planktonic foraminiferal biogeographic and surface circulation reconstructions for the late Miocene (7 Ma).

and northward migration of Antarctic waters and subsequent increase in latitudinal temperature gradients at this time. The well-documented middle Miocene Antarctic ice expansion (Shackleton and Kennett 1975; Savin 1977; Woodruff et al. 1981; Kennett et al. 1985) resulted in the migration of cold Antarctic waters into the southern Indian Ocean, as manifested by the planktonic foraminiferal assemblage at Site 281 (56°S). The high abundance of the warm-water species *Gr. mayeri/siakensis* (18%) at this site is perplexing (text-fig. 6). However, data from the southwest Pacific show similar abundances of this species in corresponding latitudes during the middle Miocene (Kennett et al. 1985).

Unusually high abundances of *Globigerinoides* spp. (57%) at Site 231 (text-fig. 6) in the Gulf of Aden combined with the complete absence of *Globorotalia* spp. may indicate that during the middle Miocene the Gulf of Aden was a semi-isolated basin. Under the restricted conditions of the modern Red Sea *Globigerinoides* spp. flourish, while *Globorotalia* spp. are absent. This modern scenario may be similar to the middle Miocene conditions at Site 231, suggesting that circulation between the Gulf of Aden and Indian Ocean was somewhat restricted at this time.

With the closure of the low-latitude inter-ocean connections (Hsu 1977; Hamilton 1979; Kennett et al. 1985), equatorial

surface circulation patterns in the Indian Ocean became similar to present-day patterns (text-fig. 11). The distinct separation of tropical and subtropical faunal provinces suggests that by the middle Miocene equatorial and subtropical circulation were independent of each other. Upon reaching the African coast, the low-latitude east to west flow of the NEC and part of the SEC were probably diverted into two branches, one flowing to the north and the other to the south. The northern branch probably formed a west to east flow which is analogous to the modern ECC. This current would then separate the tropical and subtropical water masses in much the same way as it does in the modern Indian Ocean (Wyrtki 1973). Planktonic foraminiferal assemblages at Sites 214 and 216 illustrate this division of warm-water masses (text-fig. 6). During both the early and middle Miocene, the *Gr. mayeri/siakensis* complex was very abundant at Site 216 (23% and 40%, respectively) (text-figs. 5, 6). Site 214 contained moderate abundances of *Gr. mayeri/siakensis* in the early Miocene, but by the middle Miocene, abundances of this tropical species were insignificant (<1%) at this site. This distinct separation of tropical and subtropical assemblages in the middle Miocene may have resulted from the increased latitudinal temperature gradient, but most likely corresponds to separation of surface water masses related to the development of an ECC.

Middle Miocene subtropical circulation also exhibited characteristics similar to the subtropical gyre found in the modern Indian Ocean. Part of the westward flowing equatorial current was deflected to the south and formed the western boundary current or Agulhas Current. Warm surface waters were carried south along the coast of Africa, as indicated by moderate abundances of *Globigerinoides* spp. at Site 251 (text-fig. 6). Upon meeting the Circum-Polar Current this arm of the subtropical gyre turned to the east. *Globigerinoides* spp. distributions at Sites 253 and 254 (30°S and 35°S, respectively) indicate that the warm subtropical province extended as far south as Site 253 but did not reach Site 254 (text-fig. 6). The southern boundary for this eastward flow and hence the lower limit of the middle Miocene subtropical province was located between 30 and 35°S (text-fig. 11).

Inadequate middle Miocene core coverage in the eastern Indian Ocean allows only speculation on the existence of an eastern boundary current. At present, there is only a weak northern flow (Australian Current) in the Indian subtropical gyre due to the lack of a continuous coast and surface water exchange with the Pacific. Even with the closure of the Indo-Pacific Passage, some surface exchange still occurs through this region today.

Late Miocene Biogeography and Surface Circulation

From the early Miocene to the late Miocene the latitudinal temperature gradient in the Pacific Ocean increased from 6°C to 12°C (Loutit et al. 1983), and with it came an increase in biogeographic provincialization. The late Miocene planktonic foraminiferal fauna suggest a warming of tropical regions and northward migration of cold Antarctic waters into the Indian Ocean. Moore and Lombari (1981) estimated that late Miocene surface water temperatures for equatorial and temperate areas of the Pacific were near present-day values. There is no reason to assume that the situation in the Indian Ocean would be very different.

A late Miocene increase in the abundance of *Gr. menardii* in the Indian Ocean provides evidence for the tropical warming suggested by Moore and Lombari (1981). In addition to the increased abundances of *Gr. menardii* at Sites 216 and 217 (text-fig. 7), the late Miocene equatorial warming expanded the tropical province so that it encompassed Sites 237, 238 and 214 (8°S, 12°S and 14°S, respectively) (text-fig. 12). These sites had previously been within the subtropical province during the middle Miocene (text-fig. 11).

The late Miocene subtropical province was more compressed than during the middle Miocene as a result of tropical warming and high-latitude cooling. Planktonic foraminiferal assemblages at Sites 214 and 238, both of which were clearly subtropical in the middle Miocene, have faunal characteristics of both tropical and subtropical provinces in the late Miocene. Southern expansion of the subtropical province due to equatorial warming was buffered by high-latitude cooling in the late Miocene (Hodell and Kennett 1986).

As high-latitude climates cooled in the late Miocene (Shackleton and Kennett 1975a), migration of polar waters toward the southern Indian Ocean increased the latitudinal thermal gradient and produced well-defined transitional and subpolar provinces (text-fig. 12). The subpolar species, *G. bulloides/ falconensis* and *N. pachyderma*, had higher abundances in the mid-latitude sites during the late Miocene than in the two earlier time-slices. The increase in these cold-water taxa suggests that high-latitude cooling and migration of cold surface waters occurred between the middle and late Miocene. The first polar planktonic foraminiferal species in the Indian Ocean appeared in the late Miocene with the presence of sinistral *N. pachyderma* at Sites 254 and 281. However, due to the lack of quality high-latitude sites in the Indian Ocean, we can only infer that a polar province existed south of Site 281 based on the occurrence of sinistral *N. pachyderma* in the transitional and subpolar provinces.

By the late Miocene, surface circulation in the Indian Ocean had evolved to the point where it was very similar to that of the modern Indian Ocean. Plate movement since the late Miocene has not significantly altered the basinal configuration of the Indian Ocean (Hamilton 1979). This paleogeography along with a strong Circum-Polar Current accounts for near modern-day conditions in late Miocene surface circulation patterns (text-fig. 12). Development of distinct equatorial and subtropical gyres separated the tropical and subtropical faunal provinces by this time. This separation is illustrated in the distributions of the tropical and subtropical species at Sites 214, 216, 237 and 283 (text-fig. 7).

The major components of the late Miocene equatorial circulation probably included the westward flow of the NEC and SEC, a northward flow off the coast of Somalia and the ECC (text-fig. 12). Evidence for a seasonally reversing monsoon is not readily apparent in the low-latitude planktonic foraminiferal distributions. The NEC would be expected to seasonally develop and decay with a reversing monsoon. If the NEC were replaced by an expanded ECC during the winter monsoon, evidence of upwelling should show up in the Arabian Sea (Sites 231 and 219). *Globigerina bulloides,* a species characteristically associated with upwelling (Cullen and Prell 1984), was only found in moderate abundances at Site 231. The lack of significant abundances of this species at this site does not eliminate the possibility of a monsoonal system, but simply suggests that these sites were not in areas strongly influenced by upwelling. Although the evidence is inconclusive, the presence of *G. bulloides* at Site 231 may reflect the existence of a seasonal monsoon at this time. The initiation of the monsoon system in the northwest Indian Ocean was most likely triggered by the middle Miocene uplift of the Himalayas (Gansser 1964). Manabe and Hahn (1986) demonstrated that the effect of mountains, such as the Tibetan Plateau, on air circulation patterns is sufficient to produce monsoonal conditions in this area. In addition, biogenic silica concentrations increase at Site 223 and 224 beginning in the late middle Miocene (Whitmarsh et al. 1974). This silica increase along with a late middle Miocene increase in organic carbon content at these sites is attributed to upwelling and higher productivity (Whitmarsh 1974).

A strengthened subtropical circulation during the late Miocene resulted in increased differentiation of tropical and subtropical assemblages, and enhanced the distinction between the subtropical and transitional provinces (text-figs. 7, 12).

The presence of a strong subtropical circulation at this time was manifested in the emergence of a true Agulhas Current and STC.

The Agulhas Current in the modern Indian Ocean is the western boundary current for the subtropical gyre carrying warm tropical water past the southern tip of Africa (Wyrtki 1973; Gordon 1985). As this warm water flows into higher latitudes, tropical planktonic foraminifera are found flourishing in uncharacteristically high latitudes. The existence of the Agulhas Current in the late Miocene was inferred from the high abundances of *Gr. menardii* at Sites 242 and 249 (17°S and 31°S, respectively) (text-fig. 7). In addition, an unusual assemblage of species was found in the southwest Indian Ocean during the late Miocene. In association with tropical species, Sites 242 and 249 had high abundances of transitional and subpolar species such as *Gr. conoidea, G. bulloides* and *N. pachyderma* (text-fig. 7). One explanation for such an assemblage would be the formation of anticyclonic warm core rings and cyclonic cold core rings as the Agulhas Current turns back to the east. This phenomenon is observed today as the Agulhas Retroflection which commonly spawns both warm and cold core rings (Gordon 1985). The resulting assemblage would have planktonic foraminifera characteristic of warm- and cold-water masses. Bé and Hutson (1977) found a similar mixture of warm- and cold-water faunas in surface sediments from this region of the Indian Ocean.

The mid-latitude regions appear to be the most sensitive to climatic and oceanographic changes. Middle Miocene intermediate latitude assemblages (Sites 251, 253 and 254) suggest the presence of a STC. The modern Indian Ocean transitional bioprovince (text-fig. 4) is located within the steep latitudinal temperature gradient associated with the STC (Bé and Hutson 1977). We have assumed that the position of the transitional province represents this steep temperature gradient throughout the Neogene, allowing us to position the STC during this period. By the late Miocene, this boundary between the subtropical waters and Antarctic waters was very distinct (text-fig. 12). The abundance of *Globigerinoides* spp. (text-fig. 7) decreased markedly between Sites 253 and 254, dropping from greater than 20% at Site 253 to only 4% at Site 254. The reverse situation was seen in the abundance of *G. bulloides/falconensis* (text-fig. 7). Likewise, a similar pattern is found between Sites 249 and 251 in the western Indian Ocean. By the late Miocene, the STC was positioned within a steep temperature gradient which acted as an ecologic boundary between warm- and cold-water species.

Antarctic circulation in the late Miocene continued to strengthen and occupied a more northerly position due to further high-latitude cooling which caused cold surface waters to migrate to the north (Kennett 1980). This migration was reflected in the moderate to high abundances of *G. bulloides/falconensis* and *N. pachyderma* at Site 281 (50°S) (text-fig. 7).

Early Pliocene Biogeography and Surface Circulation

During the early Pliocene, tropical-subtropical species dominated the fauna to 30°S in the Indian Ocean (text-figs. 8,

13). The evolution of *Gr. tumida* from *Gr. plesiotumida* and *N. humerosa* from *N. acostaensis* provided new species in the tropical regions (table 3). Overall, little change appears to have occurred in this province between the late Miocene and early Pliocene. Surface water temperatures were probably not very different from those in the late Miocene tropics. As a result, a relatively wide tropical belt was maintained throughout the early Pliocene (text-fig. 13). The high abundances of *Gr. menardii* found at equatorial sites in the early Pliocene (text-fig. 8) reflected the climatic warming which occurred at this time (Keigwin 1979).
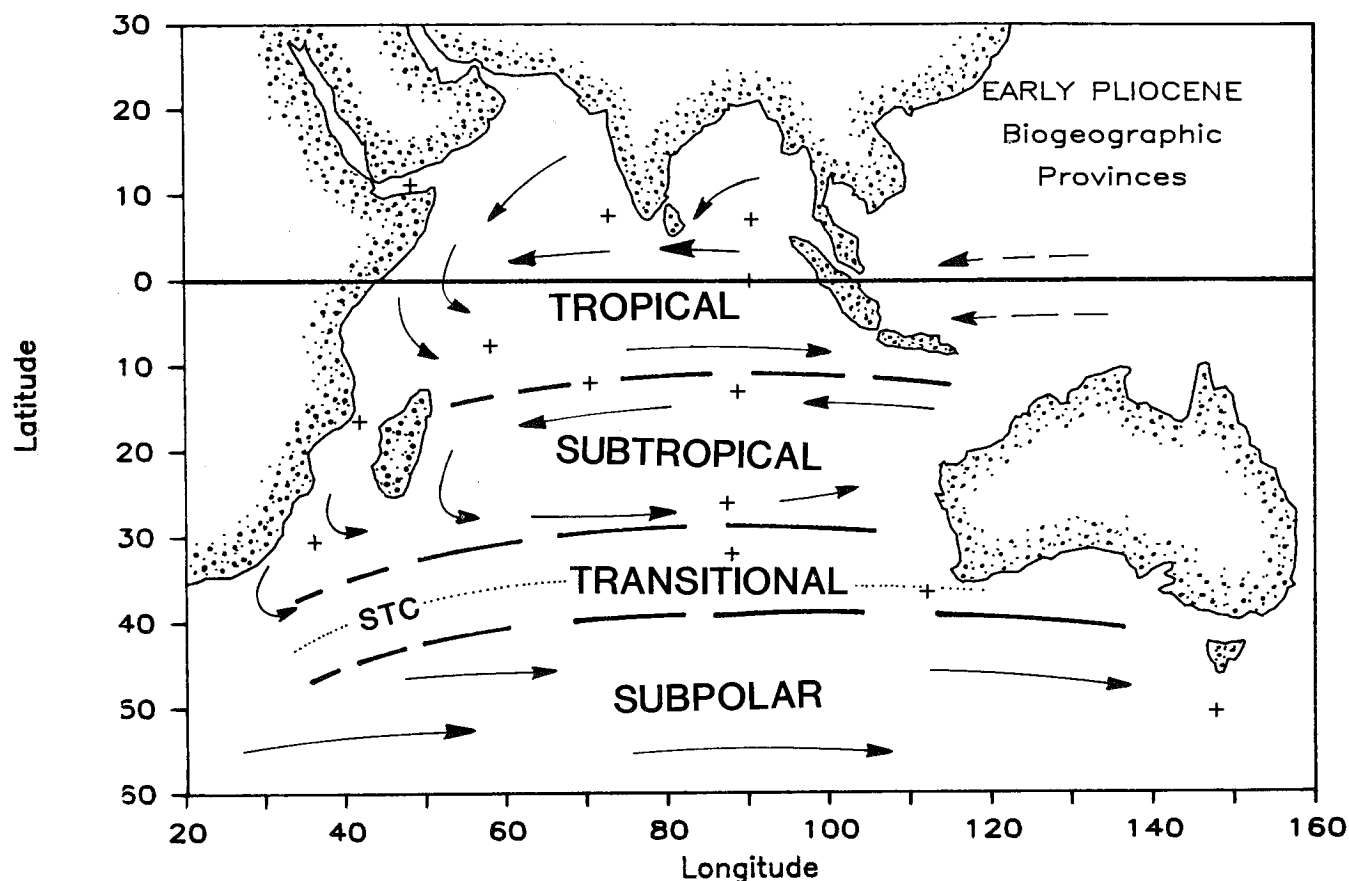
The climatic warming in the early Pliocene (Keigwin 1979; Hodell and Kennett 1986) most affected the subtropical province. This warming was readily seen at Site 253 (26°S) with *Globigerinoides* spp. composing greater than 60% of the early Pliocene planktonic foraminiferal fauna (text-fig. 8). The modern distributions of *Globigerinoides* spp. in the Indian Ocean show high abundances in the tropical and warm subtropical regions including the area around Site 253 (Bé and Hutson 1977). The STC and accompanying thermal gradient which separated warm subtropical waters from cold Antarctic waters continued to serve as an ecological boundary in the latitudinal distribution of *Globigerinoides* spp.

The early Pliocene transitional province was composed of two indigenous species, *Gr. puncticulata* and *Gr. crassaformis,* with several other co-occurring taxa (text-fig. 8 and table 3). The early Pliocene evolution of *Gr. puncticulata* as part of the *Globoconella* lineage (Kennett and Srinivasan 1983) was important biogeographically. Distributions of *Gr. puncticulata* (text-fig. 8) were similar to those of *Gr. conoidea* for the middle and late Miocene (text-figs. 6, 7). The strengthened temperature gradient served as a distinct northern boundary for the early Pliocene transitional province, however, the southern boundary was not as well delineated. *Globorotalia puncticulata* and *Gr. crassaformis* abundances showed gradual decreases in the high latitudes (text-fig. 8) which is attributed to slightly warmer high-latitude surface waters in the early Pliocene.

The subpolar province continued to be dominated by *G. bulloides/falconensis* along with high abundances of *N. pachyderma* (text-fig. 8 and table 3). The distributions of these species at Sites 253 and 254 illustrate that the STC still acted as an ecological boundary for cold-water species. There appears to have been less distinction between the transitional and subpolar provinces during the early Pliocene. Moderate to high abundances of both transitional and subpolar species were found at Sites 254, 264 and 281 (text-fig. 8), and this may be due to slightly warmer high-latitude surface waters.

Surface circulation in the early Pliocene (text-fig. 13) continued to resemble the modern Indian Ocean patterns initiated in the middle Miocene (text-fig. 11). Tropical circulation at this time probably consisted of the NEC and ECC. As in the late Miocene, moderate abundances of *G. bulloides/falconensis* at Site 231 (text-fig. 8) suggest that seasonal upwelling associated with the monsoon system probably occurred in this region.

Subtropical surface circulation in the early Pliocene followed much the same pattern as in the late Miocene. Moderate

TEXT-FIGURE 13
Planktonic foraminiferal biogeographic and surface circulation reconstructions for the early Pliocene (4.0 Ma).

abundances of *Gr. menardii* along the coast of Africa indicate that the Agulhas Current continued to be strong during this time (text-fig. 8). The most significant change from the late Miocene was the emergence of a strong temperature gradient and fully developed STC which effectively separated subtropical circulation from the Circum-Polar Current. This is most clearly reflected in the distributions of *Globigerinoides* spp. and *G. bulloides/falconensis* (text-fig. 8). The early Pliocene position of the STC was approximately 35°S.

Late Pliocene Biogeography and Surface Circulation

After a return to warmer marine conditions in the early Pliocene, high-latitude cooling associated with Northern Hemisphere glaciation during the middle and late Pliocene (Shackleton and Opdyke 1977; Thunell and Williams 1985; Shackleton et al. 1984) resulted in a northern migration of the tropical-subtropical faunal boundary and Antarctic surface waters (Kennett 1977; Kennett and von der Borch 1986). Equatorial surface water temperatures remained stable in the late Pliocene as shown by the distribution of tropical species, such as *Gr. menardii* (text-fig. 9). In response to climatic cooling during the late Pliocene, the southern boundary of the tropical province shifted to the north (text-fig. 14). Sites

214 and 238 had moderate abundances of tropical species in the early Pliocene (text-fig. 8), but by the late Pliocene subtropical species dominated the planktonic foraminiferal fauna in this region. The position of the late Pliocene subtropical province, as identified by the distribution of *Globigerinoides* spp., resembled that of the early Pliocene with the exception of the slight northward expansion (text-fig. 9). The STC continued to serve as a sharp boundary between warm- and cold-water taxa.

With warm-water biogeographical provinces remaining relatively stable in the late Pliocene, climatic cooling had a more obvious effect on the planktonic foraminiferal assemblages in the mid- to high-latitudes. As cold polar waters migrated to the north, the transitional and subpolar provinces became extremely compressed (text-fig. 14). By the late Pliocene, *Gr. inflata* had evolved as part of the *Globoconella* lineage, and together with *Gr. crassaformis* (text-fig. 9) indicates that the transitional province was restricted to the region between 35°S and 40°S (text-fig. 14).

The subpolar province continued to be dominated by *G. bulloides/falconensis* and dextral *N. pachyderma* (text-fig. 9). Differentiation of the coiling direction in *N. pachyderma* allows the recognition of both subpolar and polar bioprovinces

The presence of a strong subtropical circulation at this time was manifested in the emergence of a true Agulhas Current and STC.

The Agulhas Current in the modern Indian Ocean is the western boundary current for the subtropical gyre carrying warm tropical water past the southern tip of Africa (Wyrtki 1973; Gordon 1985). As this warm water flows into higher latitudes, tropical planktonic foraminifera are found flourishing in uncharacteristically high latitudes. The existence of the Agulhas Current in the late Miocene was inferred from the high abundances of *Gr. menardii* at Sites 242 and 249 (17°S and 31°S, respectively) (text-fig. 7). In addition, an unusual assemblage of species was found in the southwest Indian Ocean during the late Miocene. In association with tropical species, Sites 242 and 249 had high abundances of transitional and subpolar species such as *Gr. conoidea, G. bulloides* and *N. pachyderma* (text-fig. 7). One explanation for such an assemblage would be the formation of anticyclonic warm core rings and cyclonic cold core rings as the Agulhas Current turns back to the east. This phenomenon is observed today as the Agulhas Retroflection which commonly spawns both warm and cold core rings (Gordon 1985). The resulting assemblage would have planktonic foraminifera characteristic of warm- and cold-water masses. Bé and Hutson (1977) found a similar mixture of warm- and cold-water faunas in surface sediments from this region of the Indian Ocean.

The mid-latitude regions appear to be the most sensitive to climatic and oceanographic changes. Middle Miocene intermediate latitude assemblages (Sites 251, 253 and 254) suggest the presence of a STC. The modern Indian Ocean transitional bioprovince (text-fig. 4) is located within the steep latitudinal temperature gradient associated with the STC (Bé and Hutson 1977). We have assumed that the position of the transitional province represents this steep temperature gradient throughout the Neogene, allowing us to position the STC during this period. By the late Miocene, this boundary between the subtropical waters and Antarctic waters was very distinct (text-fig. 12). The abundance of *Globigerinoides* spp. (text-fig. 7) decreased markedly between Sites 253 and 254, dropping from greater than 20% at Site 253 to only 4% at Site 254. The reverse situation was seen in the abundance of *G. bulloides/falconensis* (text-fig. 7). Likewise, a similar pattern is found between Sites 249 and 251 in the western Indian Ocean. By the late Miocene, the STC was positioned within a steep temperature gradient which acted as an ecologic boundary between warm- and cold-water species.

Antarctic circulation in the late Miocene continued to strengthen and occupied a more northerly position due to further high-latitude cooling which caused cold surface waters to migrate to the north (Kennett 1980). This migration was reflected in the moderate to high abundances of *G. bulloides/falconensis* and *N. pachyderma* at Site 281 (50°S) (text-fig. 7).

Early Pliocene Biogeography and Surface Circulation

During the early Pliocene, tropical-subtropical species dominated the fauna to 30°S in the Indian Ocean (text-figs. 8,

13). The evolution of *Gr. tumida* from *Gr. plesiotumida* and *N. humerosa* from *N. acostaensis* provided new species in the tropical regions (table 3). Overall, little change appears to have occurred in this province between the late Miocene and early Pliocene. Surface water temperatures were probably not very different from those in the late Miocene tropics. As a result, a relatively wide tropical belt was maintained throughout the early Pliocene (text-fig. 13). The high abundances of *Gr. menardii* found at equatorial sites in the early Pliocene (text-fig. 8) reflected the climatic warming which occurred at this time (Keigwin 1979).
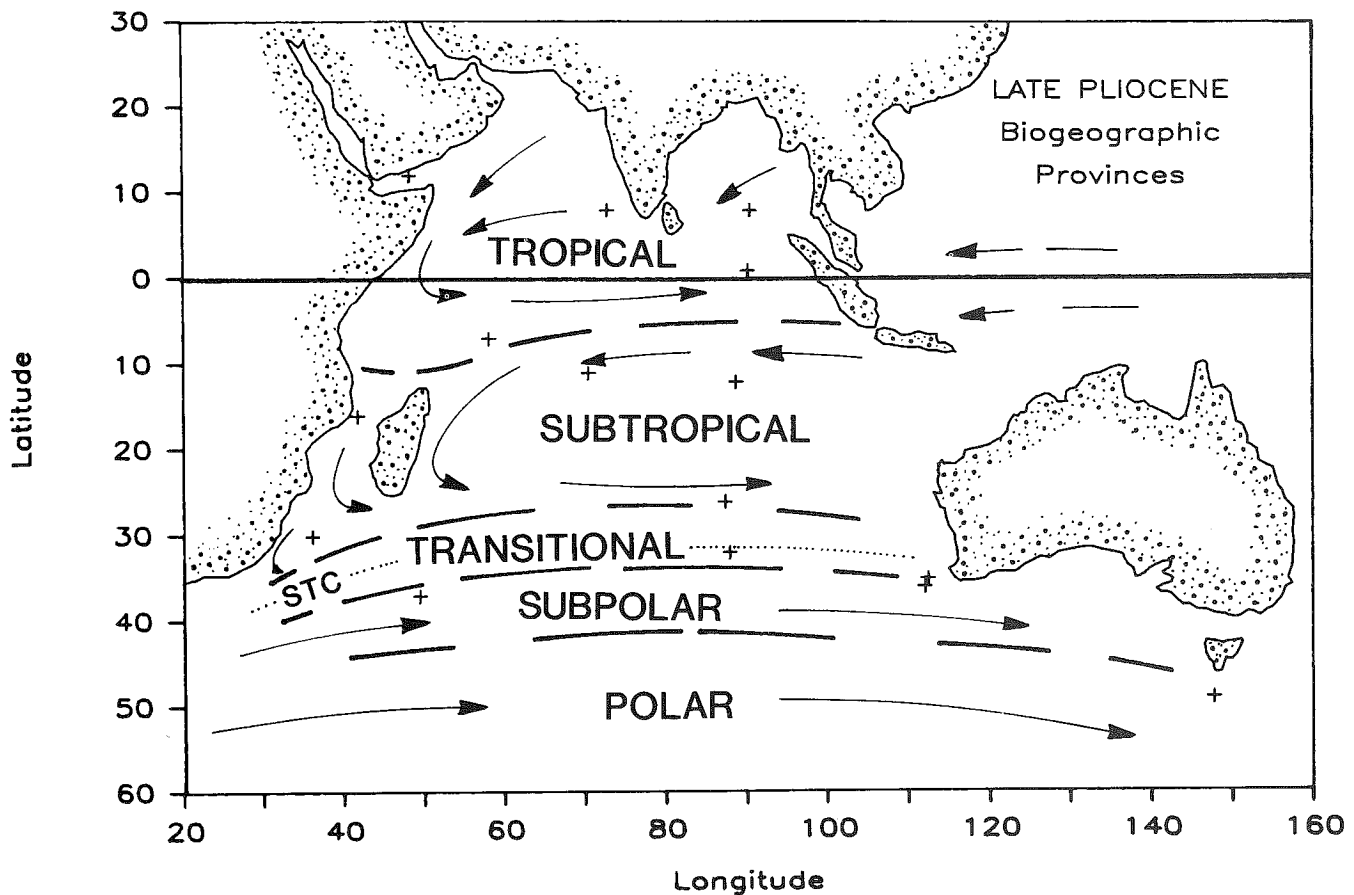
The climatic warming in the early Pliocene (Keigwin 1979; Hodell and Kennett 1986) most affected the subtropical province. This warming was readily seen at Site 253 (26°S) with *Globigerinoides* spp. composing greater than 60% of the early Pliocene planktonic foraminiferal fauna (text-fig. 8). The modern distributions of *Globigerinoides* spp. in the Indian Ocean show high abundances in the tropical and warm subtropical regions including the area around Site 253 (Bé and Hutson 1977). The STC and accompanying thermal gradient which separated warm subtropical waters from cold Antarctic waters continued to serve as an ecological boundary in the latitudinal distribution of *Globigerinoides* spp.

The early Pliocene transitional province was composed of two indigenous species, *Gr. puncticulata* and *Gr. crassaformis,* with several other co-occurring taxa (text-fig. 8 and table 3). The early Pliocene evolution of *Gr. puncticulata* as part of the *Globoconella* lineage (Kennett and Srinivasan 1983) was important biogeographically. Distributions of *Gr. puncticulata* (text-fig. 8) were similar to those of *Gr. conoidea* for the middle and late Miocene (text-figs. 6, 7). The strengthened temperature gradient served as a distinct northern boundary for the early Pliocene transitional province, however, the southern boundary was not as well delineated. *Globorotalia puncticulata* and *Gr. crassaformis* abundances showed gradual decreases in the high latitudes (text-fig. 8) which is attributed to slightly warmer high-latitude surface waters in the early Pliocene.

The subpolar province continued to be dominated by *G. bulloides/falconensis* along with high abundances of *N. pachyderma* (text-fig. 8 and table 3). The distributions of these species at Sites 253 and 254 illustrate that the STC still acted as an ecological boundary for cold-water species. There appears to have been less distinction between the transitional and subpolar provinces during the early Pliocene. Moderate to high abundances of both transitional and subpolar species were found at Sites 254, 264 and 281 (text-fig. 8), and this may be due to slightly warmer high-latitude surface waters.

Surface circulation in the early Pliocene (text-fig. 13) continued to resemble the modern Indian Ocean patterns initiated in the middle Miocene (text-fig. 11). Tropical circulation at this time probably consisted of the NEC and ECC. As in the late Miocene, moderate abundances of *G. bulloides/falconensis* at Site 231 (text-fig. 8) suggest that seasonal upwelling associated with the monsoon system probably occurred in this region.

Subtropical surface circulation in the early Pliocene followed much the same pattern as in the late Miocene. Moderate

TEXT-FIGURE 14
Planktonic foraminiferal biogeographic and surface circulation reconstructions for the late Pliocene (2.4 Ma).

(text-fig. 14). By the late Pliocene, the polar front had moved north to a position where, at least seasonally, surface waters associated with Site 281 (50°S) were dominated by sinistral *N. pachyderma* (44%) (text-fig. 9). At present, the polar front migrates from approximately 60°S in the winter months to 55°S in the summer. A similar situation probably existed in the late Pliocene resulting in the co-occurrence of transitional, subpolar, and polar species in the sediment assemblages at Site 281.

Equatorial surface circulation patterns in the late Pliocene (text-fig. 14) were probably very similar to the modern patterns. There continued to be a separation of the equatorial and subtropical surface circulation as evidenced by the distributions of *Gr. menardii* and *Globigerinoides* spp. (text-fig. 9). The equatorial system probably consisted of the NEC, a deflection off Africa and return flow via the ECC (text-fig. 14). Gyral circulation in the subtropics during the late Pliocene was similar to that of the late Miocene (text-fig. 12) and early Pliocene (text-fig. 13). The strong Agulhas Current continued to carry tropical and subtropical species, such as *Gr. menardii* (text-fig. 9), into high latitudes. Upon meeting the Circum-Polar Current the subtropical water was turned to the east along the STC. The Australian coast has never provided an adequate border to produce a strong eastern bound-
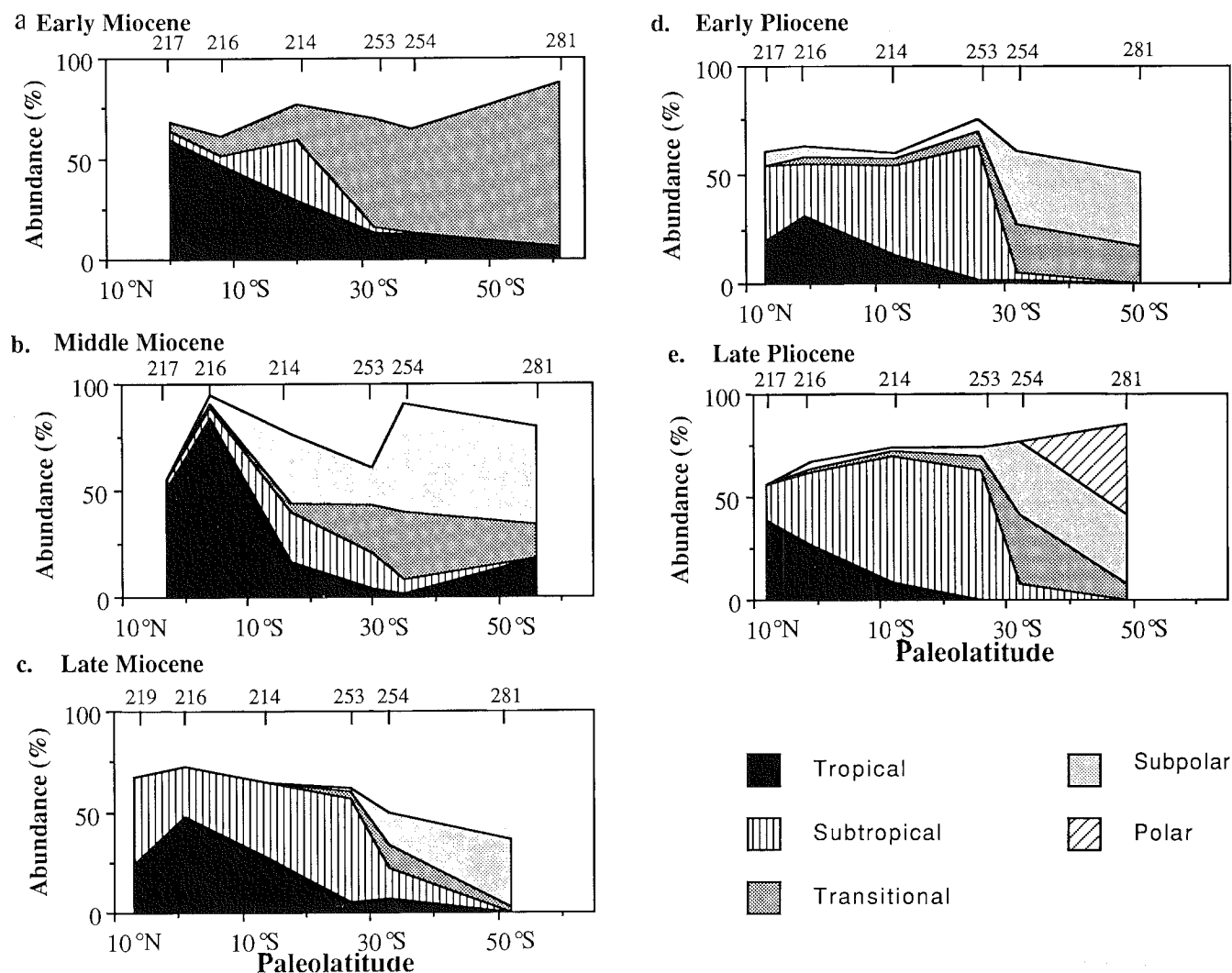
ary current. As a result, the return flow in the Australian Current was probably very weak in the late Pliocene.

Increased abundances of *G. bulloides/falconensis* and sinistral *N. pachyderma* suggest that circum-polar waters were shifted to the north during the late Pliocene (text-fig. 9). The more northerly position is reflected in the planktonic foraminiferal assemblages at Sites 254 and 264, which by this time had significant abundances (>25%) of the subpolar species *G. bulloides/falconensis*. This northern migration of cold-water species resulted from high-latitude cooling and associated Northern Hemisphere glaciation.

SUMMARY

The Ninetyeast Ridge sites provide an ideal north-south transect for summarizing latitudinal movement of biogeographic provinces during the Neogene. In addition, the sites on this ridge are supplemented by Site 281 which serves as the high-latitude end-member. Latitudinal changes in the abundances of the different faunal assemblages for each of the five time-slices are summarized in text-figure 15. The species composition of each assemblage is found in table 3.

Early Miocene climates and surface circulation patterns resulted in weak latitudinal temperature gradients, as indicated

a Early Miocene

b. Middle Miocene

c. Late Miocene

d. Early Pliocene

e. Late Pliocene

Legend:
- ■ Tropical
- ⦀ Subtropical
- ▨ Transitional
- ▨ Subpolar
- ▨ Polar

TEXT-FIGURE 15

North to south changes in the abundances of the major planktonic foraminiferal assemblages for five Neogene time-slices. This transect is based on data from the 90° East ridges DSDP sites and Site 281. The species composition for each assemblage is given in table 3.

by the lack of a sharp separation between warm- and cold-water bioprovinces. As a result, the early Miocene tropical province exerted its influence into the high latitudes (Site 281), while equatorial regions (Sites 216 and 217) also contained a transitional-subpolar faunal component (text-fig. 15a).

Middle Miocene biogeographic patterns show increased differentiation between bioprovinces (text-fig. 15b). The tropical fauna dominated a much more distinct region at this time. Equatorial surface circulation patterns responded to closure of the Paratethys, separating the tropical and sub-tropical water masses. The boundary between these two bioprovinces was found between Sites 214 and 216. The boundaries between subtropical, transitional and subpolar provinces were somewhat less distinct. Separation of the transitional and subtropical provinces resulted from a small increase in the latitudinal temperature gradient and evolution

of new species in the middle Miocene. It may be that high-latitude cooling was sufficient to produce a cooler fauna in the Indian Ocean, but not able to induce a strong subtropical circulation. This weak subtropical circulation resulted in less distinction of the mid- and high-latitude provincial boundaries as compared to the tropical-subtropical faunal boundary.

An increased latitudinal temperature gradient in the late Miocene produced surface circulation and biogeographic patterns very similar to those found in the modern Indian Ocean. Equatorial warming appears to have expanded the tropical province such that this fauna was found abundantly at Site 214 (text-fig. 15c). The subtropical fauna was very well established by the late Miocene with high abundances in the equatorial and mid-latitude regions. Warm-water species decreased sharply immediately south of Site 253, while the reverse situation was true for the transitional and subpolar

taxa. This ecologic barrier resulted from development of the STC. High-latitude cooling and equatorial warming combined to produce stronger latitudinal temperature differences. In turn, surface winds responded to these conditions generating more vigorous surface water circulation, particularly in the subtropical gyre, which effectively isolated the warm- and cold-water species.

During the early Pliocene, subtropical species continued to be abundant in the equatorial regions as well as the mid-latitudes (text-fig. 15d). The early Pliocene tropical-subtropical boundary was positioned slightly north of Site 214. The most important characteristic of this time-slice was the full development of a strong STC between Sites 253 and 254, providing a very effective ecologic boundary between warm- and cold-water taxa. High-latitude assemblages continued to be mixtures of transitional and subpolar species. An interesting feature of this time interval was the increase in transitional taxa at Site 281. This probably resulted from climatic warming allowing a small southern expansion of the transitional province.

Latitudinal temperature differences in the late Pliocene approached those found in the modern Indian Ocean. Tropical and subtropical provinces show little change from the early Pliocene, although the boundary between these provinces may have migrated slightly to the north. The STC was still positioned between Sites 253 and 254 as indicated by the strong faunal change in this area. The most significant development in the late Pliocene was the emergence of a polar province in the southern Indian Ocean. High-latitude cooling expanded the polar water such that, at least seasonally, Antarctic surface waters migrated north to Site 281. The effect of this polar expansion was to compress the transitional and subpolar provinces.

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REFERENCES

BANNER, F. T., and BLOW, W. H., 1965. Progress in the planktonic foraminiferal biostratigraphy of the Neogene. Nature, 208:1164–1166.

BÉ, A. W. H., 1977. An ecological, zoogeographic and taxonomic review of recent planktonic foraminifera. In: Ramsay, A. T. S., Ed., Oceanic micropaleontology. London: Academic Press.

BÉ, A. W. H., and HUTSON, W. H., 1977. Ecology of planktonic foraminifera and biogeographic patterns of life and fossil assemblages in the Indian Ocean. Micropaleontology, 23:369–414.

BÉ, A. W. H., and TOLDERLUND, D. S., 1971. Distribution and ecology of living planktonic foraminifera in surface waters of the Atlantic and Indian Oceans. In: Funnell, B. M., and Riedel, W. R., Eds., The micropaleontology of the oceans. London: Cambridge University Press, pp. 105–149.

BERGER, W. H., VINCENT, E., and THIERSTEIN, H. R., 1981. The deep sea record: Major steps in Cenozoic ocean evolution. Society of Economic Paleontologists and Mineralogists Special Publication no. 32, pp. 489–504.

BERGGREN, W. A., 1972. Late Pliocene-Pleistocene glaciation. In: Laughton, A. S., Berggren, W. A., et al., Initial Reports of the Deep Sea Drilling Project, Volume 12:953–963. Washington, D.C.: U.S. Government Printing Office.

————, 1981. Neogene planktonic foraminiferal biostratigraphy: Atlantic, Mediterranean, and Indo-Pacific Region. In: Proceedings of International Workshop on Pacific Neogene Biostratigraphy, Osaka, Japan.

BERGGREN, W. A., KENT, D. V., and VAN COUVERING, J. A., 1985. Neogene geochronology and chronostratigraphy. In: Snelling, N. J., Ed., Geochronology and the geologic time scale. Geological Society of London, Special Paper.

BLOW, W. H., 1959. Age, correlation, and biostratigraphy of the upper Tocuyo (San Lorenzo) and Pozon formations, eastern Falcon, Venezuela. Bulletins of American Paleontology, 39:67–251.

————, 1969. Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy. In: Bronnimann, R., and Renz, H. H., Eds., Proceedings International Conference on Planktonic Microfossils I, Geneva, 1967. Leiden: E. J. Brill, pp. 199–421.

BLOW, W. H., and BANNER, F. T., 1962. The Mid-Tertiary (Upper Eocene to Aquitanian) Globigerinaceae. In: Eames, F. E., et al., Eds., Fundamentals of Mid-Tertiary stratigraphical correlation. London: Cambridge Univ. Press, pp. 61–151.

BOERSMA, A., and PREMOLI SILVA, I., 1983. Paleocene planktonic foraminiferal biogeography and the paleoceanography of the Atlantic Ocean. Micropaleontology, 29:355–381.

BOLLI, H. M., 1957. Planktonic Foraminifera from the Oligocene-Miocene Cipero and Lengua Formations of Trinidad, B. W. I. United States National Museum Bulletin, 215:97–123.

BOLLI, H. M., and BERMUDEZ, P. J., 1965. Zonation based on planktonic Foraminifera of Middle Miocene to Pliocene warm-water sediments. Asoc. Venezolana Geologia, Mineria y Petroleo Bol. Inf., 8:119–149.

BRADY, H. B., 1877. Supplementary note on the Foraminifera of the Chalk(?) of the New Britain group. Geological Magazine, 4: 534–536.

————, 1879. Notes on some of the reticularian Rhizopoda of the Challenger Expedition. Microscopy Society London Quarterly Journal, 19:20–26, 261–299.

CHAPMAN, F., PARR, W. J., and COLLINS, A. C., 1934. Tertiary Foraminifera of Victoria, Australia—the Balcombian deposits of Port Philip, pt. 3. Journal of the Linnean Society of London, Zoology, 38:553–577.

CULLEN J. L., and PRELL, W. L., 1984. Planktonic foraminifera of the northern Indian Ocean: distribution and preservation in surface sediments. Marine Micropaleontology, 9:1–52.

CUSHMAN, J. A., and ELLISOR, A. C., 1939. New species of Foraminifera from the Oligocene and Miocene. Cushman Laboratory Foraminiferal Research Contribution, 15:1–14.

CUSHMAN, J. A., and JARVIS, P. W., 1936. Three new Foraminifera from the Miocene, Bowden marl, of Jamaica. Cushman Laboratory Foraminiferal Research Contribution, 12:3–5.

DESHAYES, G. P., 1832. Encyclopédie méthodique; histoire naturelle des vers. Paris, Mme. v. Agasse, 2, pt. 2, 594 pp., v. 3, pp. 595–1152.

D'ORBIGNY, A. D., 1826. Tableau méthodique de la classe des céphalopodes. Annales Sci. Nat. Paris, sér. 1, v. 7, pp. 95–314.

———, 1839. Foraminifères. In: Ramon de la Sagra, Ed., Histoire physique, politique et naturelle de l'île de Cuba. Paris: A. Bertrand, 224 pp.

———, 1846. Foraminifères fossiles du basin tertiaire de Vienne (Autriche). Paris, Gide et Comp., 303 pp.

EGGER, J. G., 1893. Foraminiferen aus Meeresgrundproben, gelonthet von 1874 bis 1876 von s. M. Sch. Gazelle. Bayerische Akad. Wiss., Math.-Physik. Kl. Abh., 18:193–458.

EHRENBERG, C. G., 1861. Elemente des tiefen Meeresgrundes in Mexikanischen Golfstrome bei Florida; über die Tiefgrund-Verhaltnisse des Oceans am Eingange der Davisstrasse und bei Island. K. Preuss. Akad. Wiss. Berlin, Monatsber., Berlin, pp. 222–240, 275–315.

FAIRBANKS, R. G., SVERDLOVE, M., FREE, R., WIEBE, P. H., and BÉ, A. W. H., 1982. Vertical distribution and isotopic fractionation of living planktonic foraminifera from the Panama Basin. Nature, 298:841–846.

FAIRBANKS, R. G., and WIEBE, P. H., 1980. Foraminifera and chlorophyll maximum: vertical, seasonal succession, and paleoceanographic significance. Science, 209:1524–1526.

FAIRBANKS, R. G., WIEBE, P. H., and BÉ, A. W. H., 1980. Vertical distribution and isotopic composition of living planktonic foraminifera in the western North Atlantic. Science, 201:61–63.

FINLAY, H. J., 1940. New Zealand Foraminifera; key species in stratigraphy, no. 4. Royal Society New Zealand Transaction, 69: 448–472.

GALLOWAY, J. J., and WISSLER, S. G., 1927. Pleistocene Foraminifera from the Lomita quarry, Palos Verdes Hills, California. Journal of Paleontology, 1:35–87.

GANSSER, A., 1964. Geology of the Himalayas. New York: Wiley-Interscience, 289 pp.

GORDON, A. L., 1985. Indian-Atlantic transfer of thermocline water at the Agulhas Retroflection. Science, 227:1030–1033.

HAHN, D. G., and MANABE, S., 1975. The role of mountains in the South Asian monsoon circulation. Journal of the Atmospheric Sciences, 32:1515–1541.

HAMILTON, W., 1979. Tectonics of the Indonesian Region. Geological Society of America Professional Paper no. 1078, 345 pp.

HAQ, B. U., 1980. Biogeographic history of Miocene calcareous nannoplankton and paleoceanography of the Atlantic Ocean. Micropaleontology, 24:414–443.

HAQ, B. U., and LOHMANN, G. P., 1976. Early Cenozoic calcareous nannoplankton biogeography of the Atlantic Ocean. Marine Micropaleontology, 1:119–194.

HEDBERG, H. D., 1937. Foraminifera of the middle Tertiary Carapita Formation of northeastern Venezuela. Journal of Paleontology, 11:661–697.

HODELL, D. A., and KENNETT, J. P., 1985. Miocene paleoceanography of the Atlantic Ocean. In: Kennett, J. P., Ed., The Miocene ocean: paleoceanography and biogeography. Geological Society of America Memoir, 163:317–337.

———, 1986. Late Miocene–Early Pliocene stratigraphy and paleoceanography of the South Atlantic and southwest Pacific Oceans: a synthesis. Paleoceanography, 1:285–312.

HOFKER, J., 1956. Tertiary Foraminifera of coastal Ecuador; pt.

2—additional notes on the Eocene species. Journal of Paleontology, 30:891–958.

HSU, K. J., 1977. Tectonic evolution of the Mediterranean basins. In: Nairn, A. E. M., et al., Eds., The ocean basins and margins. New York: Plenum.

JENKINS, D. G., 1960. Planktonic Foraminifera from the Lakes Entrance oil shaft, Victoria, Australia. Micropaleontology, 6:345–371.

———, 1967. Planktonic foraminiferal zones and new taxa from the lower Miocene to the Pleistocene of New Zealand. New Zealand Journal of Geology and Geophysics, 10:1064–1078.

KEIGWIN, L. D., JR., 1978. Pliocene closing of the Panama isthmus based on biostratigraphic evidence from nearby Pacific ocean and Caribbean cores. Geology, 6:630–634.

———, 1979. Late Cenozoic stable isotope stratigraphy and paleoceanography of Deep Sea Drilling Project sites from the East Equatorial and Central North Pacific Ocean. Earth and Planetary Science Letters, 45:361–382.

KELLER, G., and BARRON, J. A., 1983. Paleoceanographic implications of Miocene deep-sea hiatuses. Geological Society of American Bulletin, 94:590–613.

KENNETT, J. P., 1966. The *Globorotalia crassaformis* bioseries in north Westland and Marlborough, New Zealand. Micropaleontology, 12:235–245.

———, 1973. Middle and late Cenozoic planktonic foraminiferal biostratigraphy of the southwest Pacific—DSDP Leg 21. In: Burns, R. E., et al., Initial Reports of the Deep Sea Drilling Project, Volume 21:575–640. Washington, D.C.: U.S. Government Printing Office.

———, 1977. Cenozoic evolution of Antarctic glaciation, the Circum-Antarctic Ocean, and their impact on global paleoceanography. Journal of Geophysical Research, 82:3843–3860.

———, 1978. The development of planktonic biogeography in the Southern Ocean during the Cenozoic. Marine Micropaleontology, 3:301–345.

———, 1980. Paleoceanographic and biogeographic evolution of the Southern Ocean during the Cenozoic and Cenozoic microfossil datums. Palaeogeography, Palaeoclimatology, Palaeoecology, 31: 123–152.

KENNETT, J. P., KELLER, G., and SRINIVASAN, M. S., 1985. Miocene planktonic foraminiferal biogeography and paleoceanographic development of the Indo-Pacific region. In: Kennett, J. P., Ed., The Miocene Ocean: paleoceanography and biogeography. Geological Society of America Memoir, 163:197–236.

KENNETT, J. P., and SHACKLETON, N. J., 1976. Oxygen isotopic evidence for the development of the psychrosphere 38 m.y. ago. Nature, 260:513–515.

KENNETT, J. P., and SRINIVASAN, M. S., 1983. Neogene planktonic Foraminifera. Stroudsburg, Pa.: Hutchinson Ross Publishing, 265 pp.

KENNETT, J. P., and VON DER BORCH, C. C., 1986. Southwest Pacific Cenozoic paleoceanography. In: Kennett, J. P., et al., Initial Reports of the Deep Sea Drilling Project, Volume 90:000–000. Washington, D.C.: U.S. Government Printing Office.

LEINEN, M., and HEATH, G. R., 1981. Sedimentary indicators of atmospheric activity in the northern hemisphere during the Cenozoic. Palaeogeography, Palaeoclimatology, Palaeoecology, 36: 1–21.

LEROY, L. W., 1939. Some small Foraminifera, Ostracoda and otoliths from the Neogene ("Miocene") of the Rokan-Tapanoeli area, central Sumatra. Natuurk. Tijdschr. Nederl.-Indie, 99:215–296.

LOHMANN, G. P., and CARLSON, J. J., 1981. Oceanographic significance of Pacific late Miocene calcareous nannoplankton. Marine Micropaleontology, 6:553–579.

LOUTIT, T. S., KENNETT, J. P., and SAVIN, S. R., 1983. Miocene equatorial and southwest Pacific paleoceanography from stable isotope evidence. Marine Micropaleontology, 8:215–233.

MILLER, K. G., and FAIRBANKS, R. G., 1983. Evidence for Oligocene-middle Miocene abyssal circulation changes in the western North Atlantic. Nature, 306:250–253.

MOORE, T. C., and LOMBARI, G., 1981. Sea-surface temperature changes in the North Pacific during the late Miocene. Marine Micropaleontology, 3:581–597.

NATIONAL OCEANIC and ATMOSPHERIC ADMINISTRATION, 1984. Indian Ocean SFT—monthly mean. In: Bell, A., Ed., Oceanographic monthly summary. Washington, D.C.: National Weather Service, 4(8):9.

———, 1985. Indian Ocean SFT—monthly mean. In: Bell, A., Ed., Oceanographic monthly summary. Washington, D.C.: National Weather Service, 5(2):9.

NATLAND, M. L., 1938. New species of foraminifera from off the west coast of North America and from the later Tertiary of the Los Angeles basin. California Univ., Scripps Inst. Oceanography, Technical Service Bulletin, 4:137–164.

PARKER, W. K., and JONES, T. R., 1865. On some Foraminifera from the North Atlantic and Arctic Oceans, including Davis Straits and Baffin's Bay. Royal Society London Philosophical Transactions, 155:12–19.

PARKER, W. K., JONES, T. R., and BRADY, H. B., 1865. On the nomenclature of the Foraminifera; pt. 10 (cont.)—The species enumerated by d'Orbigny in the "annales des Sciences Naturelles". Annals & Mag. Nat. History, series 3, v. 16, pp. 15–41.

REUSS, A. E., 1850. Neues foraminiferen aus den Schichten des Österreichischen Tertiärbeckens. Akad. Wiss. Wien Denkschr., Math.-Nat. Kl., 1:365–390.

ROGL, F., and STEININGER, F. F., 1984. Neogene Paratethys, Mediterranean and Indo-Pacific seaways. In: Brenchley, P., Ed., Fossils and climate. New York: John Wiley & Sons, pp. 171–200.

ROTH, P. H., 1974. Calcareous nannofossils from the northwestern Indian Ocean, Leg 24, Deep Sea Drilling Project. In: Fisher, R. L., Bunce, E. T., et al., Initial Reports of the Deep Sea Drilling Project, Volume 24:969–994. Washington, D.C.: U.S. Government Printing Office.

SANCETTA, C., 1978. Neogene Pacific microfossils and paleoceanography. Marine Micropaleontology, 3:347–376.

———, 1979. Paleogene Pacific microfossils and paleoceanography. Marine Micropaleontology, 4:363–398.

SAVIN, S. M., 1977. The history of the earth's surface temperature during the past 100 million years. Annual Review of Earth and Planetary Science Letters, 5:319–355.

SAVIN, S. M., and others, 1985. The evolution of Miocene surface and near-surface marine temperatures: oxygen isotopic evidence. Geological Society of American Memoir, 163:49–82.

SAVIN, S. M., DOUGLAS, R. G., and STEHLI, F. G., 1975. Ter-

tiary marine paleotemperatures. Geological Society of America Bulletin, 86:1499–1510.

SCHWAGER, C., 1866. Fossile Foraminiferen von Kar Nikobar. Novara Exped. 1857–1859, Wien, 2, Geol. Theil, pp. 187–268.

SCLATER, J. G., ABBOTT, D., and THIEDE, J., 1977. Paleobathymetry and sediments of the Indian Ocean. In: Heirtzler, J., et al., Eds., Indian Ocean geology and biostratigraphy. Washington: American Geophysical Union, pp. 25–59.

SHACKLETON, N. J., HALL, M. A., and BOERSMA, S., 1984. Oxygen and carbon data from Leg 74 foraminifers. In: Moore, T. C., Jr., Rabinowitz, R., D., et al., Initial Reports of the Deep Sea Drilling Project, Volume 74:599–612. Washington, D.C.: U.S. Government Printing Office.

SHACKLETON, N. J., and KENNETT, J. P., 1975a. Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: Oxygen and carbon isotope analyses in DSDP Sites 277, 279, and 281. In: Kennett, J. P., Houtz, R. E., et al., Initial Reports of the Deep Sea Drilling Project, Volume 29:801–807. Washington, D.C.: U.S. Government Printing Office.

———, 1975b. Late Cenozoic oxygen and carbon isotopic changes at DSDP site 284: implications for glacial history of the Northern Hemisphere and Antarctica. In: Kennett, J. P., Houtz, R. E., et al., Initial Reports of the Deep Sea Drilling Project, Volume 29: 801–807. Washington, D.C.: U.S. Government Printing Office.

SHACKLETON, N. J., and OPDYKE, N. D., 1977. Oxygen isotope and paleomagnetic evidence for early Northern Hemisphere glaciation. Nature, 270:216–219.

STAINFORTH, R. M., LAMB, J. L., LUTERBACHER, H., BEARD, J. H., and JEFFORDS, R. M., 1975. Cenozoic planktonic foraminiferal zonation and characteristics of index forms. University of Kansas Paleontology Contribution, Article 62, pp. 1–425.

TAKAYANAGI, Y., and SAITO, T., 1962. Planktonic Foraminifera from the Nobori Formation, Shikoku, Japan. Tohoku University Science Reports, Series 2, v. 5, pp. 67–106.

THUNELL, R., and BELYEA, P., 1982. Neogene planktonic foraminiferal biogeography of the Atlantic Ocean. Micropaleontology, 28:381–398.

THUNELL, R. C., and REYNOLDS, L. A., 1984. Sedimentation of planktonic foraminifera: seasonal changes in species flux in the Panama Basin. Micropaleontology, 30:243–262.

THUNELL, R. C., and WILLIAMS, D. F., 1983. The stepwise development of Pliocene-Pleistocene paleoclimatic and paleoceanographic conditions in the Mediterranean: oxygen isotopic studies of DSDP Sites 125 and 132. In: Meulenkamp, J. E., Ed., Reconstruction of marine paleoenvironments. Utrecht Micropaleontological Bulletin, 30:111–127.

TODD, R., 1957. Smaller Foraminifera. In: Geology of Saipan, Mariana Islands, pt. 3, Paleontology. United States Geological Survey, Professional Paper 280-H, pp. 265–320.

TOLDERLUND, D. S., and BÉ, A. W. H., 1971. Seasonal distribution of planktonic foraminifera in the western North Atlantic. Micropaleontology, 17:297–329.

WALTERS, R., 1965. The *Globorotalia zealandica* and *G. miozea* lineages. New Zealand Journal of Geology and Geophysics, 8:109–127.

WHITMARSH, R. B., 1974. Summary of general features of Arabian Sea and Red Sea Cenozoic history based on Leg 23 cores. In: Whitmarsh, R. B., Weser, O. E., et al., Initial Reports of the Deep

Sea Drilling Project, Volume 23:115–1124. Washington, D.C.: U.S. Government Printing Office.

WHITMARSH, R. B., WESER, O. E., et al., 1974. Initial Reports of the Deep Sea Drilling Project, Volume 23:291–420. Washington, D.C.: U.S. Government Printing Office.

WOODRUFF, F., SAVIN, S. M., and DOUGLAS, R. G., 1981. Miocene stable isotope record: a detailed deep Pacific Ocean study and its paleoclimatic implications. Science, 212:665–668.

WYRTKI, K., 1973. Physical oceanography of the Indian Ocean. In: Zeitzchel, B. Ed., The biology of the Indian Ocean, New York: Springer-Verlag.