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 microfossil 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 circumglobal 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

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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

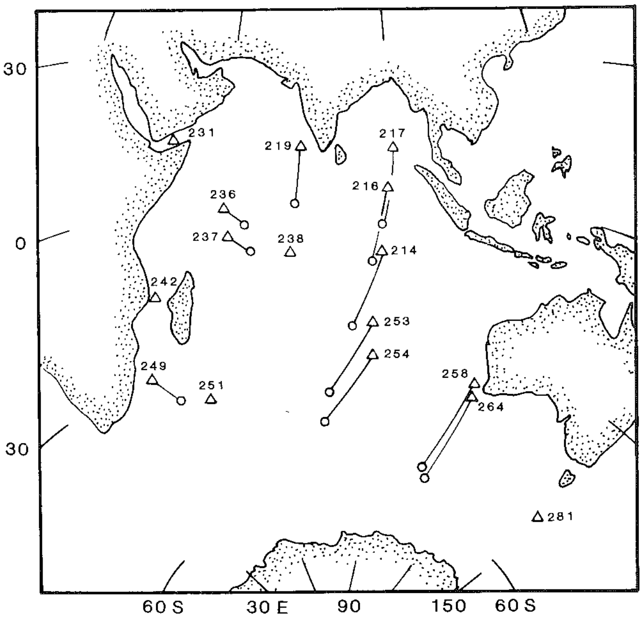
The early Miocene time-slice, Zone N4 (Blow 1969), was defined by the presence of *Globorotalia kugleri* (Bolli 1957) and *Globigerinoides primordius* (Blow and Banner 1962) and given the approximate age of 23 Ma (Berggren et al. 1985). *Globoquadrina dehiscens* (Chapman, Parr and Collins 1934) was also 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.

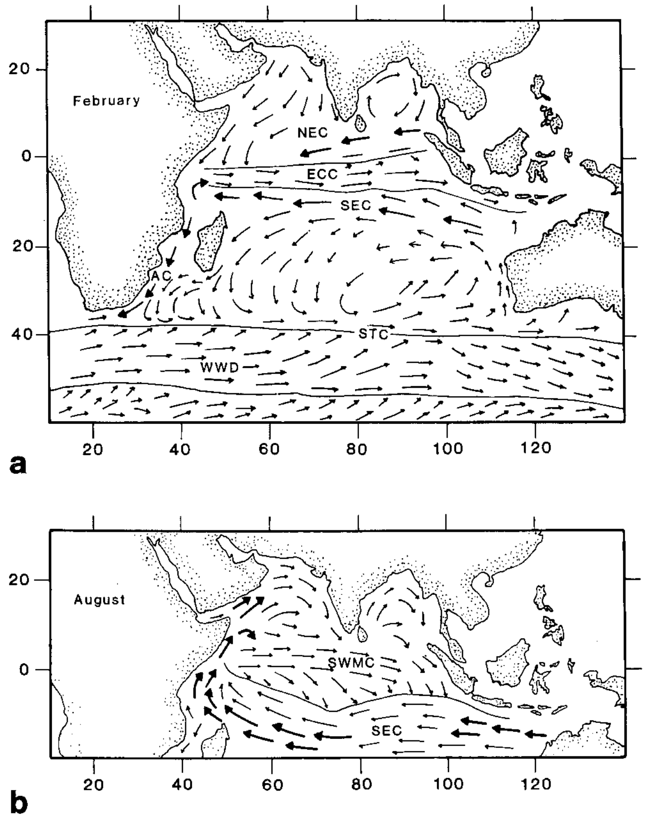
Surface Temperature Distributions

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-strati-graphic 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 planktonic 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 Plio-cene	Early-Plio-cene	Late Mio-cene	Middle Mio-cene	Early Mio-cene
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

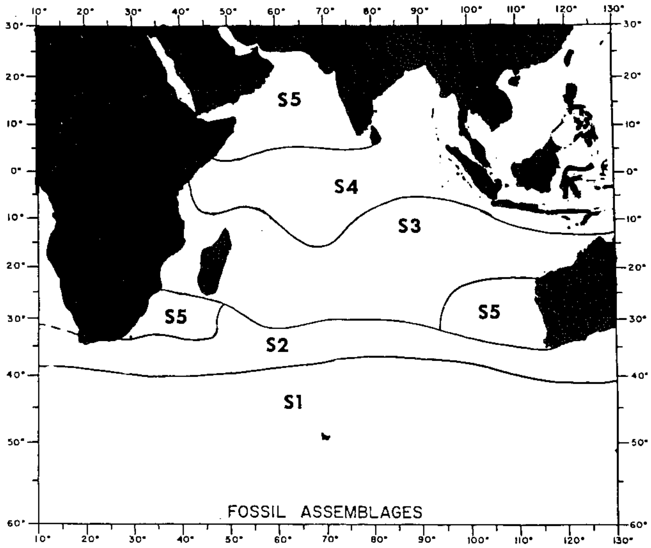
This assemblage is dominated by *Ga. glutinata, Gr. menardii* and *G. bulloides,* the last two being strongly affiliated with warm- and cold-water masses, respectively. This boundary current assemblage is found in areas having large seasonal temperature fluctuations (e.g. the upwelling region in the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

RESULTS

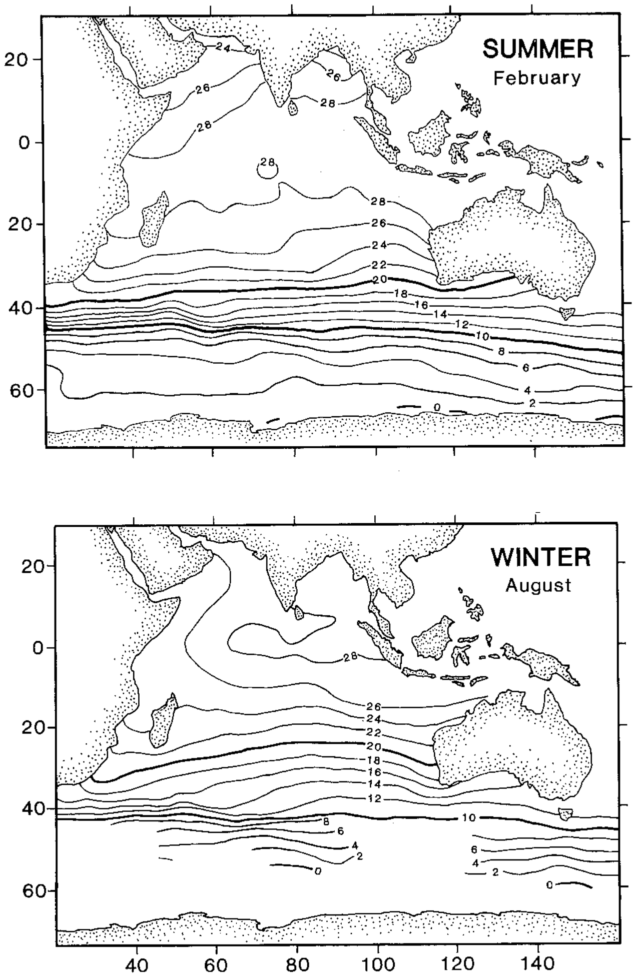
Individual species of planktonic foraminifera have been grouped into assemblages based on their abundance distributions (e.g. tropical bioprovince, subtropical bioprovince, transitional bioprovince, subpolar bioprovince and polar bioprovince), although the exact paleotemperature limits of each are not 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 presence of three bioprovinces. These provinces are designated as tropical, subtropical and transitional-subpolar (table 3).



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).

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.

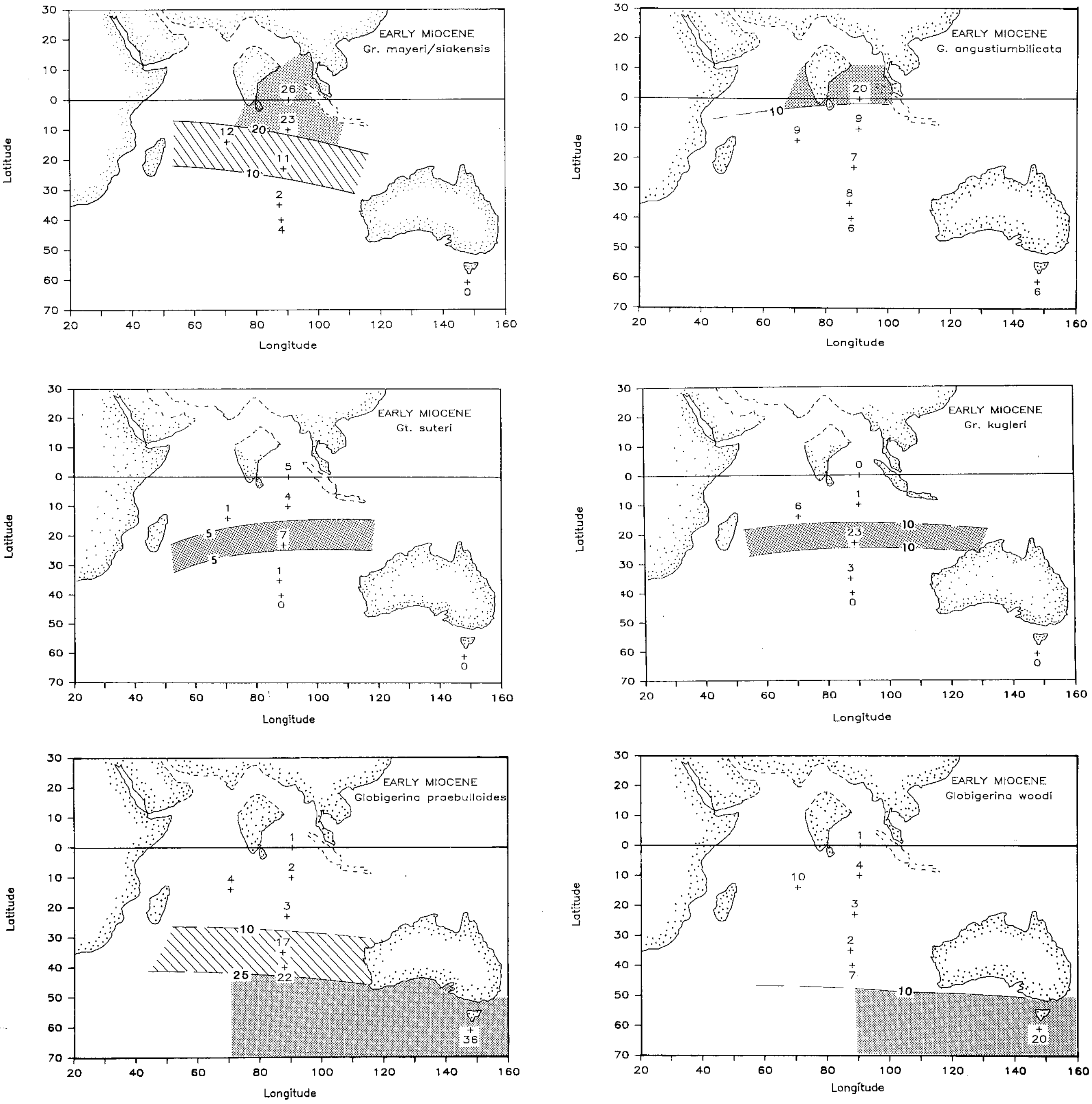
Middle Miocene (11 Ma)

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



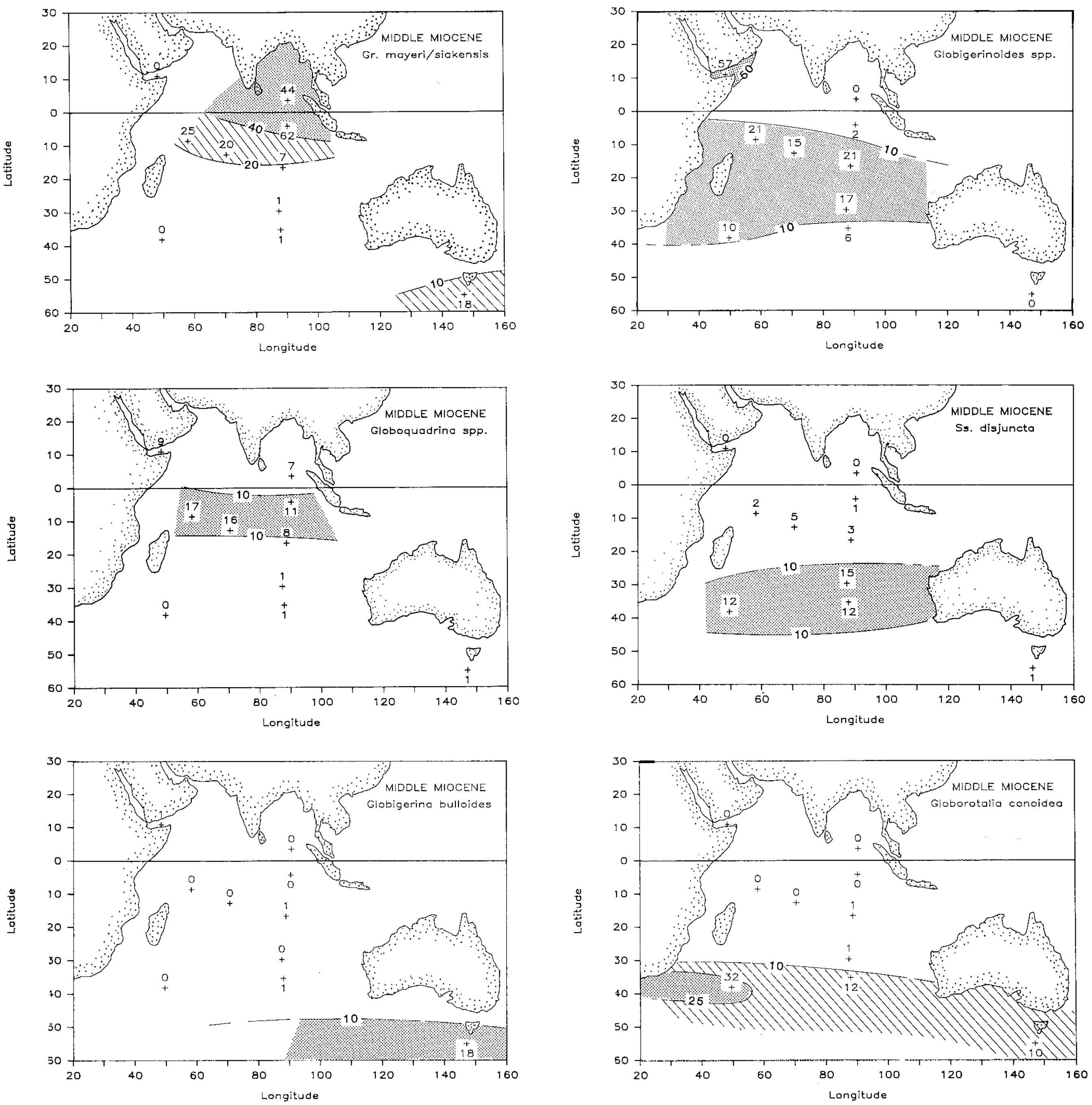
TEXT-FIGURE 5
Abundance distributions of selected planktonic foraminifera during the early Miocene (23 Ma).

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)

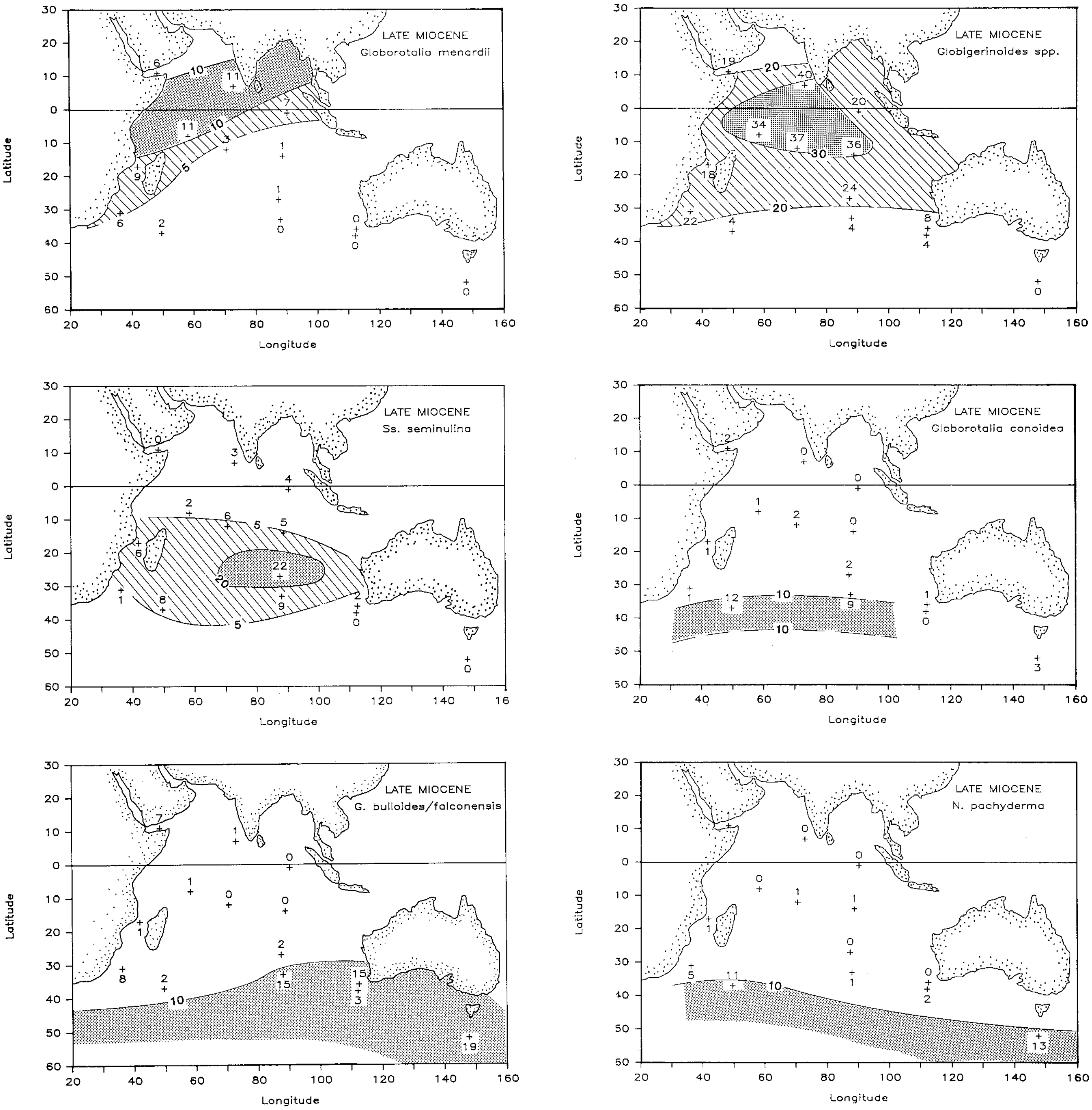
Four distinct biogeographic provinces can also be recognized in the late Miocene and are identified as tropical, subtropical, transitional and subpolar (table 3) as shown by representative



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 discussion). 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

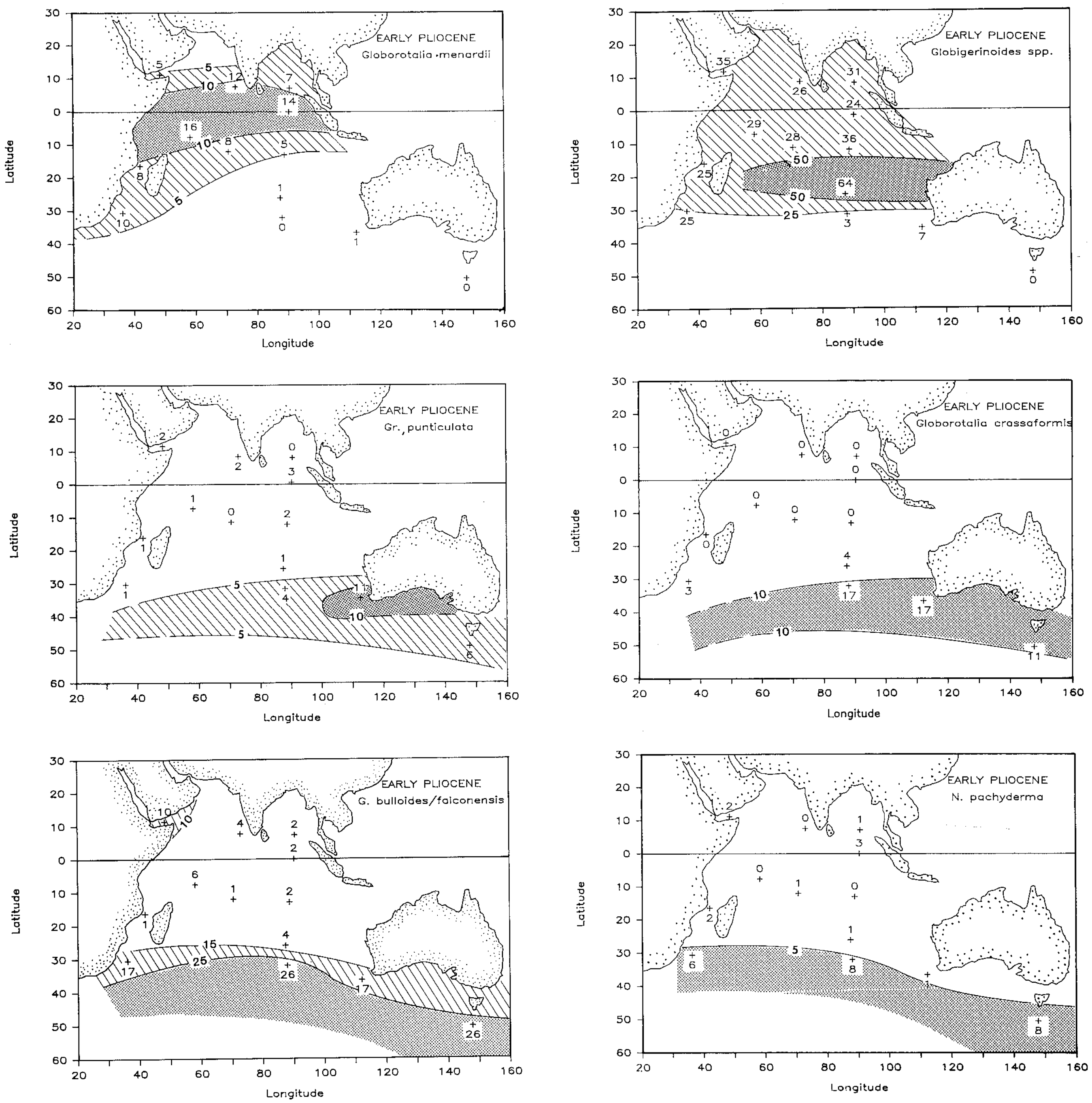


TEXT-FIGURE 7
Abundance distributions of selected planktonic foraminifera during the late Miocene (7 Ma).

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



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