

# Paleoceanographic implications of Miocene deep-sea hiatuses

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## ABSTRACT

Miocene paleoceanographic evolution exhibits major changes resulting from the opening and closing of passages, the subsequent changes in oceanic circulation, and development of major Antarctic glaciation. The consequences and timing of these events can be observed in variations in the distribution of deep-sea hiatuses, sedimentation patterns, and biogeographic distribution of planktic organisms.

The opening of the Drake Passage in the latest Oligocene to early Miocene (25–20 Ma) resulted in the establishment of the deep circumpolar current, which led to thermal isolation of Antarctica and increased global cooling. This development was associated with a major turnover in planktic organisms, resulting in the evolution of Neogene assemblages and the eventual extinction of Paleogene assemblages. The erosive patterns of two widespread hiatuses (PH, 23.0–22.5 Ma; and NH 1, 20–18 Ma) indicate that a deep circumequatorial circulation existed at this time, characterized by a broad band of carbonate-ooze deposition. Siliceous sedimentation was restricted to the North Atlantic and a narrow band around Antarctica.

A major reorganization in deep-sea sedimentation and hiatus distribution patterns occurred near the early/middle Miocene boundary, apparently resulting from changes in oceanic circulation. Beginning at this time, deep-sea erosion occurred throughout the Caribbean (hiatus NH 2, 16–15 Ma), suggesting disruption of the deep circumequatorial circulation and northward deflection of deep currents, and/or intensification of the Gulf Stream. Sediment distribution patterns changed dramatically with the sudden appearance of siliceous-ooze deposition in the marginal and east equatorial North Pacific by 16.0 to 15.5 Ma, coincident with the decline of siliceous sedimentation in the North Atlantic. This silica switch may have been caused by the introduction of Norwegian Overflow Water into the North Atlantic acting as a barrier to outcropping of silica-rich Antarctic Bottom Water.

The main aspects of the present oceanic circulation system and sediment distribution pattern were established by 13.5 to 12.5 Ma (hiatus NH 3), coincident with the establishment of a major East Antarctic ice cap. Antarctic glaciation resulted in a broadening belt of siliceous-ooze deposition around Antarctica, increased siliceous sedimentation in the marginal and east equatorial North Pacific and Indian Oceans, and further northward restriction of siliceous sediments in the North Atlantic. Periodic cool climatic events were accompanied by lower eustatic sea levels and widespread deep-sea erosion at 12 to 11 Ma (NH 4), 10 to 9 Ma (NH 5), 7.5 to 6.2 Ma (NH 6), and 5.2 to 4.7 Ma (NH 7).

## INTRODUCTION

The initiation of the Deep Sea Drilling Project (DSDP) in 1968 promised the recovery of complete stratigraphic sections containing an unbroken sedimentary record detailing the history of the oceans during the past 180 m.y. After 13 yr of drilling at over 500 sites, however, the deep-sea record is seen to contain major gaps or hiatuses, and a complete deep-sea record must be pieced together from two or more sections. Nevertheless, the key to the past oceanic environment lies largely in the biogenous sediments consisting of remains of planktic and benthic organisms. Moreover, the deep-sea hiatuses reflect the erosiveness of major bottom currents, and their distribution provides useful paleoceanographic information (Berggren, 1972; Johnson, 1972; Watkins and Kennett, 1972; Douglas and others, 1973; Rona, 1973b; Davies and others, 1975; van Andel and others, 1975; Moore and others, 1978). Hence, the history of the oceans, their paleoclimate, their paleocirculation, and even their tectonic changes are recorded in these deep-sea sediments.

An important factor in reconstructing the paleoceanography is the establishment of the paleoclimatic record. In recent years, such a record has been established based on the oxygen isotope composition of foraminifer shells (Douglas and Savin, 1973; Shackleton and Kennett, 1975; Keigwin, 1979). This method is based on the fact that shells are precipitated in equilibrium with sea water; relative to sea water, they are enriched in  $^{18}\text{O}$  in cool water and become lighter in  $^{18}\text{O}$  with increasing temperatures. The Miocene paleoclimatic record has also been studied extensively based on population studies of temperature-sensitive planktic foraminifers (Keller, 1980b, 1981a, 1981b; Srinivasan and Kennett, 1981b). But perhaps the single most important factor in reconstructing the paleoceanography is the history of circulation. Paleocirculation of currents is intimately related to the opening and closing of passages associated with shifting continents. Paleoceanographic reconstruction based on plate tectonics can put limits on the opening or closing of passages, such as the separation of Australia from Antarctica 45 to 40 m.y. ago (Weissel and others, 1977), the opening of the Drake Passage between 25 and 20 m.y. ago (Barker and Burrell, 1976), and the closing of the Straits of Panama in the early Pliocene. However, it is the biogeographic distribution of microfossils, and the ability to accurately correlate and date faunal events and, to a lesser degree, sedimentologic information, that are more reliable in pinpointing the time of formation or destruction of passages. Clearly, without an accurate method for correlating and dating paleoclimatic events, paleocirculation changes, and tectonic events, paleoceanographic reconstruction is severely limited.

Recent advances in biostratigraphic correlation, based primar-

Supplementary data for this article (Tables A, B, and C) may be secured free of charge. Request Supplementary Data 83-3 from the Documents Secretary, Publications Department, Geological Society of America.

ily on paleomagnetic stratigraphy, oxygen isotope studies, and integration of multiple microfossil stratigraphies, can now provide an average age control of 100,000 yr for the Miocene low-latitude deep-sea sediments (Keller, 1981a; Keller and others, 1983; Keller and Barron, 1981; Savin and others, 1981). This high-resolution biostratigraphy provides the unique ability to reliably identify and date short hiatuses, climatic oscillations, biogeographic patterns, and tectonic obstructions. It is this high-resolution biostratigraphy, developed from the most continuous sections of the deep-sea record, and the availability of a multitude of deep-sea cores provided by the Deep Sea Drilling Project, that now permit a more detailed paleoceanographic reconstruction of the Miocene ocean than has hitherto been possible.

The purpose of this study is to integrate the biogeographic and biostratigraphic information with the sedimentologic and tectonic information in order to gain a better understanding of the paleotectonic, paleoclimatic, and paleoceanographic history of the Miocene ocean. The major results of this study are (1) identification of Miocene deep-sea hiatuses  $\geq 0.5$  m.y. duration, using high-resolution biostratigraphy; (2) mapping the geographic distribution of each hiatus and identification of regions with complete sequences in order to isolate the effects of erosive bottom currents and regions of high biologic productivity; (3) determination of the age of major changes in type of sedimentation (siliceous, calcareous, terrigenous) and their spatial distribution through the Miocene; and (4) inference of the history of oceanic circulation, including the effects of ice-volume fluctuations on deep-sea erosion and dissolution, and the timing of interocean deep-circulation changes and their effects on surface productivity and sedimentation. What sets our study apart from earlier studies on hiatus distributions is the biostratigraphic control, which permits us to identify single erosional events of less than 0.5 m.y. and to map their distribution in the world ocean and thereby infer successive paleoceanographic, paleoclimatic, and tectonic changes during the Miocene.

Because of the complex and varied nature of the data presented here, this paper is written in four sections. The first section provides a brief review of the relevant oceanographic aspects such as glacial development, dissolution, bottom-water production, surface-water productivity, and paleocirculation. That part is followed by a discussion of possible causes of deep-sea hiatuses and the relevant stratigraphic aspects of this study. The second section discusses the distribution patterns of Miocene hiatuses and their implications for paleoclimatic and tectonic history of the Miocene ocean. The changing sediment distribution patterns, their relation to hiatus formation, and implication for paleoceanographic history are discussed in the third section. A summary and integration of the sedimentary and erosional processes of the world ocean are provided in the final section.

## PALEOCEANOGRAPHIC ASPECTS

### Cenozoic Glacial Development

The information gained from the deep-sea sedimentary record and discussed here is inferred from the biogeographic distribution of species; the paleocirculation changes; deep-sea hiatuses; dissolution; changes in the rate of sedimentation and, hence, biologic productivity; and tectonic changes. These data are directly or indirectly related to the Miocene glacial development. Therefore, it is appropriate to briefly review the evolution of Cenozoic glaciation. The

Cenozoic glacial development is intimately related to the formation of the circum-Antarctic circulation system resulting from the separation of Australia from Antarctica in middle to late Eocene time (Weissel and others, 1977). By the middle to late Eocene, a shallow circumpolar current developed, thermally isolating Antarctica (Kennett and others, 1975). Subsequent Antarctic cooling initiated the production of Antarctic bottom waters at near freezing temperatures around the continent, leading to substantially lower bottom-water temperatures in the earliest Oligocene (Kennett and Shackleton, 1975; Kennett, 1977). This dramatic drop in bottom-water temperatures is assumed to mark the onset of a deep-water circulation dominated by cold Antarctic Bottom Water, similar to the present (Shackleton and Kennett, 1975). Major oceanic circulation changes occurred in the early Miocene, triggered by the opening of the Drake Passage and formation of the deep Circum-Antarctic Current, leading to a major Antarctic glaciation by middle Miocene time (Shackleton and Kennett, 1975). Thereafter, climatic conditions stabilized, fluctuating between cold and less cool intervals.

### Dissolution

Production of cold Antarctic bottom water is directly related to dissolution of sediments due to corrosiveness of bottom waters, hiatuses caused by intensified bottom-current circulation, and increased biologic productivity resulting from increased upwelling. Changes in the chemical nature and flow of bottom water are primary causes for dissolution of sediments and deep-sea hiatuses. During periods of high-latitude cooling or glaciation, bottom-water production increases and bottom-water circulation is intensified, increasing the erosion of sediments on the sea floor and expanding the area in the ocean basins that is exposed to these corrosive waters. "Young" bottom water (that which has recently formed at or near the sea surface) is believed to be most corrosive to siliceous tests of diatoms and radiolarians, whereas "old" bottom water that is enriched in  $\text{CO}_2$  is more corrosive to calcium carbonate tests of foraminifers and coccolithophorids (Heath, 1974; Moore and others, 1978). Calcium carbonate dissolution, however, increases as a function of the organic content of the sediments, increasing depth of deposition, decreasing temperature, increasing partial pressure of  $\text{CO}_2$ , and increasing hydrostatic pressure (Berger and Winterer, 1973). Consequently, the lysocline (depth at which the dissolution rate increases) and the calcium carbonate compensation depth (CCD) (depth at which carbonate supply equals dissolution rate) rise in regions over which cold Antarctic Bottom Water flows. As a result, calcium carbonate dissolution is enhanced in upwelling regions during periods of increased productivity (Berger and Winterer, 1973; Melguen, 1978).

### Productivity

Productivity, and hence the rate of pelagic sedimentation in the deep sea, is largely a function of the availability of nutrients and sunlight and the ability of nutrient-rich deeper waters to reach the surface. Nutrients are bacterially regenerated at depth from particulate matter and dead organisms. In low-productivity areas, such as the central regions of major surface gyres, a deep, permanent thermocline forms a barrier between the nutrient-rich deep and surface waters (Berger, 1976). In high-productivity regions, the thermocline is shallow, permitting a continued replenishment of nutrients in the surface waters. High surface productivity is found in regions of

deep mixing of waters, such as the equatorial and polar front areas, and in zones of coastal upwelling. Productivity changes result from a change in the rate of deep mixing and upwelling, which is intimately associated with climatic oscillations and the rate of Antarctic Bottom-Water production. Consequently, increased upwelling, as for instance triggered by intensified circulation due to increased pole-to-equator thermal gradients, increases sedimentation rates of biogenous material while at the same time increasing carbonate dissolution due to the increasing organic content in sediments (Berger and Winterer, 1973). In deep-sea sediments, this dissolution effect can be observed in intervals that are carbonate poor and silica rich, or, if both silica and carbonate are affected by dissolution, it may result in nondeposition.

### Paleocirculation

Miocene current-circulation patterns are closely related to the opening of the Drake Passage; subsequent development of the deep Circum-Antarctic Current, which triggered a major Antarctic glaciation (Kennett, 1977); and to a lesser extent to the closing of the Tethyan seaway, which disrupted the circumequatorial flow. Apparently due to the development of the Circum-Antarctic Current, the nearly cosmopolitan distribution of Oligocene planktic assemblages was replaced by distinctive latitudinal belts of assemblages between the tropics and poles (Kennett, 1978). Intensified circulation associated with the intensification of the Antarctic Convergence resulted in a sharp division between siliceous sedimentation around the Antarctic and calcareous sedimentation toward lower latitudes (Kennett, 1978). These changes in the biogeographic distribution of planktic organisms have persisted through the Neogene and reveal fundamental changes in the global circulation patterns. The timing and nature of these circulation changes that are associated with the opening and closing of passages and major climatic changes, as well as relatively minor climatic oscillations, can be obtained from the biogeographic distribution of planktic and benthic assemblages. For instance, the paleocirculation patterns of surface currents can be inferred from the biogeographic distribution of planktic organisms based on the concept of planktic dispersion by currents (Berggren and Hollister, 1974). The paleocirculation of bottom currents is frequently inferred from the distribution of hiatuses in the deep-sea record (Johnson, 1972; Watkins and Kennett, 1972; Davies and others, 1975; McGowan, 1978; Thiede, 1981a, 1981b) and will be discussed later. Climatic information can also be obtained from the biogeographic distribution and diversity of planktic organisms, because they are largely controlled by the properties of sea water such as temperature, salinity, oxygen, and nutrients. Temperature and salinity are tied to thermohaline and wind-driven circulation, whereas oxygen and nutrients, and hence abundance and dispersion of organisms, are controlled by circulation (Berger, 1981).

### Causes and Distribution of Hiatuses

A hiatus can be defined as a gap in the sedimentary record resulting from erosion, increased dissolution, or nondeposition. Whether erosion, nondeposition, or sediment accumulation occurs is largely a function of the rate of sediment supply to the ocean floor and the rate of sediment removal. In pelagic sequences, the sediment-supply rate is largely determined by surface productivity, by the rate of sediment removal by bottom currents, and by the corrosiveness of deep waters with respect to silica and calcite (Rona, 1973a, 1973b; Davies and others, 1975; van Andel and others,

1975; Moore and others, 1978). For instance, in regions dominated by carbonate sedimentation, hiatuses are often the result of increased carbonate dissolution (corrosive bottom water) rather than physical erosion of sediments. The intensity of bottom currents and their erosiveness are determined by the amount of bottom-water production and, thus, by climatic oscillations. Therefore, the causes of oceanwide hiatuses should be linked primarily to paleoclimatically induced fluctuations in the intensity of oceanic circulation.

The distribution of hiatuses is largely determined by the flow path of major bottom currents. Tectonic movements associated with plate motion, however, can drastically alter the paths of bottom-water flow and thus change the pattern of hiatus distribution. The distribution of hiatuses is also linked to surface productivity and the intensity of bottom-water flow, which together determine the amount of sediment removed. Distinct short hiatuses, recording a single erosional (or nondepositional) event, are found in regions of high surface productivity; long hiatuses, combining two or more erosional events, occur primarily beneath the low-productivity central water masses and on topographic highs in the paths of major bottom currents. Whether a hiatus represents erosion, rather than nondeposition, can be determined from the presence of reworked older sediments. In high-productivity regions, where hiatuses are short, however, it is often not possible to determine the nature of the hiatus. It is suspected that in these regions hiatuses are generally caused by nondeposition due to increased carbonate dissolution. Previous studies, such as those of Rona (1973b), van Andel and others (1975), Moore and others (1978), and Thiede (1981a, 1981b), outlined the distribution of long hiatuses generally spanning more than 3 m.y. These hiatuses represent major erosional events often in low-productivity regions or paths of major bottom currents.

The time of maximum extent of a hiatus can be determined by the age of the overlying and underlying sediments. This provides a relatively accurate measure of the time of cessation of an erosive event. Dating the time of initiation, however, is more difficult, because the extent of sediment removal is determined by topography and the erosiveness of bottom currents. Nevertheless, an age estimate for the initiation of a hiatus can be obtained from the underlying sediments and from the regional synchronicity of a hiatus (Berger, 1972; Moore and others, 1978). In regions of low productivity, such as the central regions of major oceanic gyres, the sediment deposited upon cessation of a single erosive event may be subsequently eroded by a second erosive event, resulting in a long hiatus.

In the preceding discussion, we have assumed that deep-sea hiatuses are caused by changes in the erosive intensity and corrosiveness of bottom water. This relation would limit the occurrence of hiatuses to depths below about 2,500 m, as indeed has been observed in the deep ocean basins. However, the same hiatuses are also commonly observed on continental-slope and shelf regions, on oceanic plateaus, and in onshore marine sequences (Thiede, 1981a). We must therefore assume that the paleoclimatic events that intensify Antarctic Bottom-Water circulation also affect nearshore regions. Synchronous hiatuses in deep-sea and nearshore regions may be partly explained by the fact that the CCD is deepest in equatorial regions and shallows toward continental margins and the poles (Berger and Winterer, 1973; van Andel and others, 1975). The occurrence of these hiatuses in shallow nearshore sediments, however, is most likely due to a fall in the global eustatic sea level (downward shift of coastal onlap) owing to increased polar glaciation. In fact, many deep-sea and nearshore hiatuses coincide with

periods of downward shift of coastal onlap or rapid fall of the eustatic sea level, as has been recognized in seismic studies by Rona (1973a), Vail and others (1977), and Vail and Hardenbol (1979).

### Stratigraphy

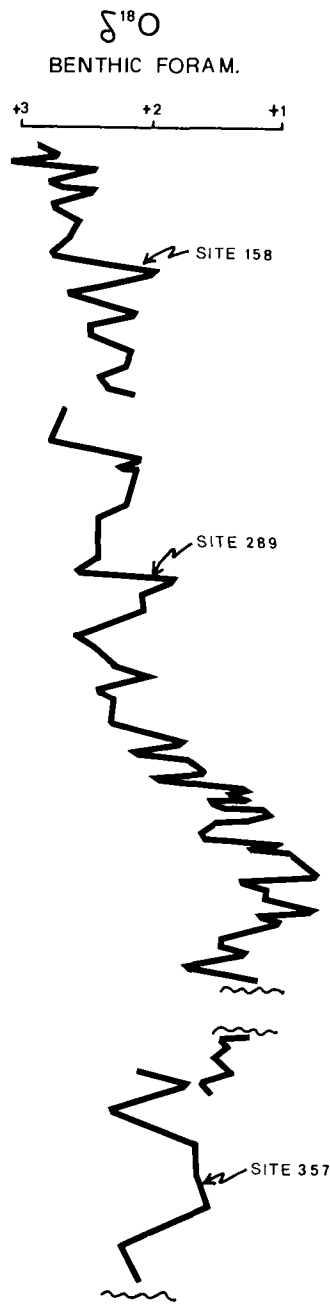
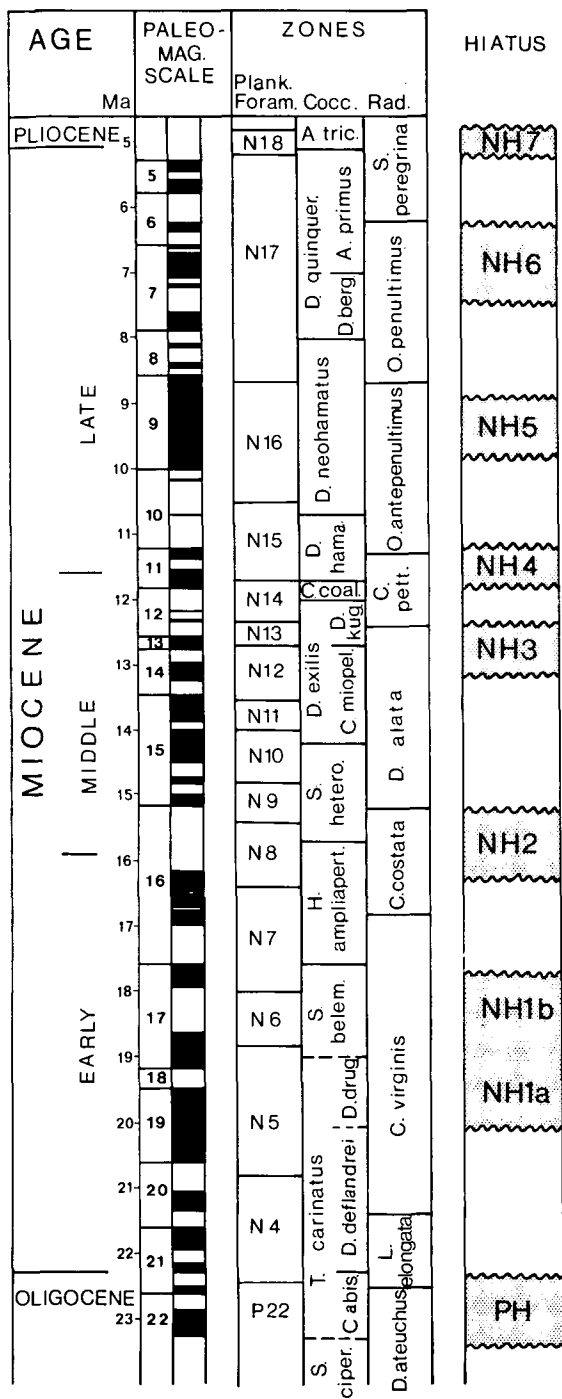
The high-resolution stratigraphy that allows us to identify the short hiatuses discussed in this paper has been developed by many workers, from the integration of multiple microfossil biostratigraphies (Ryan and others, 1974; Berggren and Van Couvering,

1974; Saito and others, 1975; Vincent, 1977; Haq and others, 1980; Keller, 1980a, 1980b, 1981a, 1981b; Keller and others, 1983; Barron and others, 1981; Keller and Barron, 1981) with paleomagnetic studies (Saito and others, 1975; Burckle, 1978b; Theyer and others, 1978), carbon and oxygen stratigraphies (Keigwin, 1979; Vincent and others, 1980; Savin and others, 1981; Woodruff and others, 1981), and carbonate stratigraphy (Kaneps, 1973; Dunn and Moore, 1981). Integration of these data has provided a high-resolution stratigraphic record allowing resolution of time down to 100,000 yr in low-latitude sequences of the Miocene, as well as a

TABLE 1. MICROFOSSIL DATUM LEVELS THAT IDENTIFY THE LATEST OLIGOCENE AND MIOCENE HIATUSES

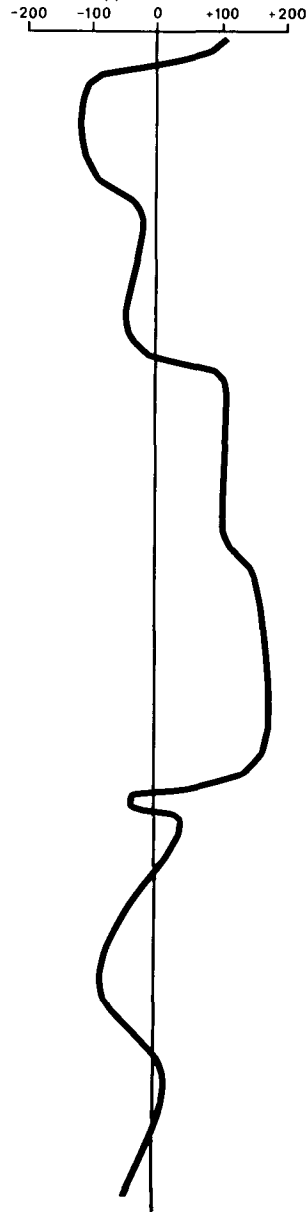
Hiatus		Planktic foram	Coccoliths	Radiolaria	Diatoms
NH 7	top	B. G. crassaformis	B. C. rugosus	B. P. prismaticus?	B. N. Jouseae
	bottom	B. G. tumida	T. D. quinquera.		T. T. miocenica
	Zone removed	N18	T. rugosus and C. acutus (CN10a, b)		T. miocenica subzone c
NH 6	top	B. P. primalis	B. A. primus	B. S. peregrina	B. T. praeconvexa
	bottom	B. G. conglobatus	B. D. quiqueramus	T. O. hughesi	T. T. burckliana
	Zone removed	T. G. kennetti*	D. berggreni sz. (CN9a)	O. penultimus (most)	N. miocenica (most)
NH 5	top	B. G. kennetti*		B. O. penultimus	B. T. burckliana
	bottom	T. G. dehiscens*		T. C. petterssoni	T. C. temperei var. delicata
	Zone removed	top of N16	D. neohamatus (short CN8)		
NH 4	top	B. N. acostaensis B. N. continuosa*	T. D. hamatus	B. O. antepenultimus	T. A. ellipticus var. moronensis B. D. dimorpha*
	bottom	T. G. siakensis T. G. mayeri	B. D. hamatus	T. C. cornuta	T. C. coscinodiscus T. D. punctata var. hustedtii
	Zone removed	N15	D. hamatus (CN7)	C. petterssoni (most)	D. hustedtii- D. lauta* sz c
NH 3	top	B. G. nepenthes	B. D. kugleri	T. D. alata	B. C. temperei var. delicata
	bottom	B. G. fohsi lobata		B. C. laticonus	B. C. yabei
	Zone removed	N13 & top N12	C. miopelagicus (sz CN5a, most)		D. hustedtii- D. lauta* sz b
NH 2	top	B. Orbulina		B. D. alata	
	bottom	B. G. archeomenardii		T. L. elongata	
	Zone removed	B. G. diminutus B. G. sicanus N8 & lower N9		C. costata (most)	
NH 1	top	T. C. dissimilis T. C. stainforthi	B. S. heteromorphus	T. D. ateuchus B. S. wolfii B. C. violina	B. D. nicobarica
	bottom		B. S. belemnos		
	Zone removed	N5 & N6 (most)	S. belemnos (CN2)		
PH	top			T. D. papillio T. A. gracilis	
	bottom	B. G. primordius	T. S. ciperoensis T. D. bisectus	B. L. elongata	
	Zone removed	P22 (upper)	C. abisectus sz. (CN1a)		

Note: Microfossil datum levels (first and last appearances) which bracket and thereby define the intervals of the eight widespread latest Oligocene through Miocene deep-sea hiatuses are shown here. B = first appearance or base of range, T = last appearance or top of range. \* = middle latitude datum or zone. Planktic foraminiferal zones of Blow (1969); coccolith zones and subzones of Bukry (1975); radiolarian zones of Riedel and Sanfilippo (1970); diatom zones and subzones of Burckle (1972) for low latitudes, and Barron (1980) for middle latitudes.



EUSTATIC SEA LEVEL CURVE

(VAIL & HARDENBOL, 1979)  
Approx. Meters



COASTAL ONLAP CURVE

(VAIL & HARDENBOL, 1979)

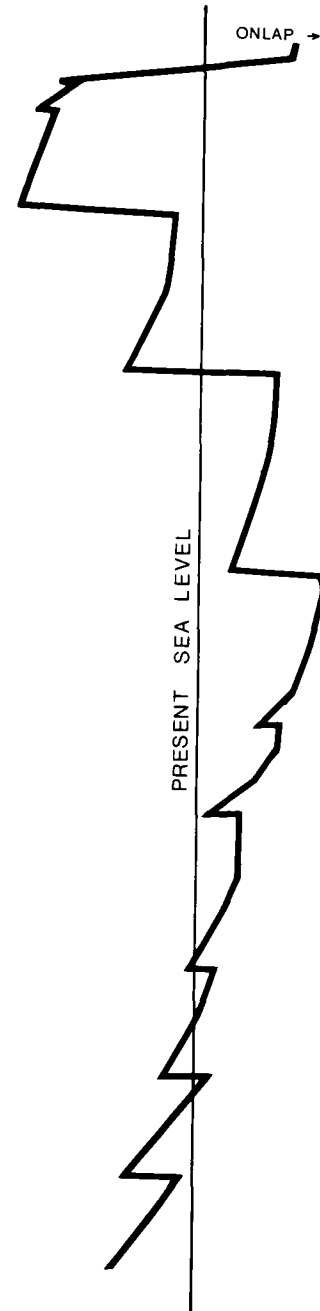


Figure 1. Miocene time scale illustrating the distribution of the eight latest Oligocene through Miocene deep-sea hiatuses, an oxygen-isotope curve for benthic foraminifers, and the eustatic sea-level curve and the coastal-onlap curve of Vail and Hardenbol (1979). The paleomagnetic time scale is that of Mankinen and Dalrymple (1979). Planktic foraminiferal zonation after Blow (1969). Coccolith zonation after Bukry (1975). Radiolarian zonation after Riedel and Sanfilippo (1970). Oxygen-isotope curve compiled from Boersma and Shackleton (1977) for the earliest Miocene, and Keigwin (1979), Woodruff and others (1981), and Savin and others (1981).

wealth of paleoclimatic and paleoceanographic information (Keller, 1981a; Keller and others, 1983; Keller and Barron, 1981; Savin and others, 1981; Srinivasan and Kennett, 1981b). The application of this high-resolution stratigraphic record to deep-sea sediments, and to identification of Miocene hiatuses in particular, is discussed in Keller (1981a) and Barron and Keller (1982), and the reader is referred to these papers. Microfossil datums (first and last appearances of species) that identify Miocene hiatuses are listed in Table 1. A simplified version of the Miocene time scale plotted against the paleomagnetic time scale of Mankinen and Dalrymple (1979) is illustrated in Figure 1.

## MIOCENE HIATUSES

### Recognition of Miocene Hiatuses

Miocene hiatuses have been recognized in deep-sea sections throughout the world ocean, making it difficult to obtain an unbroken sedimentary record. We have reconstructed the stratigraphic record based on the most complete Miocene deep-sea sections from the Pacific, as illustrated in Figure 2 (based on the time scale of Fig. 1). This figure is constructed based on planktic foraminiferal data from DSDP Sites 158, 77B, 292, 438/439, 173, 310, 470, and 319 (Keller, 1981a; Keller and others, 1982; Keller and Barron, 1981) and diatom data from DSDP Sites 158, 77B, 438/439, 173, and 470 (Barron, 1980, 1981a). The planktic foraminifers and diatoms of Site 495 were studied for this report. These data were supplemented for the remaining sites by DSDP data as well as the recent studies on radiolarians by Westberg and Riedel (1978) and studies on planktic foraminifers by Srinivasan and Kennett (1981a, 1981b).

It is notable that many of the hiatuses illustrated in Figure 2 fall between two cores. In an earlier study on Cenozoic hiatuses, Moore and others (1978) argued that stratigraphic breaks that fall between two cores may be due to incomplete core recovery rather than hiatuses. This observation is particularly relevant in regions of low sedimentation rates and where biostratigraphic control is based on one or two samples per core (shore laboratory reports of DSDP), as used in the study by Moore and others (1978). In our study, however, we consider it insignificant that many hiatuses fall between two cores, for the following reasons. Our stratigraphic control is much greater than that of Moore and others because we analyzed at least one sample per section (six per core) of sites illustrated in Figure 2. Furthermore, the average sedimentation rate is 15 to 20 m/m.y. (about two cores) in the high-productive regions, and hence our hiatuses, which average 1 m.y., can easily be determined even from sedimentation-rate curves. Finally, the eight hiatuses identified can be recognized in numerous deep-sea sections where they fall between cores as well as within core sections.

Eight distinct hiatuses can be identified in Pacific deep-sea sequences between the latest Oligocene and Miocene/Pliocene boundary (Figs. 1 and 2). We have chosen to number these hiatuses upward from the Paleogene/Neogene boundary (the lower part of planktic foraminiferal zone N4) following the practice of planktic foraminiferal and coccolith zonal notation. Consequently, each Neogene hiatus is designated "NH" for Neogene hiatus and numbered 1 through 7. The latest Oligocene hiatus here is labeled "PH" for "Paleogene hiatus" at this time; however, future detailed study of the Paleogene should allow distinct, widespread hiatuses to be identified and numbered upward from the Cretaceous/Tertiary boundary. Although these eight hiatuses vary somewhat in duration, the ages of widest geographical extent are estimated as follows: PH, 23.0 to 22.5 Ma; NH 1, 20.0 to 18.0 Ma; NH 2, 16.0 to

15.0 Ma; NH 3, 13.5 to 12.5 Ma; NH 4, 12.0 to 11.0 Ma; NH 5, 10.0 to 9.0 Ma; NH 6, 7.5 to 6.2 Ma; NH 7, 5.2 to 4.7 Ma (Fig. 1).

Figure 1 compares these eight hiatuses with a composite oxygen-isotope curve based on data from Boersma and Shackleton (1977), Keigwin (1979), and Woodruff and others (1981). As noted above, positive enrichment of  $^{18}\text{O}$  in foraminiferal tests is interpreted to reflect cooling of sea water and, hence, cooling of high latitudes and/or increased glaciation. Therefore, if deep-sea hiatuses form as a result of increased polar glaciation and intensification of bottom-water circulation and corrosiveness, times of widespread hiatus development should correspond to times of positive enrichment of  $^{18}\text{O}$ . Figure 1 shows that all Miocene hiatuses, except NH 2 (16.0–15.0 Ma) occur at times when the oxygen-isotope curve indicates rapid cooling.

Similarly, deep-sea hiatuses should correlate with onshore unconformities produced by eustatic lowering of the sea level, where both reflect periods of intensified polar glaciation. Figure 1 shows that virtually all of the times at which Vail and others (1977) and Vail and Hardenbol (1979) postulate severe downward shifts of coastal onlap, or low eustatic sea level, are correlative with the presence of hiatuses in the deep sea. Although hiatus NH 4 does not correspond to a time of major downward shift of coastal onlap, according to Vail and others, we speculate that application of high-resolution biostratigraphy to coastal sequences is likely to identify a downward shift of coastal onlap at that time.

Periods of global cooling and eustatic sea-level lowering, or downwards shifts in coastal onlap, are associated with increased oceanic sedimentation, and yet widespread hiatuses occur at these times. Where did all of the sediment go during these times of widespread hiatus formation? It must be remembered that increased sedimentation in the open ocean implies increased productivity due to more vigorous upwelling triggered by high-latitude cooling. During times of high-latitude cooling, however, bottom-water circulation is intensified, increasing the erosion of sediments on the sea floor and expanding the area in the ocean basins that is exposed to corrosive water. In addition, dissolution of both silica and carbonate increases during times of increased bottom-water production and increased upwelling, as discussed earlier. Consequently, increased sedimentation, resulting from increased upwelling and productivity during cool events, may be outweighed by increased dissolution resulting in nondeposition and/or erosion.

### Survey of DSDP Sites

A survey of DSDP sites in the Pacific, Atlantic, and Indian Oceans<sup>1</sup> reveals that hiatuses PH through NH 7 are widespread and well defined throughout the world ocean. Our survey uses microfossil-occurrence data published in the *Initial Reports of the Deep Sea Drilling Project* and applies our Miocene time scale (Fig. 1) and the data in Table 1, which characterizes each hiatus in terms of microfossil datum levels. DSDP data range from detailed occurrence charts to sparse and vague zonal assignments made on discontinuously cored material. Because our hiatuses average about 1 m.y. in duration, low sediment-accumulation rates, poor microfossil control, poor recovery, or discontinuous coring commonly prevents definitive identification of the hiatuses. Therefore, Tables A through C distinguish between definite and probable identification of each hiatus and also show where two or more hiatuses have been combined to form one long hiatus (see footnote 1).

<sup>1</sup>Supplementary tabular data have been placed in the Data Bank at GSA headquarters. For free copies of Tables A, B, and C, write or call and request Supplementary Data no. 83-3.

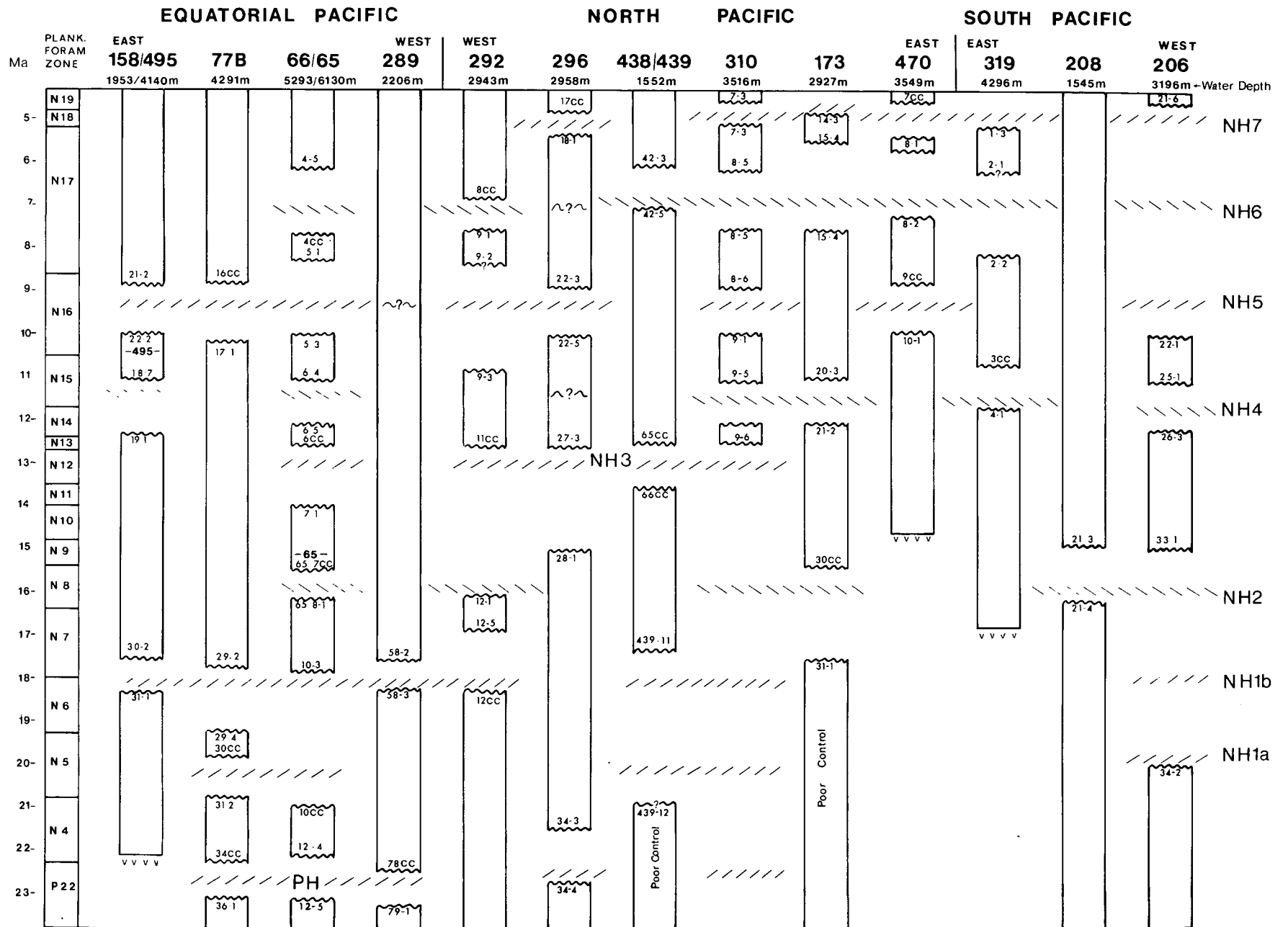


Figure 2. Occurrence and age of latest Oligocene through Miocene hiatuses in selected deep-sea sections from the Pacific. Each section is labeled by DSDP site number and water depth in metres. The occurrence of each hiatus is labeled by core and section number above and below the wavy line. The time scale is the same as that of Figure 1.

### Distribution of Deep-Sea Hiatuses

The distribution of each of the eight latest Oligocene through Miocene deep-sea hiatuses in the world ocean is outlined in Figures 3 through 10. The areas outlined by the densely stippled pattern represent regions free of the respective hiatus and are interpreted as representing highest surface productivity. Areas outlined by the less densely stippled pattern represent regions containing the respective hiatus and are interpreted as regions of intermediate to high surface productivity. Hiatuses occurring in these less densely stippled areas are discrete events representing short intervals of geologic time. Outside of the stippled areas, hiatuses are less discrete and tend to coalesce into long intervals spanning two or more hiatuses. The regions outside the stippled areas correspond primarily to the low-productivity central water masses. Isolated shallow sections on structural highs, such as the Manihiki Plateau, the Ninetyeast Ridge, and the Lord Howe Rise, are generally not included (Fig. 3). In the present ocean, regions of high biologic productivity are primarily determined by upwelling and major surface gyres, whereas hiatuses reflect intensified bottom-water circulation. It is therefore reasonable to assume that any changes in the distribution of high-productivity regions, and the distribution of hiatuses, reflect changes in the oceanic circulation pattern, including variations in the intensity of current flow and creation or destruction of tectonic barriers.

#### Hiatus PH (23.0–22.5 Ma)

The latest Oligocene hiatus PH is often difficult to identify because late Oligocene biostratigraphy has not yet achieved the refinement of Miocene biostratigraphy. In many sequences, this hiatus is characterized by increased carbonate dissolution, making it often impossible to determine whether an interval is actually missing; in such cases, we have assumed that the sequence is complete. The paucity of continuously cored sections containing this interval is a further handicap in reconstructing this hiatus. Therefore, we consider this interval to be our weakest time-slice reconstruction.

Nevertheless, certain features are outstanding. A concentration of the most complete sequences (including those with a short hiatus) forms a narrow belt through the equatorial region, although no data are available from the western equatorial Pacific to the eastern Indian Ocean. Presumably, this equatorial belt reflects high surface productivity beneath a relatively unobstructed circumequatorial surface current (Fig. 3). Major erosional unconformities are found on the Rio Grande Rise in the Atlantic Ocean, on the Hess Rise in the Pacific Ocean, and on the Naturalist Plateau in the Indian Ocean. In the present oceans, these barriers lie in the path of major deep ocean currents carrying waters from the circumpolar current northward. This implies that the major deep circulation patterns of the latest Oligocene to earliest Miocene were not significantly different from the present.

The establishment at that time of an oceanic circulation system similar to the present system can also be inferred from major evolutionary changes in planktic faunas and floras. During the latest Oligocene and early Miocene, a major faunal turnover occurred in planktic organisms, resulting in the evolution of the Neogene fauna and flora and eventual extinction of the Paleogene faunas, in changes in the global planktic biogeographic distribution patterns,

and in increased planktic diversity between tropical and polar regions (Lipps, 1970; Edwards and Perch-Nielsen, 1975; Kennett, 1978; Keller, 1980b, 1981b). The evolution of the high-diversity Neogene fauna and flora and increased latitudinal diversity imply an increased water-mass stratification and, hence, creation of new ecologic niches for speciation. Throughout the Neogene, these water-mass-related biogeographic-diversity changes largely retained their identity. Therefore, we may assume that the basic water-mass characteristics of the present-day oceans became established in the earliest Neogene (Kennett, 1978).

Based on our distribution maps for hiatuses PH and NH 1 (Figs. 3 and 4) and previous faunal analyses (Keller, 1980a, 1980b, 1981b), we suggest that a steep, vertical thermal gradient and increased water-mass stratification developed between 23 and 20 Ma, presumably caused by the opening of the deep Drake Passage and formation of the deep Circum-Antarctic Current. The full effect of this circulation change appears to have been reached between 22 and 21 Ma as indicated by a major planktic foraminiferal turnover (Keller, 1981b). Perhaps due to further thermal isolation of Antarctica, a worldwide cooling occurred by about 20 Ma, climaxing in a major erosional event (hiatus NH 1, Fig. 4), an interpretation supported by oxygen-isotope data (Boersma and Shackleton, 1977; see also Fig. 1).

#### Hiatus NH 1 (20.0 to 18.0 Ma)

The early Miocene hiatus NH 1 marks perhaps the most significant erosional event during the Miocene and, as we discuss below, predates the development of the present oceanic surface circulation. Hiatus NH 1 has a worldwide distribution in both middle and low latitudes (Keller, 1980a, 1981b), and few deep-sea sequences are complete during this interval (Fig. 4; Table 1; see also Tables A–C referred to in footnote 1 above). Increased carbonate dissolution is present at all DSDP sites between 20 and 17 Ma, although complete sequences indicate that intervals of increased dissolution alternate with well-preserved intervals (Keller, 1980a). There is some evidence that NH 1 actually represents two hiatuses, one at about 20 to 19 Ma (NH 1a) and the other at about 18 Ma (NH 1b) (Keller, 1980a). In most deep-sea sequences, however, only one hiatus can be recognized spanning the interval between 20 to 18 Ma. This suggests that the second hiatus event (NH 1b) was the stronger of the two and subsequently eroded sediment deposited between events NH 1a and 1b. Alternatively, a rapid rise in sea level following this cool event may have led to a period of nondeposition. Hiatus NH 1 has also been found in onshore sections of the eastern United States. Published (Abbott, 1978; Blackwelder, 1981) and unpublished data (J. E. Hazel and L. W. Ward, 1981, written commun.) indicate that deposits of N6 (planktic-foraminiferal zone) or younger age overlie deposits of Paleogene or very early Miocene (N4) age. Hiatus NH 1 is also recognized as a major fall in the coastal-onlap curve (Fig. 1; see also Vail and Hardenbol, 1979).

The distribution of NH 1 is illustrated in Figure 4. The most complete sequences (including those with a short duration, 0.7–1.5 Ma) outline a narrow band through the equatorial region presumably reflecting high surface productivity. This equatorial band and the existence of hiatus NH 1 on both sides of the present-day Isthmus of Panama suggest that surface waters as well as deeper erosive waters (at least 2,000 m deep) still passed through the Caribbean into the Pacific and Indian Oceans.



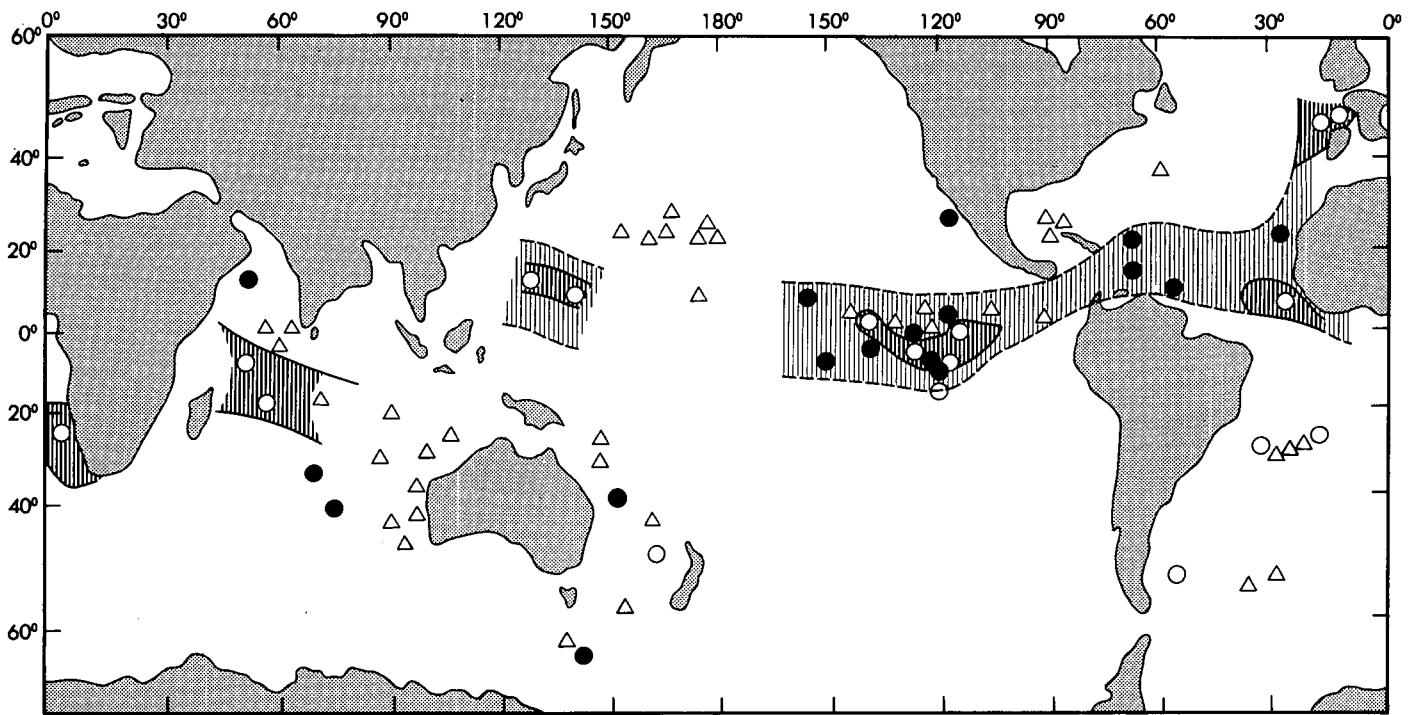


Figure 3. Distribution of hiatus PH (23.0–22.5 Ma) in DSDP sections of the world ocean. DSDP sites have been backtracked for hiatus PH and NH 1. Open circles mark complete sections not containing the hiatus. Black circles show sections where the hiatus is well defined; black/white circles mark sections in which the short hiatus could not be identified with certainty. Triangles mark hiatuses of longer duration that include the interval of this particular hiatus. Vertical lines outline regions containing complete sections (light lines) and those containing the short hiatus (heavy lines); these regions are inferred to represent high surface productivity.

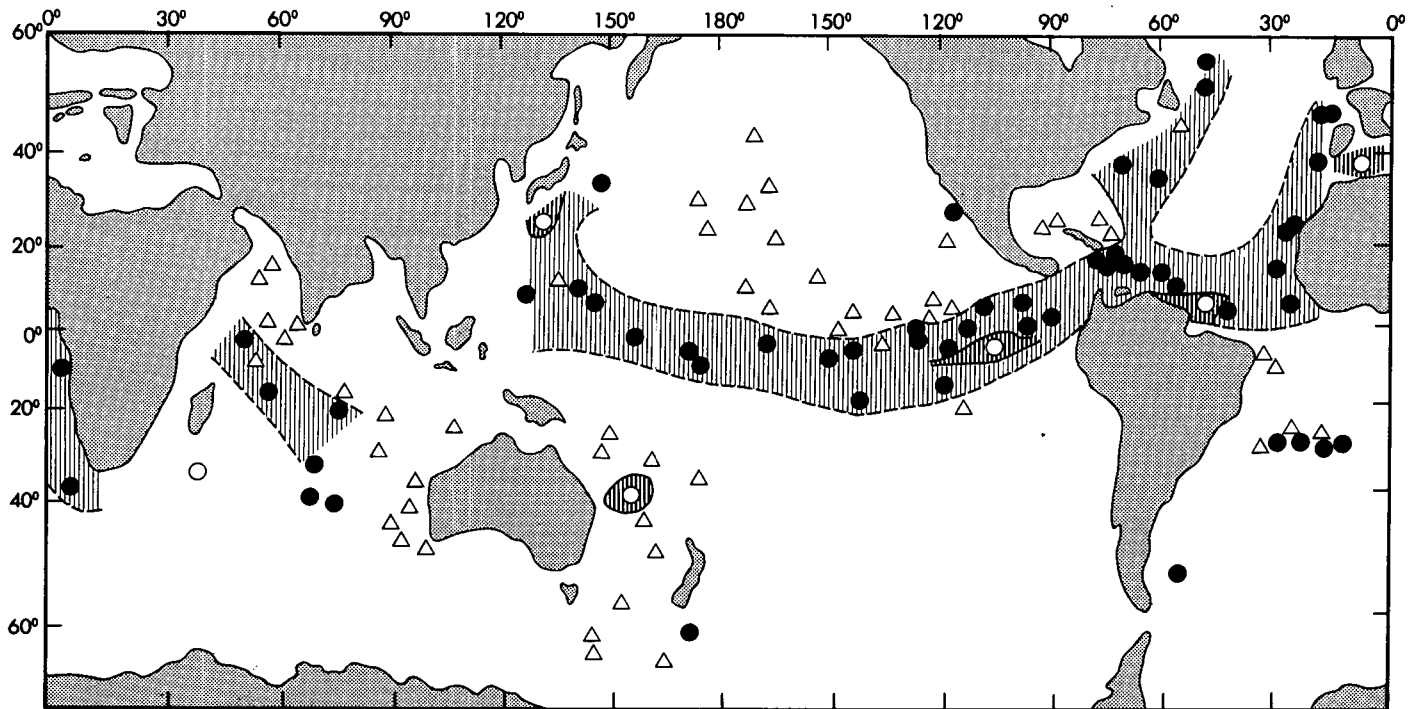


Figure 4. Distribution of hiatus NH 1 (20.0–18.0 Ma) in DSDP sections of the world ocean. See Figure 3 for explanation of symbols.

As mentioned above, hiatus NH 1 coincides with a major cooling in the oxygen-isotope curve and a lowering of the eustatic sea level (Fig. 1). Therefore, we assume that this hiatus was caused by intensified deep currents and increased corrosiveness of deep waters that lead to carbonate dissolution, sediment erosion, and a rise in the CCD and lysocline. This assumption is supported by a recent study of silicoflagellates by Bukry (1982) at DSDP Site 495 off Guatemala that shows periods of extreme cooling during planktic foraminiferal zones N5 and N6. Cool climatic conditions during the time of hiatus NH 1 are also suggested by planktic foraminiferal analyses: species evolving and dominating between 20 and 18 Ma are the cool to temperate *Globorotalia zealandica* and *G. miozea* lineages (Keller, 1980a, 1981a; Srinivasan and Kennett, 1981a, 1981b).

The absence of any significant faunal changes between 18 and 16.5 Ma may be partly attributed to the obscuring effects of carbonate dissolution. A renewed surge in evolutionary activity beginning at about 16.5 Ma apparently marks the initial development of an oceanic circulation system similar to that of the present (Keller, 1981b).

In the following discussion of Neogene hiatus events NH 2 through NH 7, note that DSDP sites have been plotted at their present location, rather than backtracked; the difference in paleolatitude is minimal and decreases upsection. Primarily, the effect would be to move high-productivity regions 1° to 3° south of their present position.

#### Hiatus NH 2 (16.0 to 15.0 Ma)

In contrast to the two earlier events (PH and NH 1), deep-sea sections containing this short hiatus are found primarily at middle latitudes (Fig. 5; see also Keller, 1981b; Srinivasan and Kennett, 1981b). The numerous sections containing an extended erosional unconformity spanning two or more hiatuses at this time (triangles, Fig. 5) generally lie beneath low-productivity regions or along major paths of bottom-water transport. A new feature, however, appears in the distribution of long erosional unconformities. All deep-sea sediments drilled in the Caribbean show the effects of major sediment erosion during this time (Fig. 5). A major change is also apparent in the distribution of complete sections representing high-productivity regions (stippling, Fig. 5). In contrast to the early Miocene, when an intermediate- to high-productivity belt spanned primarily the equatorial region, the high-productivity region during this time also expanded to the marginal North Pacific. Moreover, the high-productivity region is more widespread during NH 2 time than during any other hiatus interval during the Miocene.

In the present North Pacific, the high-productivity region extends along the marginal North Pacific, similar to its extent during NH 2 time. This high siliceous productivity is due to upwelling of nutrient-rich waters along the coast. The change in the high-productivity region and increased siliceous sedimentation in the North Pacific coincides with a silica budget transfer from the Atlantic to the Pacific and Indian Oceans at this time and presumably

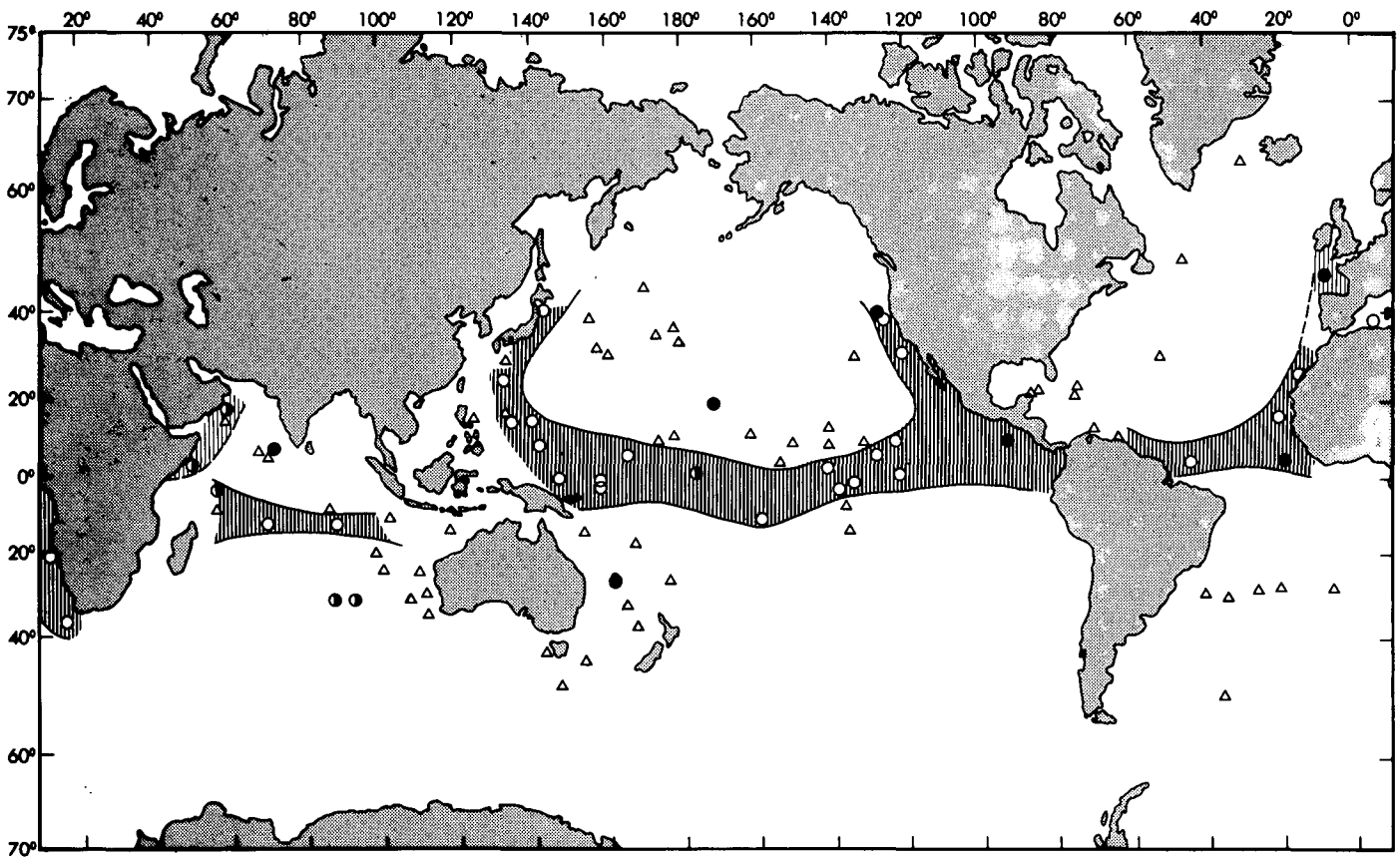


Figure 5. Distribution of hiatus NH 2 (16.0–15.0 Ma) in DSDP sections of the world ocean. See Figure 3 for explanation of symbols.

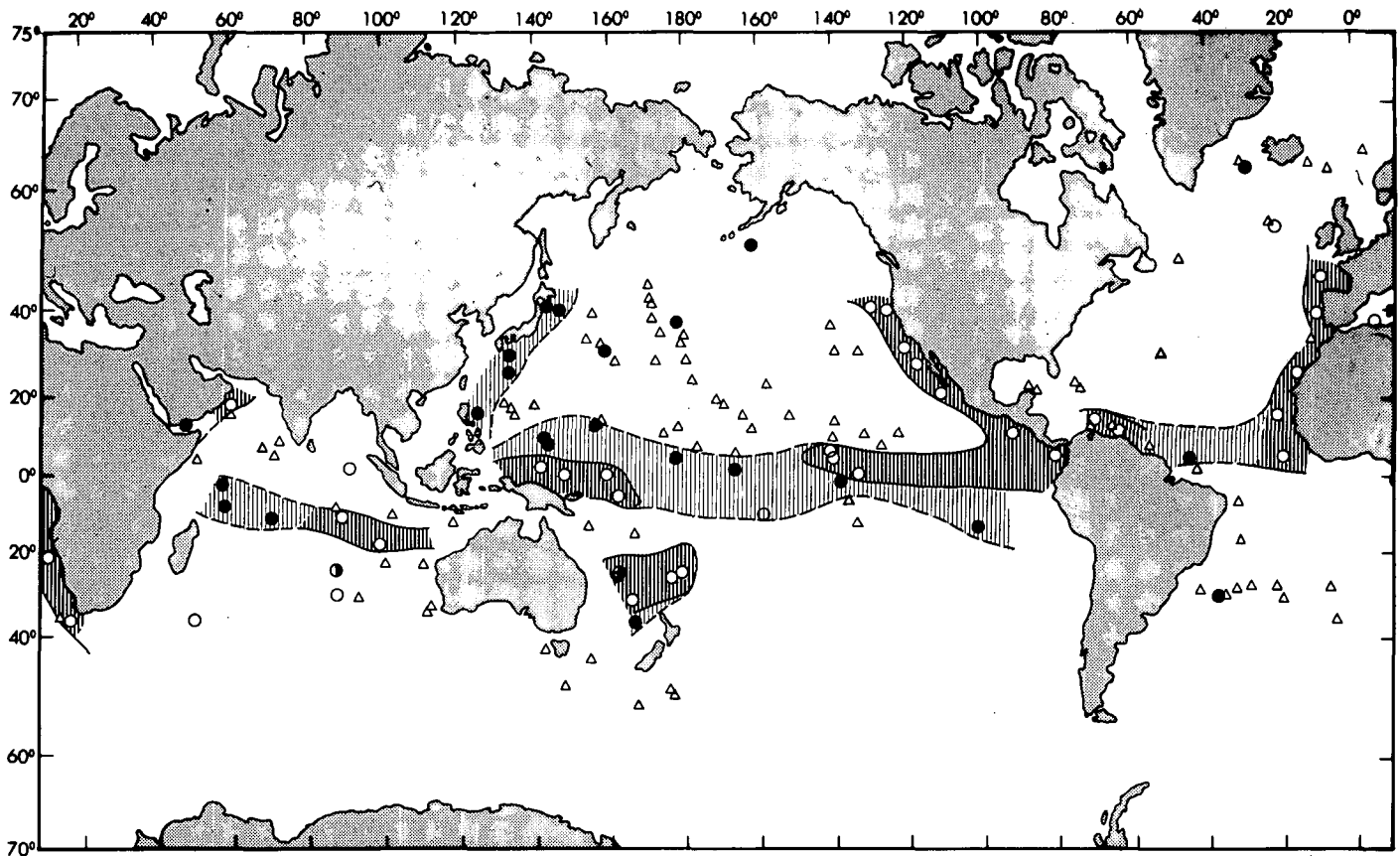


Figure 6. Distribution of hiatus NH 3 (13.5–12.5 Ma) in DSDP sections of the world ocean. See Figure 3 for explanation of symbols.

reflects a change in the source of bottom water, as will be discussed in the section on sediment distribution. In the Caribbean and along the Atlantic coast of the United States, faunal and floral changes suggest warming of the Gulf Stream during NH 2 time. Beginning at this time, the siliceous sediments progressively receded northward. Furthermore, warm water, thermophilic ostracode and mollusk assemblages expanded northward along the Atlantic coast of eastern North America during the middle Miocene (Benson, 1975; J. E. Hazel and L. W. Ward, 1981, oral commun.).

The presence of a major unconformity in sediment cores throughout the Caribbean suggests intensification of bottom currents beginning at NH 2 time (16–15 Ma). This unconformity, however, is also present in the shallow waters of the Blake Plateau (Mullins and Neumann, 1979). Pinet and others (1981) demonstrated that the erosional surfaces on Blake Plateau since late Paleocene–early Eocene were created by fluctuations in the position of the Gulf Stream as controlled by sea-level oscillations. Kaneps (1979) observed that current intensifications of the Gulf Stream during the late Neogene coincided with episodes of climatic cooling and increased polar glaciation. This study shows that each Neogene hiatus, except NH 2, is associated with an extreme cooling event (Fig. 1). During NH 2 time, however, bottom temperatures, as interpreted from oxygen-isotope data, were warmer than any other time during the Miocene (Fig. 1). In summary, hiatus NH 2 occurs in deep as well as shallow sedimentary sequences, is associated with a generally warm climate (Savin and others, 1981; Woodruff and others, 1981), and is associated with a short, fast rise and fall during an over-all rise of the eustatic sea level (Vail and Hardenbol, 1979).

Therefore, we suggest that intensification of bottom flow through the Caribbean was caused by a tectonic/paleoceanographic change, such as uplift of the Panama sill or initiation of Norwegian Overflow Water.

Very little is known, however, about the closing history of the Caribbean connection to the Pacific. Faunal and isotope data suggest that a surface barrier emerged sometime during the early Pliocene (Whitmore and Stuart, 1965; Woodring, 1966; Keigwin, 1978), although no data are available detailing the history of uplift. We believe that our hiatus- and sediment- distribution maps indicate that some tectonic uplift may have occurred sometime between 18 and 16 Ma; in fact, there is evidence of volcanism in the Panama region at this time (Weyl, 1980). If uplift of the Panama sill was responsible for intensification of bottom currents through the Caribbean, it must have been sufficient to deflect a critical mass of Atlantic deep water northward, causing major erosion throughout the Caribbean during NH 2 time (Fig. 5). Alternatively, this increased erosion could also have been caused by the initiation of Norwegian Overflow Water, which has been linked to widespread erosion near the early/middle Miocene boundary in the middle- to high-latitude (50°–60°N) North Atlantic (Roberts and others, 1979; Shor and Poore, 1979).

#### Hiatus NH 3 (13.5 to 12.5 Ma)

Hiatus NH 3 marks the onset of the late-Neogene hiatus distributions and high-productivity patterns. From this time on, the changes in distribution patterns are minimal and appear primarily

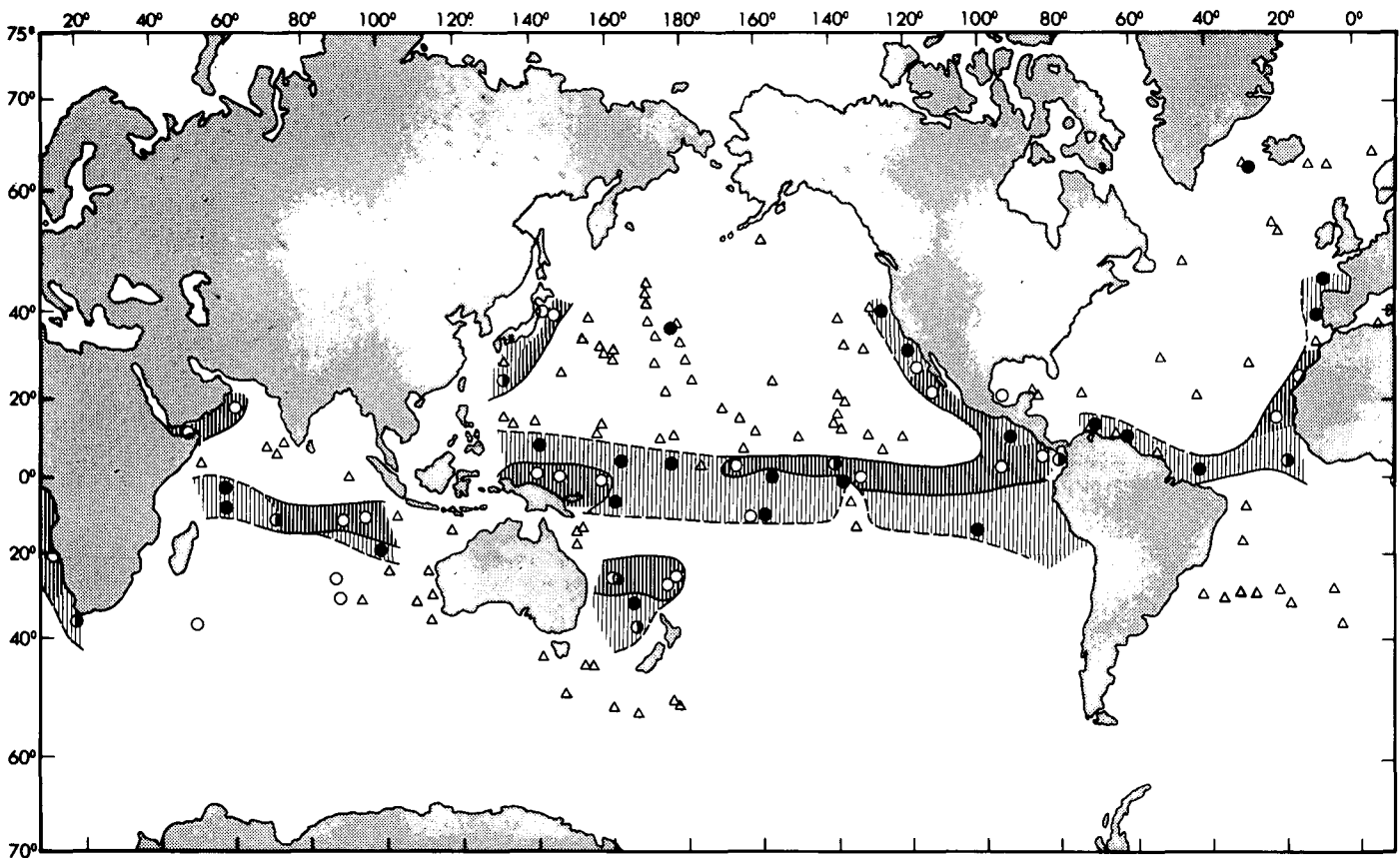


Figure 7. Distribution of hiatus NH 4 (12.0–11.0 Ma) in DSDP sections of the world ocean. See Figure 3 for explanation of symbols.

to reflect climatically induced fluctuations in current intensity and in the width of the equatorial productivity region. Therefore, we assume that the basic patterns of modern deep circulation and the areas of high productivity were established by 13.5 Ma.

Figure 6 illustrates the hiatus distribution and high-productivity regions during NH 3 time. High-productivity regions are concentrated in a narrow band in the equatorial region and in the marginal northeastern Pacific and Atlantic. Three features in the western Pacific distinguish this distribution pattern from that during NH 2 time: a general narrowing of the high-productivity zone in the western (Caroline and Nauru Basins) and eastern equatorial Pacific; increased dissolution or erosion in the central equatorial and northwest Pacific; and the development of an area of continuous sedimentation free from hiatuses in the South Fiji Basin north of New Zealand (Fig. 6). These features have persisted through the Neogene with only minor variations.

The productivity changes in the western equatorial and northwestern Pacific may be linked to the collision of Australia with Indonesia, which is assumed to have occurred during middle Miocene time (Edwards, 1975). This collision would have restricted the Indo-Pacific seaway deflecting water northward along the marginal northwestern Pacific, thereby causing increased carbonate dissolution and erosion.

The onset of continuous sedimentation in the South Fiji Basin beginning during NH 3 time appears to be linked to closing off of the Antarctic deep-water passage northwest of New Zealand, presumably due to uplift of the Lord Howe Rise. Prior to NH 3 time, major unconformities were present throughout the region.

The third Neogene hiatus appears to have primarily affected sedimentation in the middle to high latitudes of the central and northwestern Pacific (Keller, 1980a), and western Indian Oceans. Some evidence of this hiatus is also found in land sections in the Virginia and Maryland region, where the St. Marys Formation, dated at about 12.0 to 12.3 Ma (Blackwelder, 1981), unconformably overlies the Choptank Formation, which is assigned to planktic foraminiferal zones N11/N12 (Abbott and Andrews, 1979). In Washington state, the unconformity between the Montesano Formation and the underlying Astoria Formation correlates with hiatus NH 3 (Barron, 1981b). We speculate that this erosional pattern is primarily due to intensified current circulation during a rapid fall of the sea level. Oxygen-isotope data indicate rapidly declining temperatures through the middle Miocene, presumably in response to the growth of a major Antarctic ice sheet (Kennett and others, 1975; Shackleton and Kennett, 1975; Woodruff and others, 1981). Benthic and planktic foraminiferal changes associated with this climatic deterioration lend further support of a major paleoclimatic event (Keller, 1980b, 1981b; Srinivasan and Kennett, 1981a, 1981b; Woodruff and Douglas, 1981). The response of the benthic fauna is particularly striking; Oligocene to lower Miocene assemblages essentially disappear by about 13.5 Ma and more characteristic Neogene assemblages appear (Woodruff and Douglas, 1981). The benthic faunal change presumably reflects the increasing amount of young cool and dense Antarctic Bottom Water entering the deep Pacific. The rapid turnover of short-lived species in low-latitude planktic floras and faunas during this time suggests highly stressful environmental conditions (Haq, 1980; Keller, 1980a, 1980b).

Although primarily middle-latitude sequences were affected by erosion, low-latitude sections were marked by increased carbonate dissolution at this time (Keller, 1980a, 1980b), which suggests a general rise in the CCD attributable to the influx of more corrosive, young Antarctic Deep Water.

#### Hiatus NH 4 (12.0 to 11.0 Ma)

Hiatus NH 4 coincides with a climatic cooling in the oxygen-isotope curve (Fig. 1) and is separated from the preceding hiatus (NH 3) by a brief warm interval (Keller and Barron, 1981). No unusual pattern is apparent in the distribution of this hiatus; in fact, both complete sections and those with the hiatus are found in low and middle latitudes (Fig. 7; see also Keller, 1980b; Keller and others, 1983; Barron, 1981a). All complete sections, however, show a marked increase in carbonate dissolution (Keller, 1981a; Srinivasan and Kennett, 1981b) that presumably indicates an influx of corrosive Antarctic Bottom Water. Siliceous floras also appear to have been affected. Hiatus NH 4 at DSDP Sites 173 and 469 off California correlates with intervals of silica dissolution at Sites 470 and 472 immediately to the south (Barron, 1981a).

Regions of high productivity remain essentially unchanged relative to those of the preceding hiatus NH 3 (Figs. 6 and 7). Outside these high-productivity areas, complete sequences are found on structural highs above the reach of Antarctic Bottom Water, such as on the Ninetyeast Ridge and the Manihiki Plateau. The hiatus distribution and productivity maps suggest that the NH 4 event is another cold pulse reflecting increased polar glaciation. However, planktic faunas and floras respond with the most drastic changes since the early Miocene. Among planktic foraminifers, middle Miocene assemblages disappear and are replaced by a relatively cool, low-diversity fauna that persists through the late Miocene (Keller, 1980b, 1981a). Provincialism is greatly enhanced between low and middle latitudes among all planktic faunas and floras (Ingle, 1973; Haq, 1980; Keller, 1981a; Keller and Barron, 1981; Lohmann and Carlson, 1981; Srinivasan and Kennett, 1981b). From this time to the present, the cool to temperate middle-latitude and tropical low-latitude faunal and floral assemblages are separated, and few species are present in both provinces. The presence of separate faunal and floral provinces in middle and low latitudes suggests that a strengthened latitudinal thermal gradient, comparable to that at present, was established at this time sufficient to act as an ecological barrier to migration.

#### Hiatus NH 5 (10.0 to 9.0 Ma)

Further refrigeration between 10 and 9 Ma led to the fifth Neogene hiatus event, NH 5 (Keller, 1980b; Keller and others, 1982; Barron, 1981a). The erosional intensity of this event appears to have been greater than that of any other hiatus event of the middle and late Miocene (Fig. 8); oxygen-isotope data indicate that the coolest temperatures of the Miocene occurred during NH 5 time (Woodruff and others, 1981), and Vail and Hardenbol (1979) recognized a major fall in eustatic sea level at this time (Fig. 1). Only a few sequences preserve this time slice, in middle latitudes of the marginal North Pacific, the South Fiji Basin, the Caroline Basin, and the equatorial Indian Ocean, and nearly all sequences in the Atlantic and eastern equatorial Pacific contain this hiatus. Furthermore, all deep-sea sections in the Pacific and Indian Oceans, even those in shallow regions, are severely affected by dissolution (Vincent, 1977; Keller, 1981a; Keller and Barron, 1981; Poore, 1981; Srinivasan and Kennett, 1981a, 1981b). A general carbonate

low is found in sediments throughout the equatorial Pacific during this time (Dunn and Moore, 1981).

Faunal and floral assemblages reflect cold climatic conditions during NH 5 time (Barron, 1973; Ingle, 1973; Kennett and Vella, 1975; Haq, 1980; Keller and Barron, 1981; Lohmann and Carlson, 1981), and further isolation takes place between middle- and low-latitude planktic assemblages. Woodruff and Douglas (1981) suggested that a change in benthic assemblages to an essentially modern fauna during this time reflects the establishment of an intermediate water mass similar to that of the present. Warm climatic conditions that prevailed after this hiatus between 9.0 and 7.5 Ma were followed by another severe cooling and hiatus.

#### Hiatus NH 6 (7.5 to 6.2 Ma)

Hiatus NH 6 is widely distributed at low, middle, and high latitudes (Fig. 9); see also Shafik, 1975; Barron, 1980; Keller, 1980b; Keller and others, 1982; Ciesielski and others, 1981), as well as in onshore sections in California (Addicott and others, 1978; Barron, 1981a) and Japan (Koizumi and others, 1980). The latest Miocene sea-level regression observed by Huddlestun and Wright (1977) in the southeastern United States also correlates with hiatuses NH 6 and possibly NH 7. Complete sections can be found in the high-productivity equatorial regions. The distribution of this hiatus and high-productivity regions do not differ significantly from those of other late Miocene hiatuses. What makes NH 6 different, however, is the essentially permanent depletion in  $\delta^{13}\text{C}$  values by about 0.5‰ that occurs during this time in the Pacific and Indian Oceans (Keigwin, 1979; Vincent and others, 1980; Woodruff and others, 1981). There appears, however, to be no appreciable  $\delta^{13}\text{C}$  shift in North Atlantic deep-sea sediments. Also at about this time, the Pacific CCD becomes shallower than the Atlantic CCD, whereas before the  $^{13}\text{C}$  shift the Pacific CCD was deeper than the Atlantic CCD (van Andel and others, 1975). Coincidentally, the rate of sediment accumulation in high-productivity areas increased two-fold during NH 6 time (Barron, 1980; Keller, 1980b; Vincent and others, 1980).

No significant planktic foraminiferal changes distinguish this hiatus from previous or succeeding hiatuses. In diatom floras, however, a distinct provincialism is established during this time between northwestern Pacific-Bering Sea assemblages and northeastern Pacific assemblages (Barron, 1980). A major faunal change is also evident in benthic foraminifers (Woodruff and Douglas, 1981). Similar to other late Miocene events, planktic faunas and floras indicate cool climatic conditions, and sediments in the Pacific and Indian Oceans are affected by increased carbonate dissolution (Dunn and Moore, 1981), presumably attributable to a rise in the CCD. Atlantic sediments, however, reflect no significant increase in dissolution (Poore, 1979, 1981). Cool climatic conditions are also indicated by  $\delta^{18}\text{O}$  values at this time (Keigwin, 1979; Vincent and others, 1980; Woodruff and others, 1981). All of these factors, with the exception of the change in the Atlantic versus the Pacific CCD, are also present at other hiatuses and are therefore unlikely causes for the permanent  $\delta^{13}\text{C}$  depletion.

#### Hiatus NH 7 (5.2 to 4.7 Ma)

Hiatus NH 7, which spans the Miocene-Pliocene boundary (5.2–4.7 Ma), is primarily found in middle- to high-latitude sequences of the marginal and central North Pacific (Harper, 1977; Keller, 1978, 1979; Keller and others, 1983) and western North Atlantic. Deep-sea sections that are complete through this interval

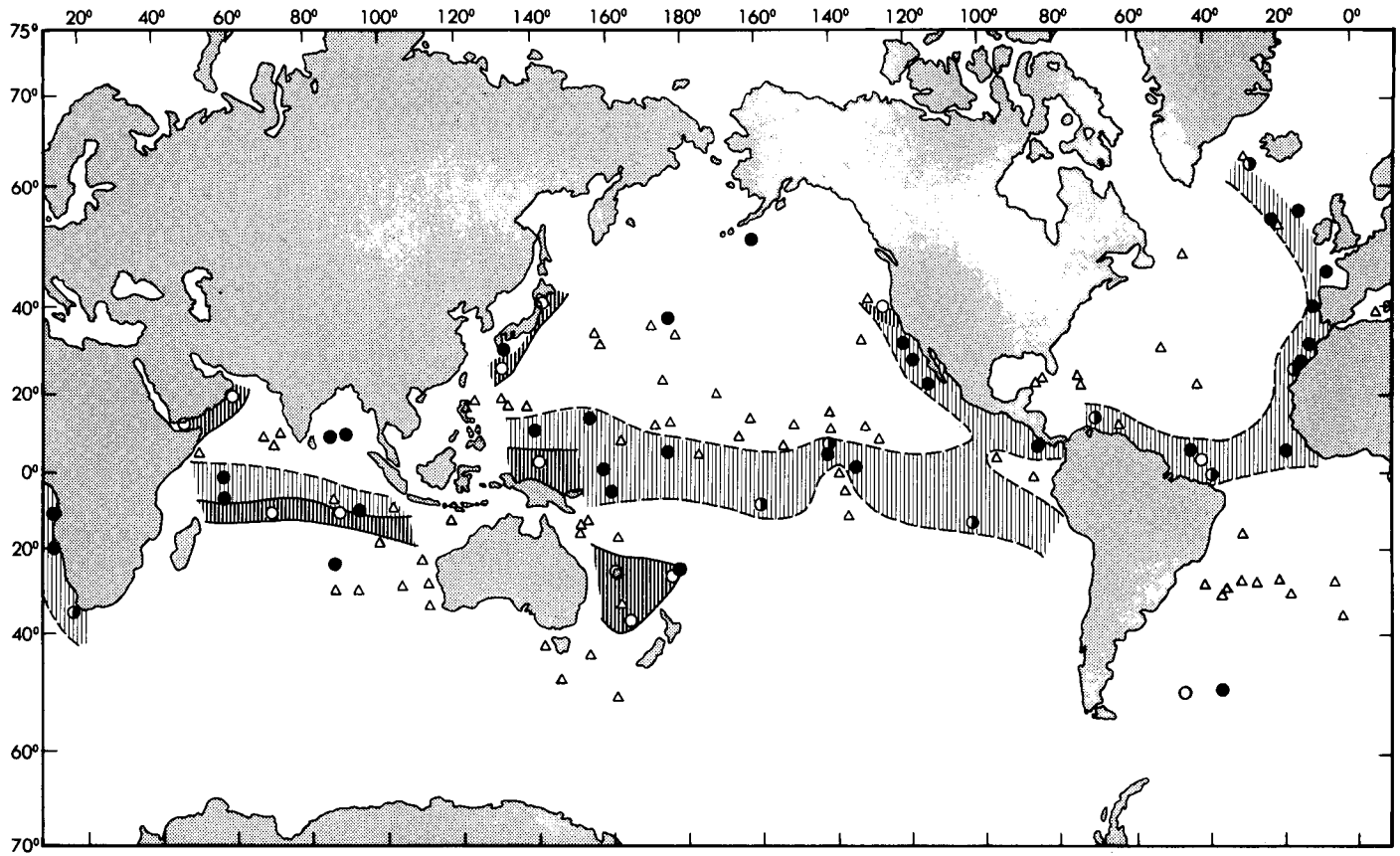


Figure 8. Distribution of hiatus NH 5 (10.0-9.0 Ma) in DSDP sections of the world ocean. See Figure 3 for explanation of symbols.

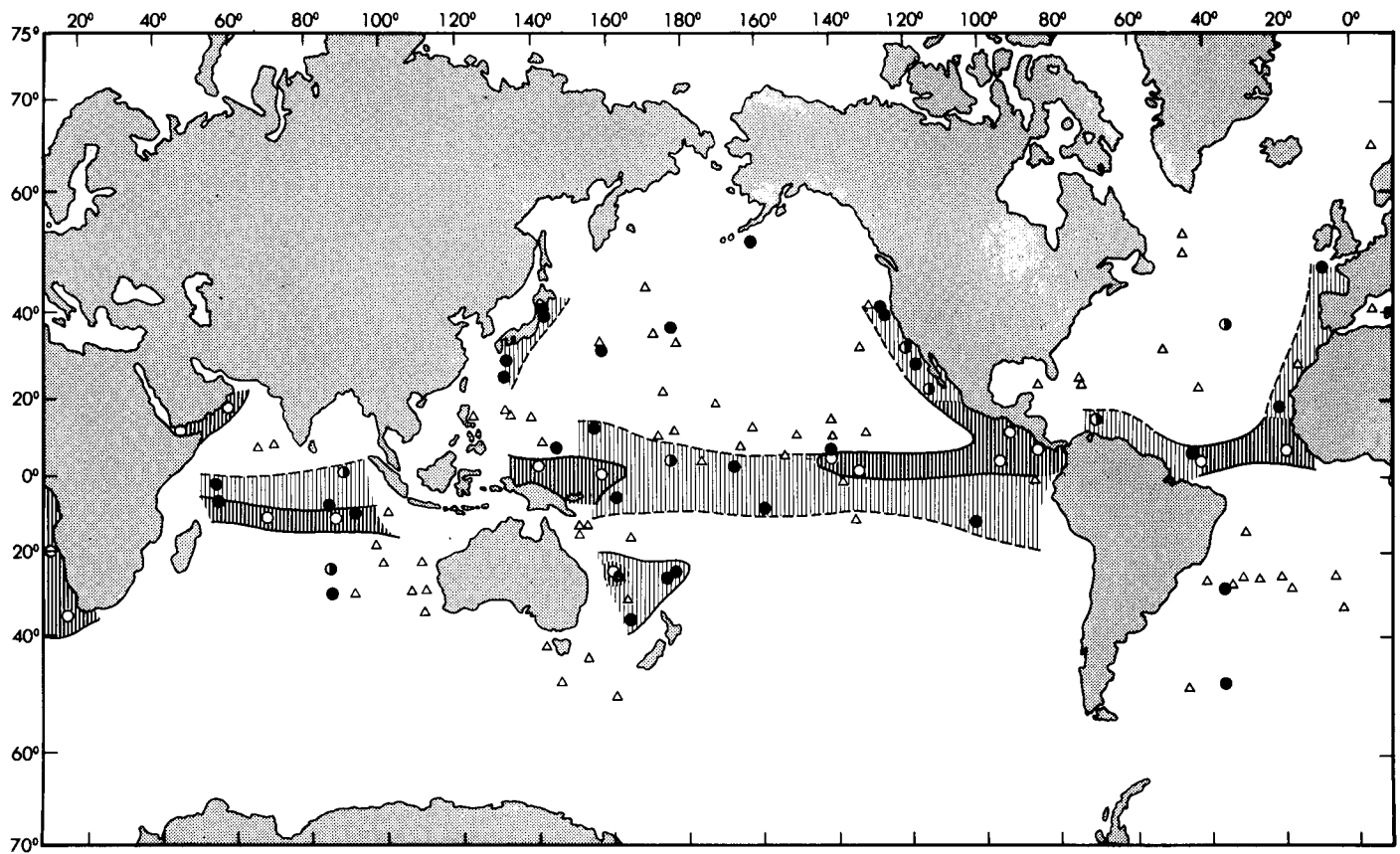


Figure 9. Distribution of hiatus NH 6 (7.5-6.2 Ma) in DSDP sections of the world ocean. See Figure 3 for explanation of symbols.



are from the high-productivity equatorial regions and South Fiji Basin (Fig. 10). The numerous complete sections during NH 7 time suggest that productivity was higher, or carbonate dissolution lower, than during NH 3 to NH 6 time.

This hiatus event appears to have been less extensive than any of the Neogene hiatus events with the possible exception of NH 2, partly because hiatus NH 7 is very short (often  $< 0.3$  m.y.) and may therefore elude the biostratigrapher. Detailed faunal analyses indicate that paleoclimatic and paleoceanographic conditions in middle to low latitudes were less severe during NH 7 time (Keller, 1978, 1980b), although carbonate studies (Kaneps, 1973; Dunn and Moore, 1981) show brief but severe dissolution in the equatorial Pacific during this time. Approximately at this time, the Mediterranean became isolated from the Atlantic, and the Messinian evaporite deposits formed (Burckle, 1978a). In the high-latitude South Atlantic, this hiatus marks a major erosional event attributable to increased glaciation (Ciesielski and others, 1981).

Oxygen-isotope studies reveal that generally cool but oscillating temperatures prevailed during the latest Miocene after hiatus NH 6 (Fig. 1; see also Keigwin, 1979; Loutit and Kennett, 1979; Woodruff and others, 1981; Keller and others, 1982). A short cooling event is apparent at the Miocene-Pliocene boundary corresponding to hiatus NH 7.

## SEDIMENT DISTRIBUTION

The spatial distribution of deep-sea hiatuses reflects passage of bottom currents and fluctuations in their intensity and corrosiveness, whereas the distribution of pelagic sediments in the oceans reflects paleoceanographic conditions as a function of both surface productivity and bottom-current circulation. Thus, a study of sediment distribution patterns, in conjunction with the hiatus distribution discussed above, can reveal the paleoceanographic history of the Miocene ocean.

We have compiled generalized sediment distribution maps for the Miocene from DSDP data. Sediment types are here reduced to four broad categories: carbonate ooze and chalk, siliceous ooze, mixed siliceous-carbonate ooze, and terrigenous sediment (clay, marl, and detrital sediments). In the category of siliceous-carbonate ooze, we have placed carbonate oozes containing more than 15% silica, as determined from smear slides.

Four distinct sediment distribution patterns are apparent through the Miocene: the earliest Miocene (23.0–18.0 Ma), the late early Miocene through middle middle Miocene (18.0–12.5 Ma), the latest middle Miocene through middle late Miocene (12.5–7.5 Ma), and the latest Miocene (7.5–5.0 Ma). During each of these four intervals, sediment distribution patterns are relatively constant, and the major changes appear to coincide with three Neogene hiatuses: NH 1 (20–18 Ma), NH 2 (16.0–15.0 Ma), and NH 6 (7.5–6.2 Ma).

### Early Miocene (23.5 to 18.0 Ma)

Sediment distribution during the early Miocene is illustrated in Figure 11. We have not backtracked DSDP sites for this interval, because we believe that the changing pattern of sediment distribution through the Miocene can be observed more clearly if all maps are plotted on the same projection. Thus, we have used the present site location and continent configuration maps. Significant changes that occurred since the early Miocene will be pointed out in the discussion that follows.

The early Miocene is characterized by a high rate of carbonate sedimentation in the equatorial region, north of the Tethys in the

Atlantic Ocean (lat. 40°N), and south of Japan in the Pacific Ocean (lat. 40°N backtracked). The southern ocean appears to be primarily calcareous to about lat. 50°S (backtracked). Mixed siliceous and calcareous sediments are present between about 50° to 60°S latitude in the Atlantic and Indo-Pacific Oceans. In the northeastern Atlantic, between Greenland and northern Europe, siliceous ooze dominates, and a front of mixed siliceous and calcareous sediment occurs to the south. Siliceous ooze is also present in the northwestern Atlantic along the coast of North America, whereas mixed carbonate and siliceous sediments are found in the Caribbean. A pocket of this mixed sediment also occurs in the eastern equatorial Pacific.

Data are sparse for the North Pacific middle latitudes and absent for high latitudes. In the marginal northeastern Pacific, carbonate ooze is present to at least lat. 30°N (backtracked). In the marginal northwestern Pacific, siliceous ooze is present at lat. 40°N (backtracked). Data from the Indian Ocean indicate calcareous sediment between about lat. 3°N and 40°S (backtracked), whereas terrigenous sediment dominates the northern region (Fig. 11).

The broad equatorial band of silica-poor carbonate ooze deposition suggests that a deep circumequatorial circulation existed through the Tethys Sea into the Atlantic, Caribbean, Pacific, and Indian Oceans. The distribution of the latest Oligocene and early Miocene hiatuses PH and NH 1 clearly supports this conclusion (Figs. 3 and 4). This observation is also supported by plate-tectonic studies that suggest that the Tethyan seaway closed by about 18 Ma (Berggren and Hollister, 1974). Very restricted upwelling appears to have occurred in the eastern equatorial Pacific. Deposition of calcareous ooze as far south as lat. 50°S and restricted deposition of siliceous ooze south of lat. 60°S suggest that the circum-Antarctic flow had not reached its present width and intensity prior to hiatus NH 1 (20–18 Ma). Terrigenous sedimentation in the northern Indian Ocean reflects the buildup of the Zambesi, Bengal, and Indus Fans due to the northward migration of India (Kidd and Davies, 1978).

The paleocirculation of the Atlantic presents a more complex problem. The South Atlantic is assumed to have attained its present configuration by early Miocene time (van Andel and others, 1977). Sclater and others (1977) suggested that the present general circulation of the Atlantic was established by 21 Ma when Norwegian Overflow Water filled the North Atlantic. This age is refuted in a recent study by Blanc and others (1980), who argued, on the basis of oxygen and carbon isotope data, that major production of Norwegian Overflow Water started at about 12 Ma. Vogt (1972), Roberts and others (1979), and Shor and Poore (1979), however, date the initiation of Norwegian Overflow Water at 16 Ma. Middle Miocene changes in North Atlantic siliceous sedimentation patterns provide important insight to these questions.

### Late Early to Middle Miocene (18.0 to 12.5 Ma)

A striking change in oceanic sedimentation occurred during the latest early Miocene coincident with major changes in oceanic circulation, as implied by the distribution of hiatus NH 2 discussed earlier. Northward restriction of siliceous sedimentation is apparent in both the northeastern and northwestern Atlantic (Fig. 12). The circumequatorial sedimentation pattern so conspicuous during the earliest Miocene appears to have been disrupted by the closing of the deep connection through the Caribbean or intensification of bottom currents. Erosional unconformities (NH 2) occur throughout the Caribbean region and suggest intensification of bottom currents at this time. These unconformities are associated with a

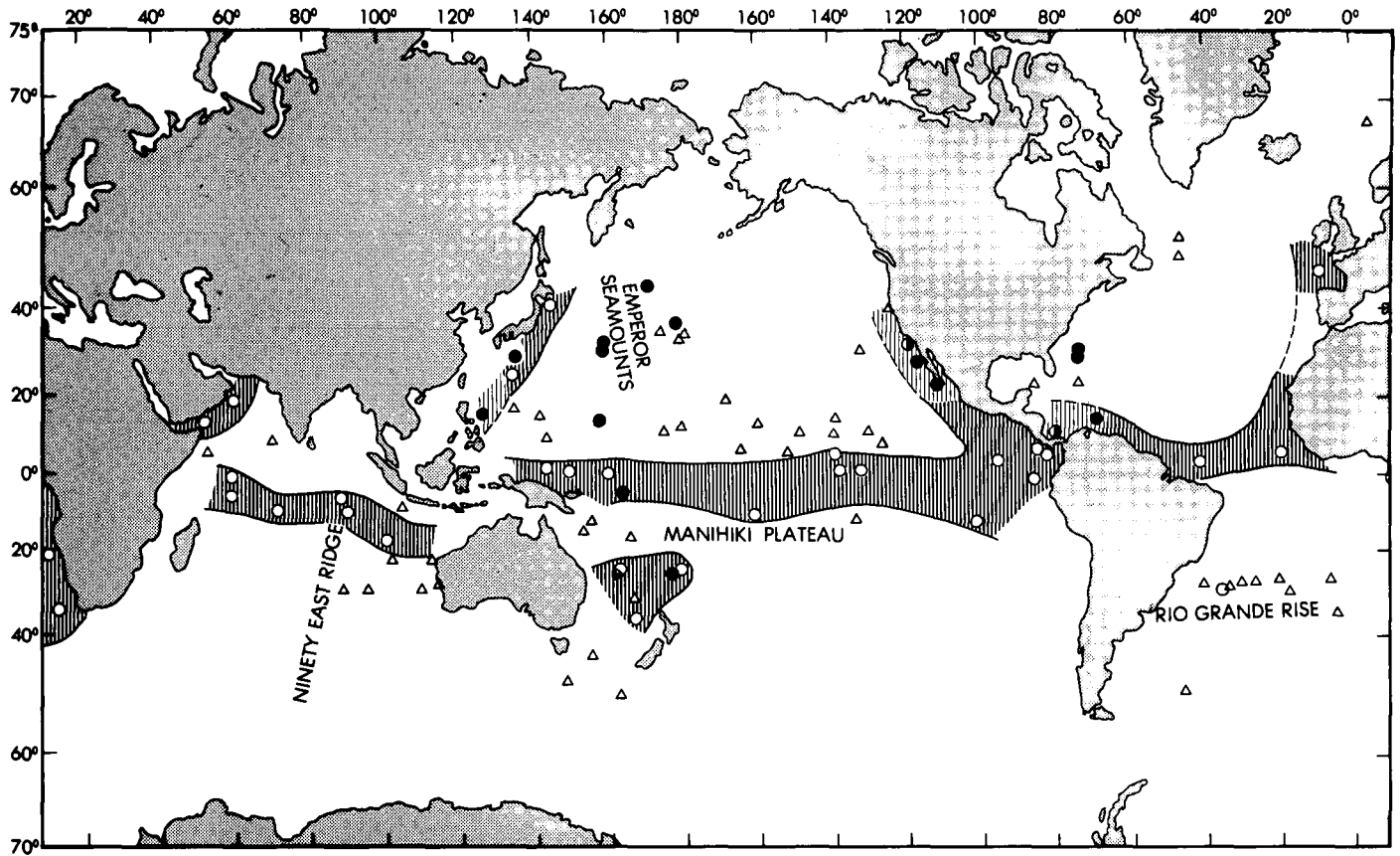


Figure 10. Distribution of hiatus NH 7 (5.2-4.7 Ma) in DSDP sections of the world ocean. See Figure 3 for explanation of symbols.

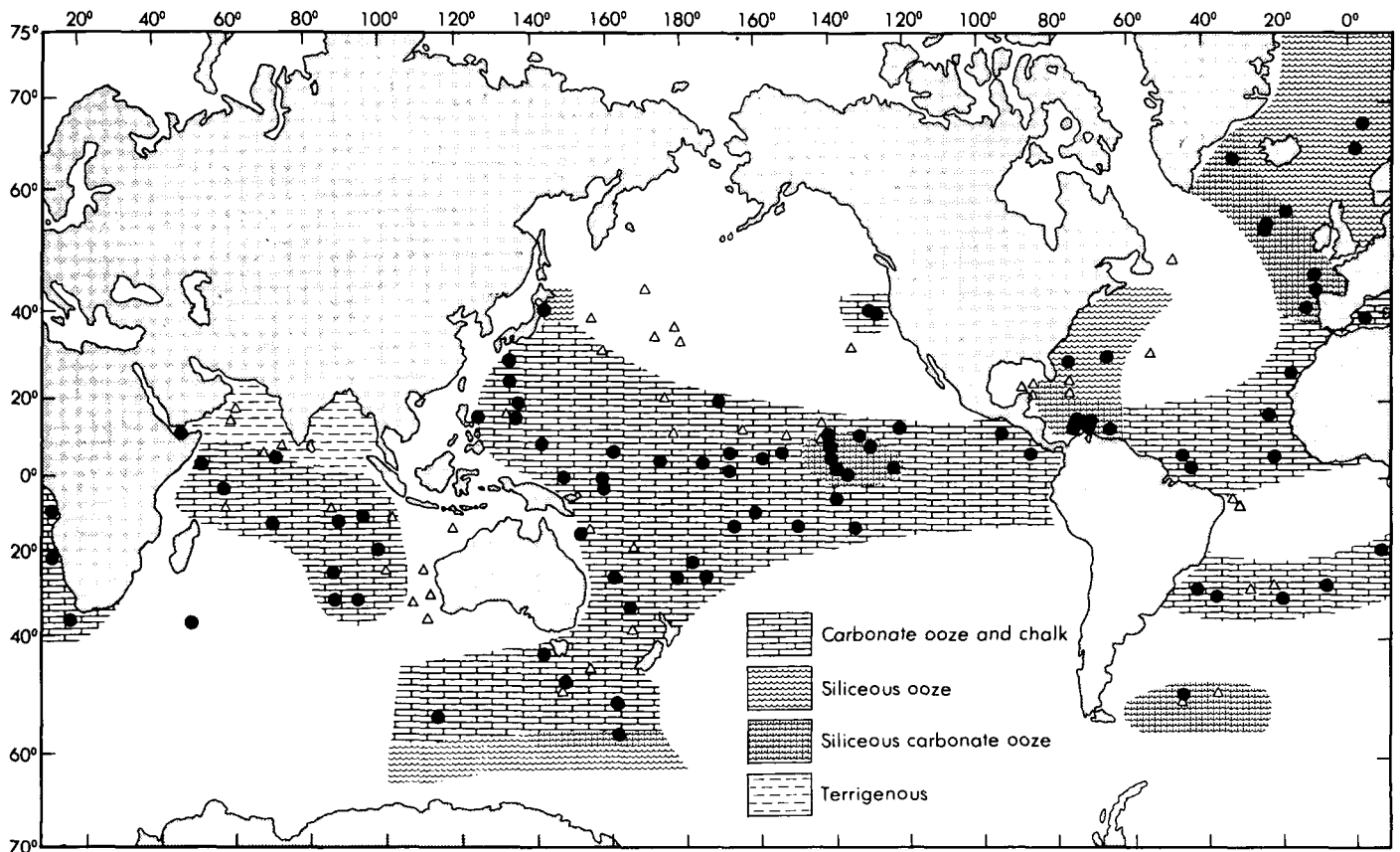


Figure 11. Deep-sea sediment distribution in the earliest Miocene between 23.0 and 18.0 Ma. DSDP sites containing sediment data are marked with black circles. Triangles show DSDP sites at which this interval is removed by a hiatus.



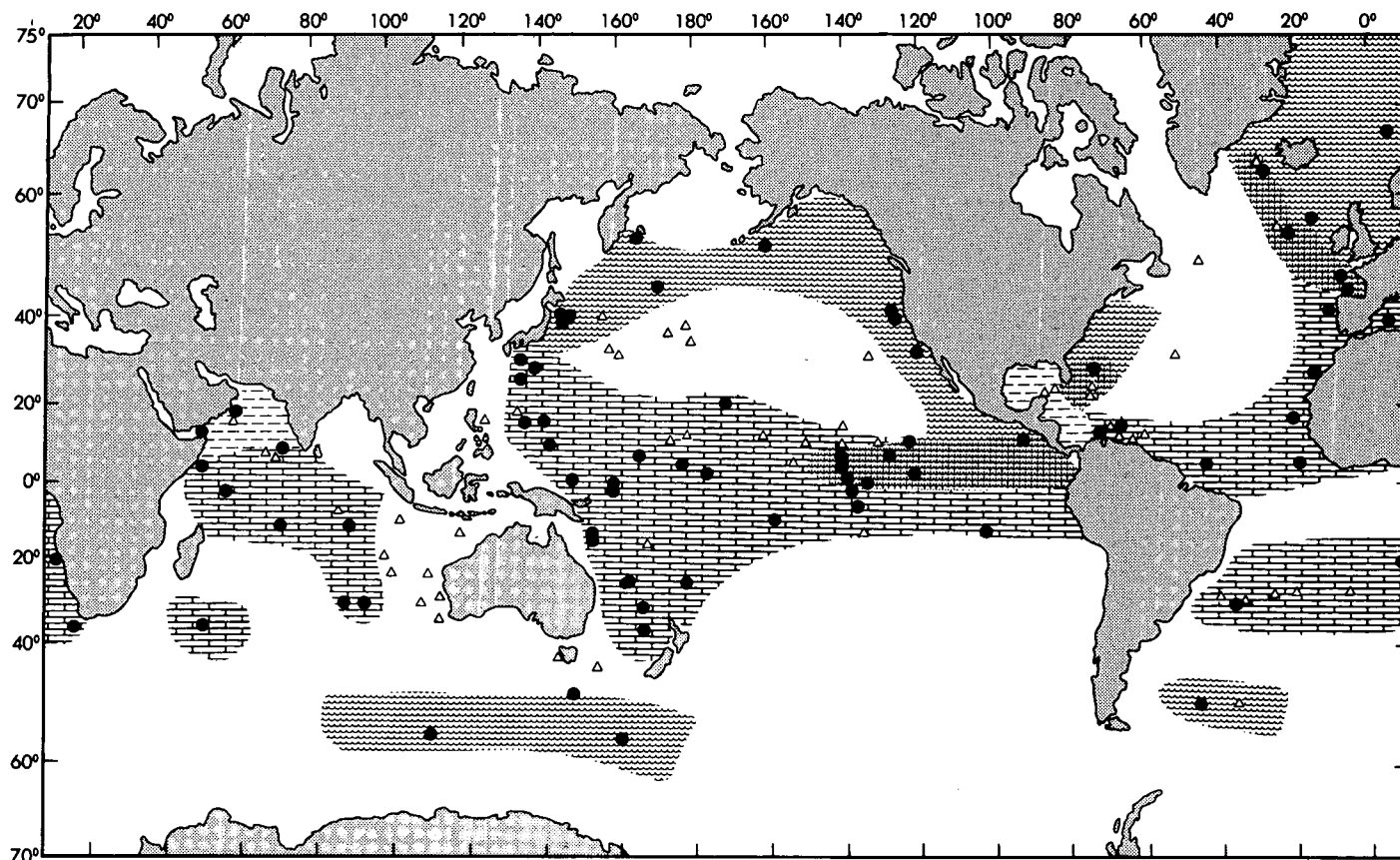


Figure 12. Deep-sea sediment distribution in the late early through middle Miocene (18.0–12.5 Ma). See Figure 11 for explanation of symbols.

sharp drop followed by an immediate rise in the eustatic sea level (Fig. 1; see also Vail and Hardenbol, 1979). Increased volcanism and uplift in Costa Rica and Panama during the late early through middle Miocene are suggested by radiometric ages on basalt of  $17.5 \pm 0.6$  Ma and  $12.6 \pm 0.8$  Ma (Weyl, 1980).

Carbonate sedimentation still predominates in the equatorial Pacific region. Biogenic silica sediment, however, first becomes a significant component in the eastern equatorial Pacific at about 18 Ma (Leinen, 1979), presumably as a result of increased upwelling. This is followed by a drastic increase in deposition of siliceous ooze throughout the marginal-northeastern, middle- and high-latitude North Pacific at about 16 Ma (Fig. 12). This time also corresponds with the sharp increase in diatomaceous sedimentation observed in onshore sections around the North Pacific by Ingle (1981). In addition, deposition of siliceous ooze is also expanded around Antarctica (Fig. 12).

The coincidental sudden appearance of abundant biogenic siliceous oozes in the North Pacific by about 16 Ma and beginning of a gradual decline in siliceous sedimentation in the North Atlantic poses one of the most puzzling questions in Miocene sedimentation. Was this changeover in the silica budget from one ocean to another gradual or instantaneous? Was it associated with a paleoclimatic or tectonic event, or both? To answer these questions, we have surveyed the onset and termination of abundant siliceous sedimentation in deep-sea sites across latitudes in the North Atlantic, North Pacific, and Indian Oceans; Figure 13 illustrates our results. Highly

siliceous sediments appear at the same time (about 16.0–15.5 Ma) in the Indian and Pacific Oceans, with the exception of the eastern equatorial Pacific, where significant siliceous sediment appears earlier at about 18 Ma. In the North Atlantic, the disappearance of siliceous deposits was more gradual. In the low-latitude Caribbean, the Gulf of Mexico, and off of the Northwest African coast, silica disappeared between 16 and 15 Ma. At middle latitudes (30°N), silica was intermittently present through the late Miocene (Fig. 13). Thus, the gradual northward restriction of siliceous sedimentation in the North Atlantic beginning in the early middle Miocene coincides with the first appearance of increased siliceous deposition in the North Pacific and Indian Oceans.

During the late early and early middle Miocene, the major tectonic events in the North Atlantic are the growth of Iceland, beginning about 16 Ma, and the subsidence of the Iceland-Faeroe Ridge (Sclater and others, 1977). Vogt (1972), Roberts and others (1979), and Shor and Poore (1979) also date the subsidence of the Iceland Faeroe Ridge and initiation of Norwegian Overflow Water at about 16 Ma. It is plausible that the progressive restriction of silica in the North Atlantic beginning about 15 to 16 Ma was caused by the introduction of Norwegian Overflow Water into the North Atlantic, forming North Atlantic Deep Water and acting as a barrier to the upwelling of silica-rich Antarctic Bottom Water (Berger and Winterer, 1973; W. H. Berger, 1981, oral commun.).

A major paleoceanographic change between 15 and 13.5 Ma is implied by the rapidly fluctuating, though generally increasing,  $^{18}\text{O}$

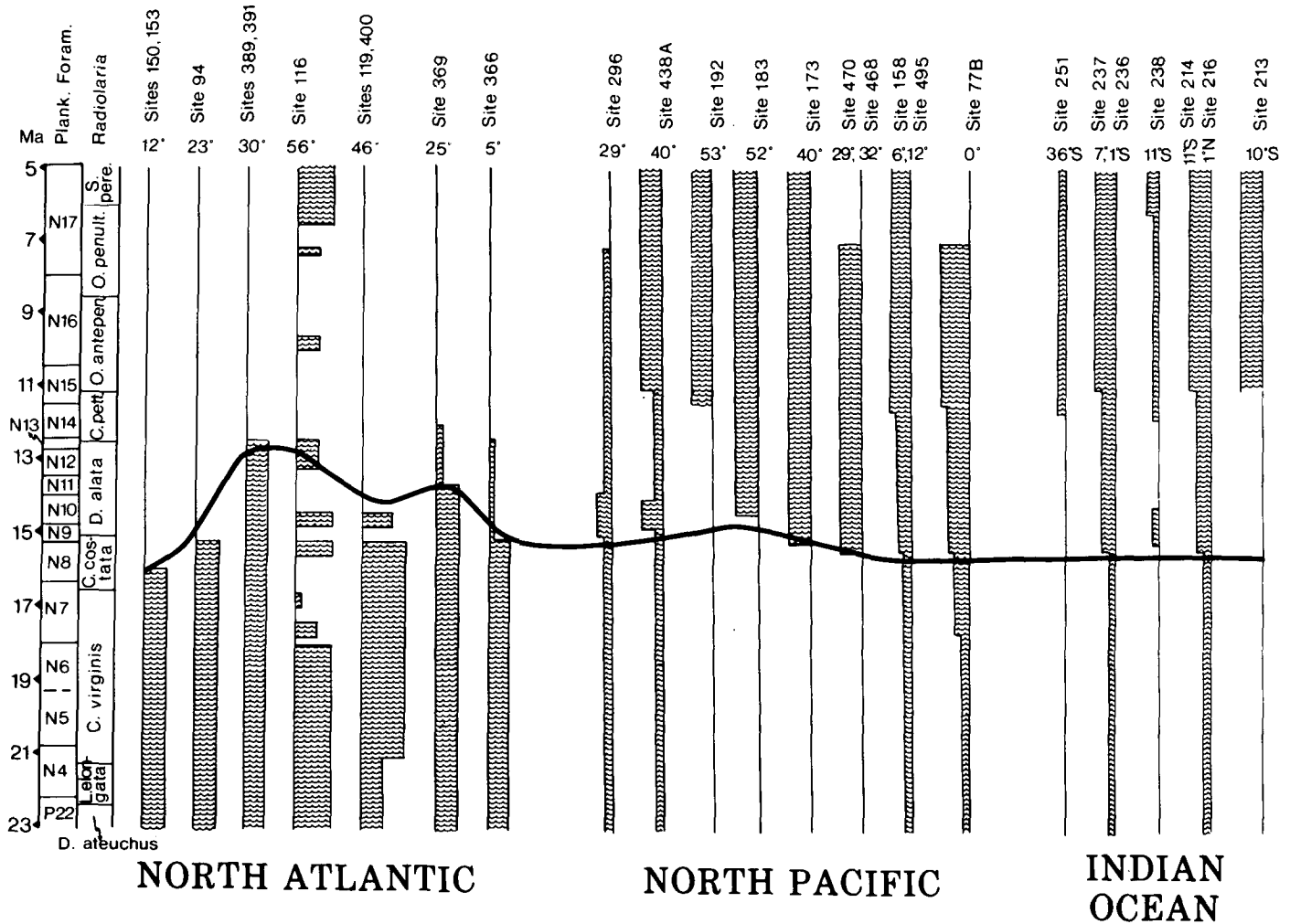


Figure 13. Siliceous sedimentation in selected DSDP sites of the North Atlantic, North Pacific, and Indian Oceans during the Miocene. Thickness of columns indicates relative abundance of silica in sediments. Heavy black line marks the time during which siliceous sedimentation disappears in the Atlantic and appears in the Pacific and Indian Oceans.

content in benthic foraminifer tests (Woodruff and Douglas, 1981). This major change in  $^{18}\text{O}$  values implies either the growth of a major East Antarctic ice sheet at this time (Shackleton and Kennett, 1975; Savin and others, 1975; Woodruff and others, 1981) and/or reorganization of and general cooling in the structure of deep water (Matthews and Poore, 1980). This major cooling initiated the generally cool, though fluctuating, climatic regime of the late Neogene dominated by a major Antarctic ice cap exhibiting periodic ice-volume changes (Kennett, 1977). Increasingly cool conditions are also implied by widening of the belt of siliceous sedimentation to about lat.  $50^{\circ}\text{S}$  (backtracked) around Antarctica in the early middle Miocene (Fig. 12). We suggest that the increased siliceous sedimentation in the Indian and Pacific Oceans was probably due to the combined effect of (1) the introduction of Norwegian Overflow Water into the North Atlantic, and (2) increased production of Antarctic Bottom Water as a result of increased Antarctic glaciation.

#### Late Middle to Late Miocene (12.5 to 7.5 Ma)

Few changes are apparent in the sediment distribution after the late middle Miocene cooling event at about 13.5 to 12.5 Ma (Figs. 1

and 15). Sedimentation in the Indian Ocean during this time remained essentially unchanged relative to that during the early Miocene (Fig. 14; see also Davies and Kidd, 1977). Terrigenous sedimentation from the Bengal, Indus, and Zambesi Fans persisted as India continued its northward migration. Closure of the Arabian Sea and opening of the Gulf of Aden resulted in the destruction of the Tethys (Stoneley, 1974; Haq, 1980). Volcanism increased from the middle Miocene to the Holocene (Vallier and Kidd, 1977).

Over-all sedimentation in the Pacific remained unchanged, although there was a narrowing of the eastern equatorial calcareous/siliceous zone beginning at hiatus NH 3 (13.5–12.5 Ma) as observed by van Andel and others (1975). Leinen (1979) noted that after the middle Miocene, opal accumulation rates along the equator markedly increased in the eastern Pacific. She speculated that the Equatorial Undercurrent did not reach its modern level of influence on sediment deposition in the region until about 10 Ma. Narrowing of the eastern-equatorial high-productivity region and enhancement of an east-west gradient in opal accumulation probably resulted from an increased gyral circulation at the end of the middle Miocene due to high-latitude cooling. As discussed above, the pronounced strengthening of floral and faunal provincialism

between the tropics and middle latitudes during this time also appears to reflect increased latitudinal thermal gradients.

In the Antarctic region, increased erosion and ice rafting occurred around 10.0 to 9.0 Ma (NH 5) and 7.5 to 6.2 Ma (NH 6) (Ciesielski and others, 1981). Siliceous ooze sedimentation around the Antarctic up to 50°S latitude remained essentially unchanged through the middle and late Miocene (Figs. 12 and 14; see also Brewster, 1980).

The sediment distribution in the North Atlantic changed significantly between 12.5 and 7.5 Ma (NH 4 to NH 6). By early late Miocene time, biogenic silica sedimentation was restricted to north of 50° N latitude (Fig. 14) as compared to lat. 45°N during the early middle Miocene (Fig. 12). Distribution of calcareous sediments became more widespread in the equatorial and eastern North Atlantic. Terrigenous sedimentation increased in the Caribbean, the Gulf of Mexico, and off the coast of eastern North America, whereas siliceous sediment disappeared from this region (Fig. 14). In the South Atlantic, however, sediment distribution remained unchanged.

Uplift continued in the Caribbean during the early late Miocene, as evidenced by a shallowing of marine facies and continued volcanism in the Panama area (radiometric ages  $12.6 \pm 0.8$  Ma and  $10.3 \pm 0.4$  Ma; Weyl, 1980). Thus, northward deflection of an increasingly greater water mass northward through the Gulf of Mexico and along the east coast of North America may have resulted in increased erosion. The disappearance of biogenic silica

from the northwestern Atlantic between 12 and 10 Ma also suggests a further increase in Norwegian Overflow Water.

In the northeastern Atlantic, the Iceland-Faeroe Ridge continued to subside, and the formation of Iceland was complete by 10 Ma (Sclater and others, 1977). Perhaps as a result of continued subsidence, Norwegian Sea Overflow Water reached major proportion by about 12 Ma, filling the Atlantic and flowing south to mix with Antarctic Bottom Water. Restriction of biogenic silica deposition to north of lat. 50°N suggests that outcropping of Antarctic Bottom Water in the North Atlantic ceased by 12.5 Ma, presumably because of increased production of Norwegian Overflow Water. A different bottom-water source in the North Atlantic beginning at about 12 Ma is also indicated by a change in the isotopic composition of benthic foraminiferal calcite (Blanc and others, 1980). Although Blanc and others (1980) have suggested that this change in isotopic composition indicates that production of Norwegian Overflow Water started at this time (12 Ma), we suggest that this isotopic event marks the time when Norwegian Overflow Water first dominated the North Atlantic. Production of North Atlantic Bottom Water appears to have started during early middle Miocene, as discussed above.

#### Latest Miocene (7.5 to 5.0 Ma)

Sediment distribution during the late Miocene is essentially identical to that of the present, indicating that the present oceanic

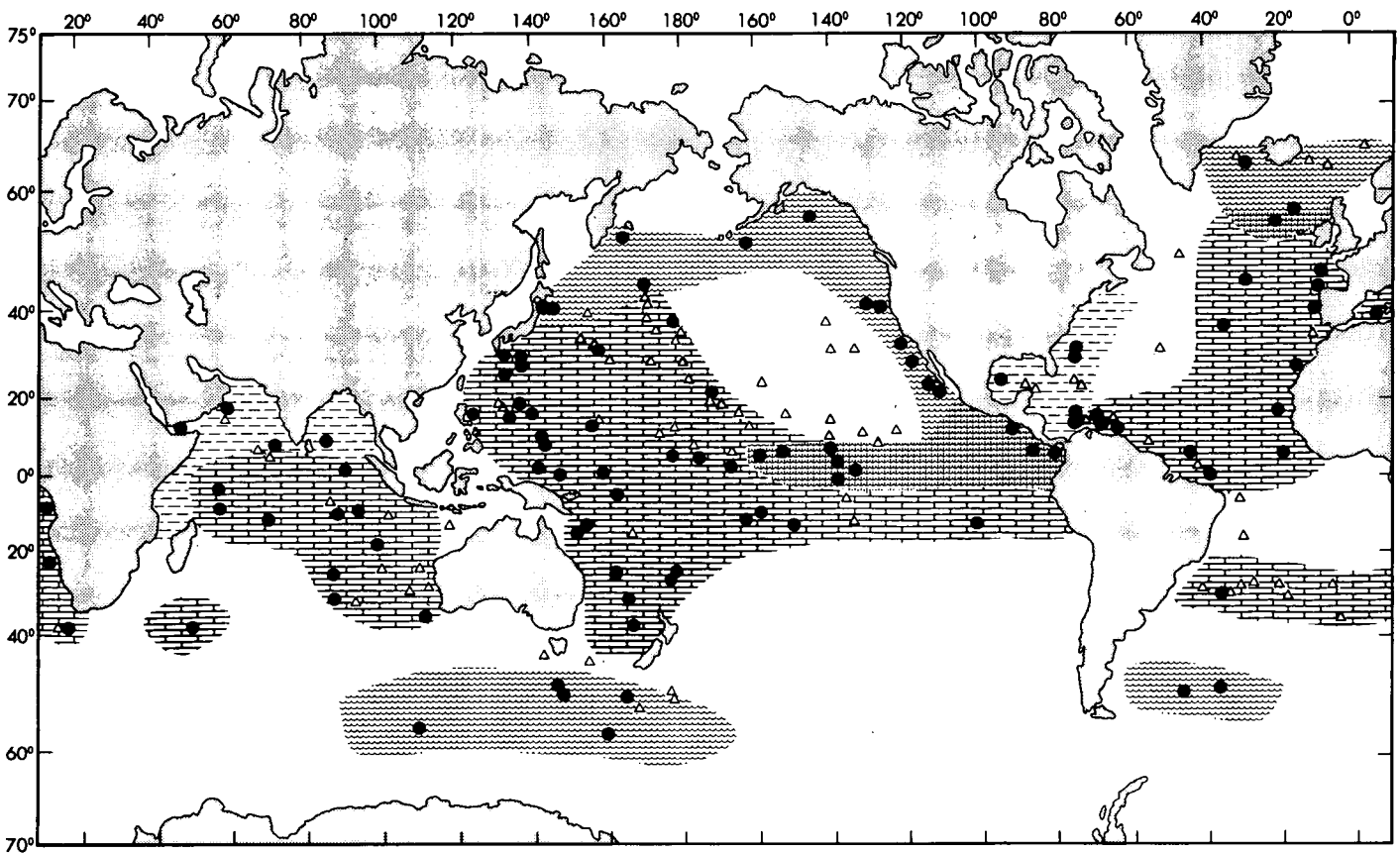


Figure 14. Deep-sea sediment distribution in the latest middle through early late Miocene (12.5–7.5 Ma). See Figure 11 for explanation of symbols.

circulation system was established by that time (Fig. 15). In the Indian Ocean, appearance of siliceous sediments in the Wharton and Crozet Basins suggests that a circulation system similar to that of the present was established by about 7.5 Ma (Fig. 15; see also Davies and Kidd, 1977). Sedimentation in the Pacific remained essentially unchanged except for increased rates of accumulation in high-productivity regions (Barron, 1980; Keller, 1980a; Keller and others, 1982).

Sedimentation in the Atlantic was similar to that of the early late Miocene. Carbonate-ooze sedimentation was pushed to lat. 60° N between Greenland and Iceland (Fig. 15), whereas siliceous-ooze deposition was restricted to the Norwegian Sea.

### SUMMARY DISCUSSION

The global paleoceanographic evolution exhibits major changes through the Miocene resulting from continental drift, the closing and opening of passages, the subsequent changes in oceanic circulation, and the development of a major Antarctic glaciation. The consequences and timing of these evolutionary changes can be observed in the changing sedimentation patterns, variations in the distribution of deep-sea hiatuses, and changing biogeographic patterns of planktic organisms. These major climatic and oceanic circulation changes, apparent in the early, middle, and late Miocene (summarized in Table 2), led to the evolution of the present-day oceanic circulation system and climatic regime.

Development of an oceanic deep circulation system similar to the present was initiated during the latest Oligocene to early Miocene by the opening of the deep Drake Passage (25–22 Ma) and the subsequent development of the deep Circum-Antarctic Current. Antarctic cooling accompanied these circulation changes, presumably as a result of thermal isolation of Antarctica. The oxygen-isotope record indicates that these circulation changes were accompanied by a minor cooling in the latest Oligocene followed by a relatively warm stable period, which climaxed in a major cooling by about 20 Ma. Among planktic organisms, a major faunal turnover occurred, resulting in the evolution of the Neogene faunas, eventual extinction of the Paleogene faunas, and major changes in the global planktic biogeographic distribution patterns. These faunal changes, which largely persisted through the Neogene, suggest that the basic water-mass characteristics of the present-day ocean became established at this time. In contrast to the present-day equatorial surface circulation, however, the erosion patterns of hiatuses PH (23.0–22.5 Ma) and NH 1 (20.0–18.0 Ma) and the broad equatorial band of carbonate ooze deposition suggest that a virtually unobstructed circum-equatorial circulation existed through the Tethys Sea into the Atlantic, Caribbean, Pacific, and Indian Oceans during the early Miocene.

Dramatic circulation changes occurred near the early/middle Miocene boundary, as indicated by the erosion pattern of hiatus NH 2 (16–15 Ma) and the sediment distribution changes. The circum-equatorial circulation appears to have been disrupted at this

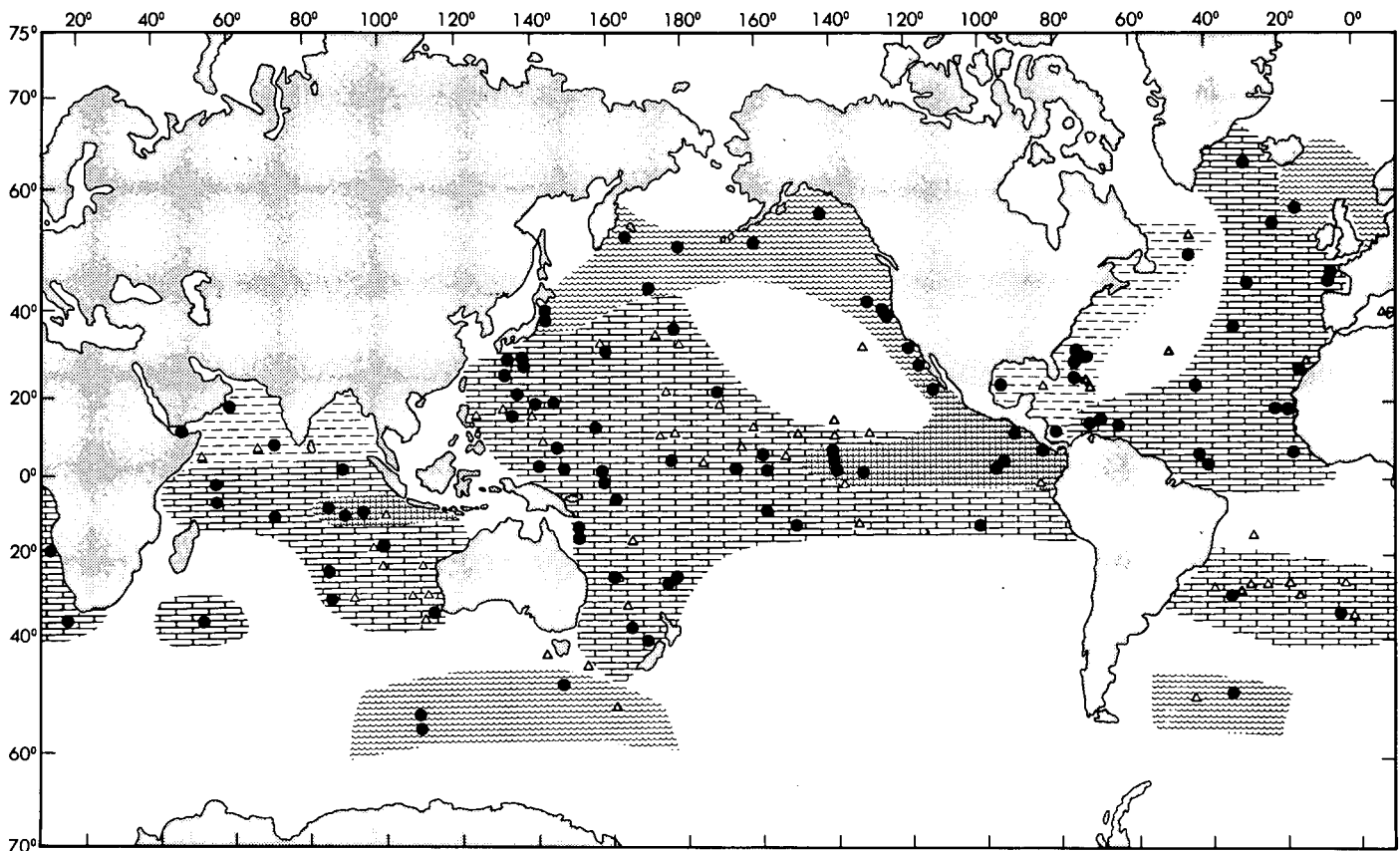


Figure 15. Deep-sea sediment distribution in the late Miocene (7.5–5.0 Ma). See Figure 11 for explanation of symbols.

TABLE 2. SUMMARY DIAGRAM ILLUSTRATING THE PALEOCEANOGRAPHIC HISTORY OF THE OCEANS DURING THE MIOCENE

Ma	HIATUS	FAUNAL/FLORAL CLIMATIC EVIDENCE	FAUNAL/FLORAL RESPONSE	SEDIMENT DISTRIBUTION CHANGES	MAJOR TECTONIC EVENTS	MAJOR OCEANOGRAPHIC EVENTS
4						
5	NH 7	I COLD (1,2)		Present pattern world sediment distribution established		★ Isolation of Mediterranean (24)
6		I WARM (2,3,4)		Increased sediment rate in high productive areas (5,6,19)	★ Uplift at Gibraltar (20)	★ C <sup>13</sup> - West Antarctic Ice Sheet established? (25), CCD in Pacific becomes shallower than in Atlantic (26)
7	NH 6	I COLD (2,3,5, 6,7,8)	★ Increased provincialism - diatoms (5)	Silica increases in Indian Ocean, further silica restriction in North Atlantic		
8		I WARM (3,5,6, 7,8)				
9						
10	NH 5	I COLD (3,5,6, 8,9)				★ Initial growth of West Antarctic Ice Sheet? (25)
11		I WARM (3,7)				
12	NH 4	I COLD (3,4,6, 8,10)	★ Increased provincialism - all planktic groups (3,15,16)	★ Silica increases in Pacific, disappears from mid latitude North Atlantic		★ Permanent latitudinal thermal gradient established between tropics and mid latitudes ★ Major increase in production of Norwegian Overflow Water (27)
13		I WARM (3,7,8, 10)				
14	NH 3	I COLD (3,8,11)	★ Extinction of Paleogene benthic foram. fauna (17); high turnover of planktic faunas (4,16)			
15					Collision of Australia and Indonesia (28) Uplift of Lord Howe Rise	
16	NH 2	I COLD (7,11,12)		★ Major enrichment of silica in Pacific and Indian Oceans and major decline in Atlantic	★ Subsidence of Iceland-Faroe Ridge (21) ★ Further uplift in Central America (22)	★ Initiation of Norwegian Overflow Water ★ Closing of intermediate water connection across Central America?
17		I WARM (7,11, 12,13)			★ Uplift in Central America (22)	
18			★ Major evolution - radiolarians (18)	★ Enrichment of silica in equatorial Pacific, decline in Caribbean	★ Collision of Africa & Europe (23)	★ Closing of deep water connection across Central America?
19	NH 1	I COLD (7,12,13)				
20			Development of provincialism - coccoliths (7)			
21			Increased diversity - planktic foram evolution of Neogene fauna (12,16)			★ Steep vertical thermal gradients established in the oceans (12)
22						
23	PH	I COLD (12,14)				
24					Opening of deep water Drake Passage (11,12,21)	

REFERENCES: (1)-Keller, 1978  
(2)-Bukry, 1982  
(3)-Keller and Barron, 1981  
(4)-Weaver et al, 1981  
(5)-Barron, 1980  
(6)-Keller, 1980  
(7)-Haq, 1980

(8)-Bukry, 1981  
(9)-Barron, 1973  
(10)-Barron, 1981  
(11)-Kennet et al, 1975  
(12)-Keller, 1981a  
(13)-Bukry, 1982  
(14) Boersma & Shackleton, 1976

(15)-Lohmann & Carlson, 1981  
(16)-Keller, 1981  
(17)-Woodruff & Douglas, 1981  
(18)-Goll, 1979  
(19)-Vincent et al, 1980  
(20)-Hsu et al, 1980  
(21)-Slater et al, 1977

(22)-Weyl, 1980  
(23)-Berggren & Holister, 1974  
(24)-Burckle, 1978b  
(25)-Ciesielski et al, 1981  
(26)-van Andel et al, 1975  
(27)-Blanc et al, 1980  
(28)-Edwards, 1975

Note: diagram compares intervals of widespread deep-sea hiatuses, relative paleoclimatic trends from microfossil studies, major changes in microplankton assemblages, major changes in sediment distribution, significant tectonic events, and major oceanographic changes. Asterisks indicate time constraints of events.

time as a result of the closing of the Tethyan Seaway and uplift in Central America, which disrupted the deep-water connection between the Atlantic and the Pacific Oceans. Beginning at this time, major sediment erosion occurred throughout the Caribbean, presumably caused by northward deflection of deep currents or by intensification of the Gulf Stream. The hiatus distribution NH 2, which marks the onset of this circulation change, is associated with a sharp fall followed by an immediate rise in the eustatic sea level.

Sediment distribution patterns changed dramatically by about 16.0 to 15.5 Ma with the onset of siliceous ooze deposition throughout the marginal North Pacific and eastern equatorial Pacific, accompanied by a decline in the siliceous sedimentation in the North Atlantic. This silica switch from the Atlantic to the Pacific appears to be related to the subsidence of the Iceland-Faeroe Ridge and introduction of Norwegian Overflow Water into the North Atlantic, which acted as a barrier to the upwelling of silica-rich Antarctic

Bottom Water. More Antarctic Bottom Water could thus be introduced to the Pacific and Indian Oceans, intensifying oceanic circulation and initiating upwelling patterns and siliceous sedimentation similar to that of the present in the marginal North Pacific.

Paleoclimatic conditions were generally warm, although oscillating at the early/middle Miocene boundary, but rapidly declined thereafter, climaxing in a major cool event by about 13.0 Ma that was associated with widespread deep-sea erosion (NH 3, 13.5–12.5 Ma). This major cooling probably resulted from the growth of a major East Antarctic ice cap, which initiated the generally cool although fluctuating climatic regime of the late Neogene. Antarctic glaciation was associated with a broadening belt of siliceous ooze sedimentation around Antarctica and increased siliceous sedimentation in the marginal and east-equatorial North Pacific and Indian Oceans. As a result of global cooling in the late middle Miocene, a permanent latitudinal gradient, similar to that of the present, was established between the tropics and middle latitudes by 11 Ma, resulting in increased provincialism between all planktic groups (Table C; see footnote 1 above). The eustatic sea level, which gradually declined during the middle Miocene, dramatically dropped in the early late Miocene (~10 Ma) coincident with widespread erosion at the time of hiatus NH 5 (9–10 Ma). This sea-level low stand coincides with a severe Antarctic cooling resulting from the growth of a West Antarctic ice sheet. In the North Atlantic, continued northward restriction of siliceous sedimentation is associated with a major increase in the production of Norwegian Overflow Water by about 12 Ma. Sediment distribution and deep-sea erosion patterns in the Pacific and Indian Oceans remain essentially unchanged through the late Miocene.

The latest Miocene is characterized by further provincialism in diatom floras, and by a rise in the CCD in the Pacific, but not in the Atlantic. The rise in the CCD nearly coincides with a shift to lighter  $\delta^{13}\text{C}$  values and may be related to the permanent establishment of the West Antarctic ice sheet and increased production of Antarctic Bottom Water. Development of present sediment distribution patterns during this time indicates that present oceanic conditions were established by the latest Miocene.

#### ACKNOWLEDGMENTS

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