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PALEODEPTH DISTRIBUTION OF NEOGENE DEEP-SEA HIATUSES

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Abstract. The depth of formation of Miocene to middle Pliocene deep-sea hiatuses (NH1 to NH8)has been determined using 152 Deep Sea Drilling Project sites in the Atlantic, Pacific and Indian oceans. Megahiatuses representing maxima in deep-sea erosion, occur at three water depths: below 3800 m, at intermediate depths between about 2000 and 3000 m, and in shallower waters above 1500 m paleodepth. Both the paleodepths and distribution of these hiatus maxima suggest that flow of Antarctic Bottom Water, Antarctic Intermediate Water, and North Atlantic Deep Water masses largely caused this erosion. Correlation of the hiatuses with oxygen isotope, carbonate and sea level records indicates that prior to 11 Ma, brief hiatuses including those resulting from nondeposition in high-productivity equatorial regions largely correlate with global cooling episodes, high-carbonate content, and lowstands of sea level. During the last 11 m.y., hiatuses also seem to correlate with cooling episodes, but carbonate dissolution is characteristic and sea levels may have been rising or at a lowstand. During the NH4, NH7, and NH8 intervals, it is possible that a rise in sea level corresponds with polar cooling, but there is uncertainty in correlation. Brief hiatuses during rising sea levels can be explained by basin-shelf fractionation of carbonates. Hiatuses during sea level lowstands and cooling episodes may result from intensified bottom water circulation and increased corrosiveness of bottom water due to higher levels of CO_2 and increased productivity during increased upwelling.

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INTRODUCTION

The pelagic marine sedimentary record of the upper Neogene is commonly interrupted by as many as eight short hiatuses which have been documented to occur over wide areas of the world ocean [Keller and Barron, 1983; Ledbetter and Ciesielski, 1986; Barron, 1987]. These events can also be recognized in the deep-sea seismic record [Mayer et al., 1985, 1986]. Each of these widespread unconformities represents an interruption in sediment record spanning one million years or less as calculated by high resolution stratigraphic studies in the high-productivity equatorial Pacific region [Barron and Keller, 1982; Keller and Barron, 1983]. In general, the amount of missing sediment per hiatus is dependent on the rate of sediment flux to the ocean floor. In high-fertility regions with high-sediment flux, hiatuses tend to be short in duration. Presumably, these unconformities are caused by nondeposition or dissolution of the biogenic component (carbonate disso-

Table 1. Ages of Neogene Hiatus Events

Hiatus Events	Keller and Barron [1983]	This Paper[a]
NH8	-	3.7-3.2 Ma
NH7	5.2-4.7 Ma	5.2-4.7 Ma
NH6	7.5-6.2 Ma	7.0-6.0 Ma
NH5	10-9 Ma	8.6-8.0 Ma
NH4	12-11 Ma	10.5-9.2 Ma
NH3	13.5-12.5 Ma	12.9-11.8 Ma
NH2	16-15 Ma	16.1-15.1 Ma
NH1	[20.0-18.0] Ma	18.2-17.2 Ma
NH1a		20.5-19.5 Ma

[a]See also Barron et al. [1985].

lution), rather than by mechanical erosion. In regions of low sediment flux, or in the paths of major currents, hiatuses are of longer duration, often spanning several millions of years. In this setting, unconformities tend to be caused by chemical and mechanical erosion.

Most investigations of hiatuses have concentrated on those of long duration because they are easily recognized by missing biozones or entire epochs [Kennett et al., 1972; Rona, 1973; van Andel et al., 1975, 1977; Moore et al., 1978; Thiede et al., 1981; Ehrmann and Thiede, 1985]. Although extended hiatuses are important features of the sedimentary record, they provide few paleoceanographic clues as to their origin, except where they developed in regions of low sedimentation and below the calcium carbonate compensation depth (CCD) [Berger, 1972]. Moreover, long hiatuses best provide information regarding cessation rather than the onset of erosion because of the extent of downcutting. Although it is not possible to obtain a complete history of erosive events and their paleoceanographic and paleoclimatic causes, the determination of the timing and distribution of short hiatuses and of carbonate dissolution patterns on the past ocean floor provides valuable paleoceanographic data.

Our high-resolution biostratigraphic time scale [Keller and Barron, 1983; Barron et al., 1985; Keller et al., 1987] permits recognition of hiatuses as brief as 0.5 million years. This time scale is based on integration of multiple microfossil biostratigraphies (planktonic foraminifera, nannofossils, radiolaria, diatoms). There are several purposes to this investigation. First, we review and update the record of Miocene deep-sea hiatus stratigraphy including recent developments in magnetostratigraphy [Berggren et al., 1985]. Consequently, the ages of the Miocene hiatuses of Keller and Barron [1983] have changed as indicated in Table 1. We also now recognize a widespread middle Pliocene hiatus (3.7-3.2 Ma). In addition, descriptions of a detailed carbonate curve for the east equatorial Pacific by Dunn [1982] and a revised eustatic sea level and coastal onlap curve by Haq et al. [1987] have provided a useful opportunity to investigate relationships between hiatuses, carbonate sedimentation, sea level changes, and climatic history and provide further insights into the causes of hiatuses. We have also determined the paleodepth of each of the Neogene hiatuses using the program of Sclater et al. [1985] for paleodepth backtracking (Appendix 1).[1] Knowledge of paleodepths of hiatus formation provides critical insights about the causes of erosion that form widespread deep-sea hiatuses.

METHODS

The biochronologies of Keller [1981a,b], Berggren et al. [1985], Barron et al. [1985], and Barron [in press] have been used to identify hiatuses and compressed intervals in 152 Deep Sea Drilling Project (DSDP) sites from the Atlantic, Pacific and Indian Oceans (Table 2). This adds 47 sites to those that were considered in our earlier paper [Keller and Barron, 1983]. Age versus depth curves and other graphical correlation plots were constructed for many of these sections and used in the manner of Keller and Barron [1983], Barron et al. [1985], and Stein et al. [1986] to reveal compressed intervals and hiatuses. Many of the microfossil datum sequences in Pacific sites were taken from our own studies; for other sites the biostratigraphies were taken from the Initial Reports and from papers published subsequently. Where age versus depth curves were not constructed, biostratigraphic summaries were examined for evidence of unconformities, missing or compressed microfossil zones, and zonal boundaries which were offset with respect to one another compared to the

[1]Supplement (Appendix 1) is available with entire article on microfiche. Order from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009. Document P87001; $2.50. Payment must accompany order.

biochronologies of Keller [1981a,b], Berggren et al. [1985], and Barron et al. [1985]. Offset zonal boundaries by themselves are the weakest evidence of hiatuses or compressed intervals, and the data on Table 2 reflects ambiguity in such cases.

STRATIGRAPHY

The stratigraphy of widespread Miocene deep-sea hiatuses was discussed by Keller and Barron [1983]. Since then, changes in age assignments of magnetic polarity chrons [Berggren et al., 1985] require a recalibration of ages of these hiatuses (Table 1).

The stratigraphic positions of the Miocene to early Pliocene hiatuses are illustrated in Figure 1 along with standard microfossil zonations [Barron et al., 1985], the eustatic sea level and coastal onlap curves of Haq et al. [1987], a composite percent carbonate curve based on data from Dunn [1982] and Bode and Cronin [1973], oxygen isotope data from Woodruff et al. [1981] and Kennett [1986], and paleomagnetic stratigraphy based on Berggren et al. [1985]. Hiatuses are labeled NH for Neogene Hiatus and numbered sequentially 1 to 8 from the base of the Miocene to the middle Pliocene. Ages for hiatus events NH1 to NH8 represent the shortest duration for each hiatus event that could be determined in regions marked by high rates of sediment flux (calcareous ooze) in the equatorial Pacific and are assumed to approximate the duration of the erosive events.

The earliest Neogene Hiatus NH1 spans the interval between 20.5 and 17.2 Ma, affecting the record of the uppermost part of planktonic foraminiferal Zone N4, plus Zones N5 and N6. In high productivity regions, however, NH1 is represented by two shorter erosive events, NH1a and NH1b, which are separated by an interval of continuous sedimentation spanning the interval from about 19.4 to 18.2 Ma. Therefore in areas of high sedimentation, NH1a is short (20.5 - 19.5 Ma), affecting the upper part of foraminiferal Zone N4 (N4c) and the upper part of the diatom Zone Rossiella paleacea (Subzone c). Hiatus NH1b (18.2 - 17.2 Ma) is identified by the absence of foraminiferal Zone N6, nanno- fossil Zone CN2, radiolarian Zone Stichocorys wolffii, and the lower part of diatom Zone Denticulopsis nicobarica (Figure 1).

Hiatus NH2 marks the earliest middle Miocene (16.1-15.1 Ma) and is identified by the absence of most of foraminiferal Zone N8 and the lower part of diatom Zone Cestodiscus peplum. Middle Miocene hiatus NH3 (12.9-11.8 Ma) is identified by the absence of the upper half of foraminiferal Zone N12 and of the diatom Zone Coscinodiscus gigas var. diorama. Hiatus NH4 (10.5-9.2 Ma) is recognized by the absence of much of foraminiferal Zones N14 and N15, by severe carbonate dissolution in the remaining part of Zone N15, and by absence of nannofossil Zone CN6 and Subzone CN7a (Figure 1).

The early late Miocene hiatus NH5 (8.6-8.0 Ma) is recognized by the absence of foraminiferal Zone N16, nannofossil Subzone CN8a, and the upper part of diatom Subzone A of the Coscinodiscus yabei Zone. Hiatus NH6 (7-6 Ma) is best identified by the absence of radiolarian Zone Diartus penultima and diatom Zone Nitzschia miocenica. The Miocene-Pliocene boundary hiatus NH7 (5.2 - 4.7 Ma) is identified by the absence of foraminiferal Zone N18, nannofossil Subzones CN10a and b, and diatom Subzone C of the Thalassiosira convexa Zone (Figure 1).

A newly recognized widespread middle Pliocene hiatus occurring between 3.7 and 3.2 Ma has been added and labeled NH8 [Barron, 1987]. This unconformity occurs in the upper part of foraminiferal Zone N19, near the CN11/CN12a nanno- fossil boundary, and in the upper part of the Nitschia jouseae diatom Zone. A correlative hiatus was also reported by Ciesielski and Grinstead [1986] as a major erosional event which they believe was caused by increased production of Antarctic Bottom Water (AABW). These authors estimated the age of this hiatus to be between 3.86 and 3.18 Ma, or the late Gilbert to early Gauss polarity Chron. Stein et al. [1986] report an additional younger mid-Pliocene hiatus at DSDP sites 366, 397, and 544 off north- west Africa with peak erosion at about 2.75 Ma. Ledbetter and Ciesielski [1986] recently proposed an "NH8" label for their latest Pliocene to Pleistocene hiatus (2.5-1.5 Ma). In view of our recognition of an earlier widespread middle Pliocene hiatus we suggest that Ledbetter and Ciesielski's [1986] younger hiatus be labeled NH9.

POSSIBLE CAUSES OF HIATUS FORMATION

In an earlier paper [Keller and Barron, 1983] we documented the global distribution of seven Miocene deep-sea hiatuses in the world ocean. We suggested that some hiatuses are related to major tectonic events, such as the opening of the deep Drake Passage in the early Miocene (NH1), others were related to major changes in oceanic circulation

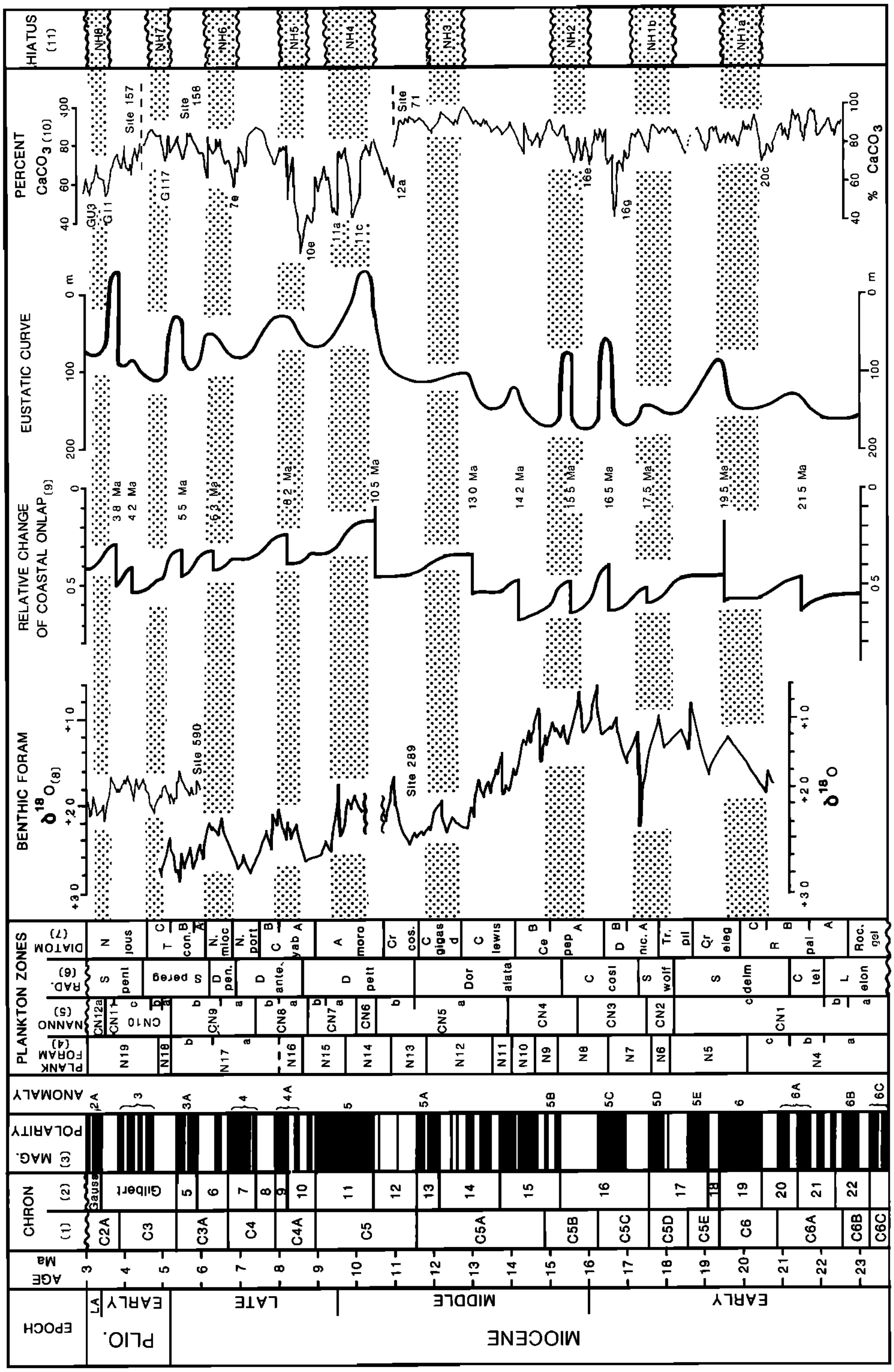

Fig. 1. Miocene to early Pliocene deep-sea hiatuses and their correlation to paleomagnetic stratigraphy (1, Tauxe et al. [1983]; 2, LaBrecque et al. [1977]; 3, Berggren et al. [1985]), microfossil zonations (4, Blow [1969]; Srinivasan and Kennett [1981]; Keller [1983]; 5, Okada and Bukry [1980]; 6, Reidel and Sanfilippo [1978]; 7, Burckel [1972]; and Barron [1985]), benthic foraminiferal oxygen isotopes (8, Woodruff et al. [1981] and Kennett [1986]), coastal onlap and eustatic sea level curves (9, Haq et al. [1987]), and percent carbonate (10, Dunn [1982] and Bode and Cronin [1973]).

such as major enhanced North Atlantic Deep Water (NADW) production which may have caused the switch in siliceous sedimentation from the Atlantic to the Pacific and Indian oceans near the early/middle Miocene boundary (NH2). It was also proposed that Miocene hiatuses generally corresponded to intervals containing positive increases in $\delta^{18}O$ values, indicating polar cooling episodes. Similar to Kennett and Watkins [1976], we assumed that deep-sea hiatuses are primarily caused by intensified deep water circulation driven by increased bottom water production during times of polar cooling. A general correlation between coastal offlap and hiatus formation in the deep sea was also observed [Keller and Barron, 1983], and it was assumed that this was related to growth of polar ice and intensified bottom current circulation. However, Figure 1 clearly shows that not all polar cooling events are associated with hiatuses and that some hiatuses occur during warm events. Thus climate appears to be an important, but not sole cause for hiatus formation.

Loutit and Kennett [1981] have argued that highstands in global sea level should result in maxima in deep-sea hiatus abundance, whereas lowstands should yield minima in deep-sea hiatuses. Loutit and Kennett [1981] used Berger's [1970] basin-shelf fractionation model to suggest that during sea level highstands, terrigenous material and organic carbon are trapped on the shelf, restricting the supply of dissolved material to the open ocean and increasing carbonate dissolution in the deep sea. The basin-shelf fractionation model invokes increased storage of carbonate on the shelf during times of sea level transgressions and decreased supply to the open ocean resulting in carbonate dissolution (increased hiatus formation) in the deep sea [Berger, 1970; Berger and Winterer, 1974]. Sea level regressions result in decreased carbonate sedimentation on shelves and increased supply to the deep-sea. Recently, Haq et al. [1987] argued that the period of maximum flooding of the continents, which they refer to as the "downlap surfaces," are correlative with our intervals of widespread deep-sea hiatuses.

Recent studies in carbonate fluctuations in sediments by Dunn [1982], as well as the appearance of revised, updated, and more detailed coastal onlap and eustatic sea level curves by Haq et al. [1987], justify a new look at the possible relationships between hiatuses and sea level fluctuations, climate and carbonate accumulation on the ocean floor.

In Figure 1 we have calibrated sea level, carbonate, and oxygen isotope curves to the Berggren et al. [1985] time scale with minor modifications, as discussed by Barron et al. [1985]. The Haq et al. [1987] time scale differs from both the Berggren et al. [1985] and Barron et al. [1985] time scales. In correlating the sea level events of Haq et al. [1987] we have mostly used calcareous nannofossil zones because these were the primary means of correlation of Cenozoic sea level events [B. U. Haq, oral communications, 1987]. Following Pisias et al. [1985], we suggest errors of correlation of these various curves to approximately 100,000-300,000 years.

The stippled pattern in Figure 1 marks hiatus events. Because the time of onset of an erosive event is generally uncertain and since sediments predating that event are frequently removed by erosion, we are much more confident with dating the cessation of a hiatus-producing event than with dating its onset. The time of initiative of an erosional event is approximated here by the youngest age at the base of the shortest-duration unconformities in the sediment records of high-fertility areas.

Figure 1 illustrates that, within the uncertainties of dating and correlation the cessation of Neogene hiatus-producing erosive events tend to coincide with positive oxygen isotope increases, or polar cooling episodes. Exceptions may be the late Miocene hiatuses NH5 and NH6, which could correlate with either cooling or warming episodes within our assumed margin of error. This supports our earlier suggestion that these hiatuses generally formed as a result of intensified bottom water circulation and increased corrosiveness of bottom waters during times of polar ice growth and increased production of young corrosive bottom water. However, correlation between hiatuses, sea level, and carbonate curves indicates that the apparent cold-event-hiatus-relationship may be obscured by other causal factors.

Figure 1 shows that during the late Miocene and Pliocene sea level was falling during NH5 and NH6 times but rising during NH4, NH7, and NH8 times. At the same time the percent carbonate in equational Pacific sediments was generally low except during NH7 time. It should be pointed out, however, that Dorn [1987] correlates hiatus events NH5 and NH6 with relative sea level highstands, noting that these erosive events ceased at times of rapid coastal offlap [see Figure 1 and Haq et al. 1987]. Earlier, we noted that carbonate dissolution was associated with hiatuses [Barron and

Keller, 1982; Keller and Barron, 1983], an observation which has been supported by Mayer et al. [1985, 1986], who studied seismic reflectors and their correlation to hiatuses and carbonate dissolution events in the equatorial Pacific.

The Miocene carbonate record prior to 11 Ma (NH4) does not show the high-amplitude variation of carbonate maxima and minima that typifies the late Miocene record. Moreover, hiatus events NH1b, NH2, and NH3 correlate with relatively low sea levels but intervals of high-carbonate sedimentation. Within our 0.1- to 0.3-m.y. error of correlation, hiatus NH1a may occur either during a highstand or a lowstand of sea level, but it also coincides with high carbonate sedimentation. It should also be noted that the carbonate record for NH1b was derived from a section (DSDP site 71, Dunn [1982]) that may contain this hiatus as noted by Keller [1981a].

We believe that the observed relationship between sea level changes and carbonate sedimentation is real and significant, not merely due to inherent errors in integrating Haq et al.'s [1987] time scale of sea-level events with our time scale. But further high resolution correlation of each hiatus event with sea level changes are necessary to confirm the relationships indicated here.

Our data suggest that during the Miocene prior to 11 Ma, deep-sea hiatuses generally coincide with sea level lowstands, enriched carbonate in deep-sea sediment, and times of polar cooling. After 11 Ma, deep-sea hiatuses appear to correlate with either polar cooling, sea level highstands [NH4, NH7, NH8] or lowstands [NH5, NH6], and carbonate dissolution [except for hiatus NH7].

If we assume that the relationships between cool events, sea level, carbonate accumulation and deep-sea hiatuses noted above are real, then times of enhanced deep-sea hiatus formation are the result of multiple causes. Global climate and its effect on the geographic pattern and supply of nutrients, the sources and production of bottom water, and the intensification of bottom currents are the primary factors influencing the development of hiatuses. Additional modifying factors are tectonic events that change ocean circulation patterns. Generally, unconformities occurring during episodes of polar cooling would coincide with times of lowered sea level which reflect increased ice accumulation at the poles. Increased polar cooling likely results in intensified bottom currents arising from increased production of bottom water, but the same polar cooling would also cause increased fertility and hence higher rates of carbonate sedimentation. In such cases, increased sedimentation may reduce or obliterate the effects of erosion due to intensified bottom currents, as observed in high-productivity equatorial regions. Berger's [1970] basin-shelf carbonate fractionation model, which postulates high-carbonate sedimentation in the deep-sea during sea level lowstands, but low-carbonate sedimentation during sea level highstands, is consistent with this scenario. This interpretation appears to fit Neogene hiatus events prior to 11 Ma, although these hiatuses also coincide with major tectonic-oceanographic events as discussed below.

A change in the mechanism of hiatus formation appears to have occurred after 11 Ma which at times seems to have overriden the cold-event-sea level-lowstand-high-carbonate-hiatus-relationship. During three hiatus events (NH4, NH7, NH8), sea level appears to have been rising during cool events. If this relationship is real, then lowered sea level due to polar ice accumulation may have been compensated by other factors, which are not evident at this time. In any case, the low-carbonate sedimentation associated with rising sea levels is consistent with the basin-shelf fractionation model.

Hiatus formation during sea level lowstands and cooling episodes, as observed during NH5 and NH6 time, may result from both intensified bottom circulation and increased corrosiveness of bottom water as a consequence of higher levels of CO_2 and nutrients during increased upwelling.

We have argued earlier that some hiatus events appear to have been related to tectonic-oceanographic events which may also cause modifications in the cold-event-hiatus-relationship. For instance, the opening of the deep Drake Passage at NH1 time is likely to have affected oceanic deep water circulation globally. Roberts et al. [1979] and Miller and Tucholke [1983] have suggested that increased outflow of Norwegian Sea water into the north Atlantic during the early middle Miocene (NH2) time may have been responsible for widespread erosion in the Atlantic, an idea which we supported in our earlier paper [Keller and Barron, 1983]. The erosive character of this event in the North Atlantic has been documented by Montadert et al. [1979] and Miller and Tucholke [1983]. If North Atlantic Deep Water (NADW) formation increased significantly at this time, global abyssal circulation patterns would have been affected, and erosive hiatuses may have developed independent of sea level change.

Hiatus event NH3 (12.9-11.8 Ma), which coincides with the major middle Miocene cool event [Woodruff et al., 1981], also

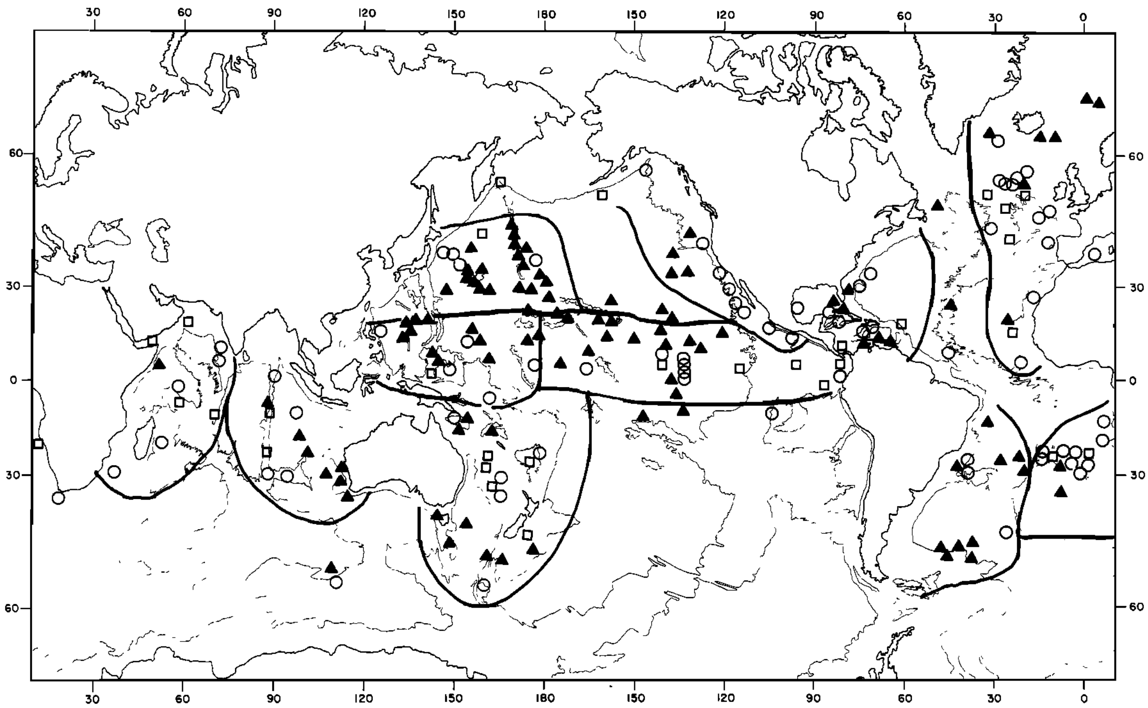

Fig. 2. Miocene to early Pliocene DSDP site locations used in this study. Geographic regions discussed are outlined. DSDP sites are marked with the following symbols: open squares, <50% of hiatuses NH1 to NH8 present; open circles, >50% of short hiatuses NH1-NH8 present; solid triangles, predominantly megahiatuses present. Contour line marks the 2000-m-depth level.

occurs at the time of the final closure of the eastern end of the Mediterranean Sea [Steininger, 1983] which led to increased salinities in the Mediterranean. Outflow of this saline water into the north Atlantic may have affected production of NADW.

Collision of the Australian subcontinent with Indonesia also occurred at about NH3 time [Kennett et al., 1985], causing changes in both surface and intermediate water circulation in the equatorial Pacific. These circulation changes may have affected fertility patterns and pelagic sedimentation in the western north Pacific, an area of widespread expression of NH3 erosional gaps [Keller and Barron, 1983; Ujiie, 1984]. Therefore NH3 may have been due to increased erosion by abyssal deep water and/or to changes in pattern of surface water productivity. Mayer et al. [1985, 1986] identified a seismic reflector (mM-R) which they considered correlative with NH3 (12.9-11.8 Ma), but their event, dated at 14.2-13.6 Ma, is slightly older. No major tectonic-oceanographic events have been identified at the time of the younger hiatus events NH4 to NH8. In summary, major Miocene tectonic events affected oceanic circulation patterns causing widespread erosion, but apparently did not change the cold-event-high-carbonate-hiatus-relationship significantly.

PALEOBATHYMETRIC DISTRIBUTION OF HIATUSES

We have estimated the paleodepth at which hiatuses formed at individual deep-sea locations using the program of Sclater et al. [1985] for paleodepth backtracking. Appendix 1 lists hiatuses and paleodepth for the corresponding intervals NH1 to NH8 at DSDP sites that reached basement, or for which basement age could be estimated from magnetic anomaly maps. The paleobathymetry of deep-sea unconformity occurrence during Miocene and Pliocene time has been investigated for the specific oceanographic regions illustrated in Figure 2. Reflecting differences in sea-floor topography and deep-water circulation patterns, each of these oceanographic regions shows a distinctly different paleodepth distribution of

HIATUS DISTRIBUTION IN THE PACIFIC OCEAN

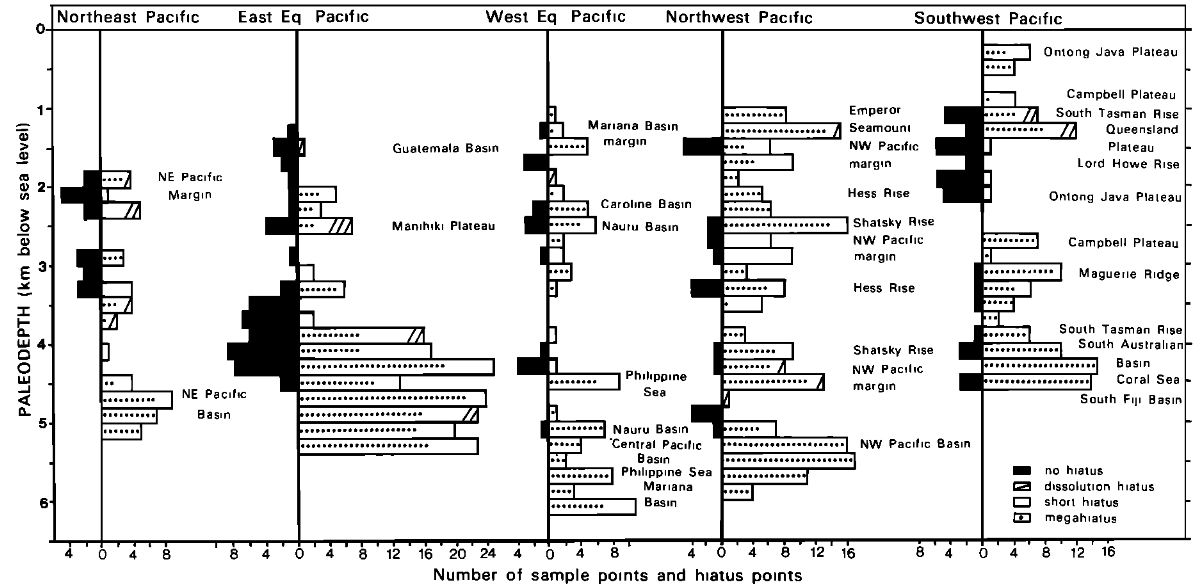

Fig. 3. Paleodepth distribution of Miocene to early Pliocene hiatuses NH1 to NH8 for specified regions in the Pacific Ocean. Deep-Sea sections without hiatuses during NH1 to NH8 events are plotted to the left. Hiatuses are classified as (1) intervals of dissolution or nondeposition generally spaning less than 0.5 m.y., (2) short hiatus restricted to specific intervals NH1 to NH8, and (3) megahiatus spanning two or more hiatus intervals.

deep-sea hiatuses. In general, however, there is little change in the paleodepth at which these erosive/dissolution events formed during the Neogene, except for an overall decrease in paleodepth of hiatus formation in the north Atlantic beginning in the late Miocene at about 8 Ma (NH5) (Appendix 1). It is possible that this shoaling of deep-sea erosion in the Atlantic is a result of increased production of North Atlantic Deep Water (NADW) which introduced more "young" less corrosive water into the oceans, resulting in a decrease in deep water hiatus formation. Increased production of North Atlantic Deep Water during the late Miocene has been noted by several workers [Blanc et al., 1980; Berggren, 1982; Mayer et al., 1985].

The paleodepth of deep-sea unconformities during the Neogene is summarized in Figures 3-5. Categories are: (1) no hiatus present, (2) disruption in sedimentation due to interval of severe dissolution or nondeposition, (3) short hiatus restricted to particular events NH1 to NH8, and (4) megahiatus, or major unconformity with erosion spanning two or more hiatus events. In most cases, megahiatuses mark erosion by bottom current scour or deposition below the carbonate compensation depth (CCD). Short unconformities and disruptions in sedimentation due to dissolution or nondeposition are generally found in high-productivity regions or protected basins. Table 2 lists the paleodepths at which both the maximum and minimum of deep-sea hiatuses are found with the percentage of deep-sea sections containing hiatuses given for intervals of maximum hiatus development (megahiatuses in parentheses).

Pacific Ocean

The paleodepth distribution of Miocene to Pliocene deep-sea unconformities in the Pacific Ocean is illustrated in Figure 3 for different oceanic regions. In the northeast Pacific, few continuously cored deep-sea sites are available (Figure 2), and these show a maxima in hiatus formation below 4400 m paleodepth with 16% short hiatuses and 84% megahiatuses. In most of these sections, megahiatuses span Eocene to Pliocene sediments. Erosion at these depths is likely caused by bottom currents acting on areas with reduced sediment supply which lie below the CCD. Two maxima in deep-sea unconformity distribution also occur between 2800 and 3800 m (62% hiatuses) and 1800 and 2400 m (53% hiatuses) paleodepths (Figure 3,

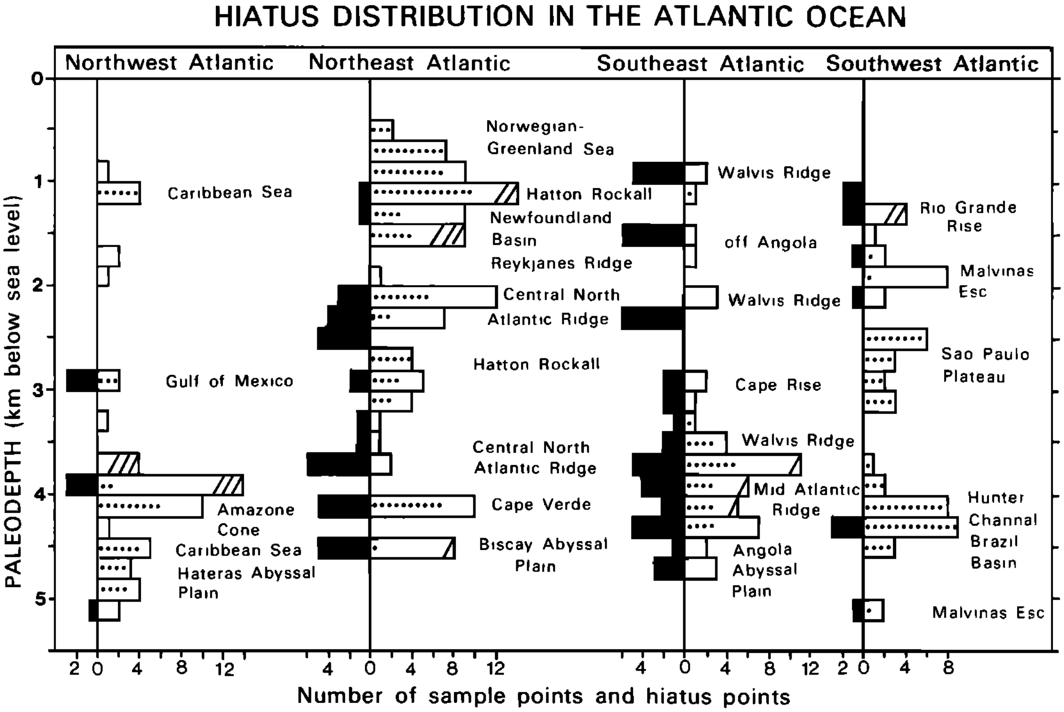

Fig. 4. Paleodepth distribution of Miocene to middle Pliocene hiatuses NH1 to NH8 for specified regions in the Atlantic Ocean. See Figure 3 for complete caption.

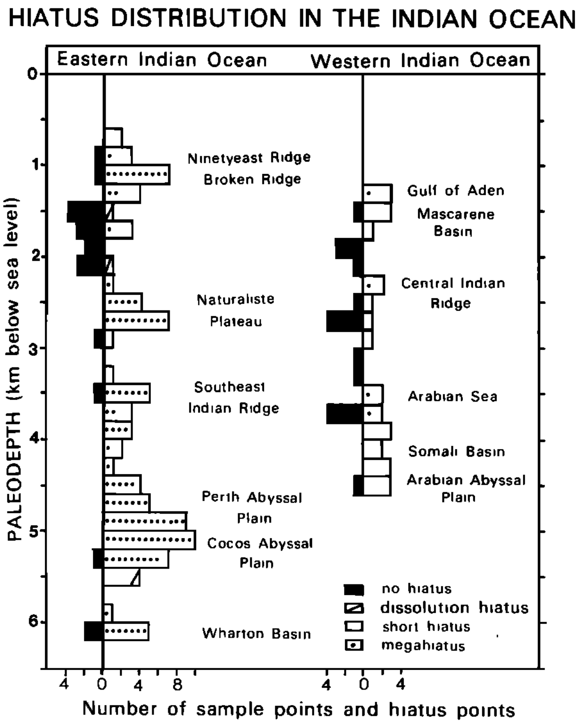

Fig. 5. Paleodepth distribution of Miocene to middle Pliocene hiatuses NH1 to NH8 for specified regions in the Indian Ocean. See Figure 3 for complete caption.

Table 2). These maxima cluster in eastern basins and may be due to erosion by eastern boundary currents.

The paleodepth distribution of hiatuses in the equatorial Pacific is quite different in the eastern and western regions and therefore are plotted separately (Figure 3). The eastern equatorial Pacific has a deep maximum in unconformity occurrence between 3800- and 5400-m paleodepth. Below 4600 m all deep-sea sections contain hiatuses and 79% of these are megahiatuses. A similar maximum deep-sea unconformity occurrence is also observed in the western equatorial Pacific, where sediments in the deep water Philippine Sea, Nauru Basin, and Mariana Basin show hiatuses in 98% of the sections (86% have megahiatuses, Table 2). Van Andel et al. [1977] estimated that the equatorial Pacific CCD was about at 4500 m depth during most of the Miocene. We conclude therefore that the maxima in unconformities seen below 4600 m is partly due to deposition below the CCD, although the high percentage of megahiatuses suggests active erosion by bottom water currents as a major contributor below 3800-m paleodepth.

A minimum in deep-sea hiatus occurrence (13% hiatuses) is present between 3400- and 3800-m paleodepth in the eastern equatorial Pacific, and a similar

Table 2. Summary of Paleodepth Distribution of Neogene Hiatuses

Depth, m	Hiatus	Depth, m	Hiatus
East Equatorial Pacific		**West Equatorial Pacific**	
1200-2000	hiatus minimum	1200-2000	hiatus 70% (53%)
2000-3400	hiatus 72% (33%)	2000-3400	hiatus 78% (59%)
3400-3800	hiatus minimum	3400-4400	hiatus minimum
3800-4600	hiatus 74% (46%)	4400-5400	hiatus 98% (86%)
4600-5400	hiatus 100% (79%)	5400-6200	hiatus 100% (86%)
Northwest Pacific		**Southwest Pacific**	
1000-1800	hiatus 87% (70%)	200-1400	hiatus 89% (85%)
2000-3600	hiatus 87% (52%)	1400-2200	hiatus minimum
3800-4600	hiatus 95% (83%)	2600-3600	hiatus 91% (90%)
4600-5000	hiatus minimum	3800-4600	hiatus 87% (100%)
5000-6000	hiatus 99% (95%)		
Northeast Pacific			
1800-2400	hiatus 53% (70%)		
2800-3800	hiatus 62% (46%)		
4400-5200	hiatus 100% (84%)		
Northwest Atlantic		**Northeast Atlantic**	
800-2000	hiatus 100% (50%)*	600-1600	hiatus 93% (66%)
2800-3400	hiatus 50% (66%)*	2000-3200	hiatus 66% (37%)
3600-4200	hiatus 91% (25%)	3200-3800	hiatus minimum
4400-5200	hiatus 94% (86%)	4000-4600	hiatus 65% (44%)
Southwest Atlantic		**Southeast Atlantic**	
1000-2000	hiatus 74% (11%)	800-2400	hiatus minimum 32%
2400-3200	hiatus 100% (100%)	2800-3600	hiatus minimum 44%
3600-4600	hiatus 89% (100%)	3600-4800	hiatus 63% (44%)
West Indian Ocean		**East Indian Ocean**	
600-1400	hiatus 88% (37%)	600-1400	hiatus 89% (55%)
1400-2200	hiatus minimum	1400-2200	hiatus minumum
2200-3400	hiatus 40% (0%)	2200-3000	hiatus 93% (93%)
3400-4600	hiatus 75% (13%)	3400-6200	hiatus 96% (91%)

Asterisk indicates incomplete coverage of DSDP sites in that depth range. Percentage of sections with hiatuses, parentheses: percentage with mega-hiatuses.

minimum occurs in the western region between 3400- and 4400-m. Differences in paleodepth of hiatus formation may be partly due to differences in surface productivity between east and west equatorial Pacific. Increased fertility in the eastern equatorial region beginning in the late early Miocene is reflected by increased diatom and radiolarian productivity. Increased influx of organic matter to the seafloor resulted in increased CO_2 levels in deep waters and hence increased dissolution of carbonate. In areas removed from intense biosiliceous sedimentation a net decrease in sedimentation to the ocean floor may occur. Consequently, hiatus formation continued to a shallower depth than in the western region.

A maximum in hiatus occurrence at intermediate depths of 2000-3400 m is present in both the eastern and western regions with 72% and 78% hiatuses, respectively, in the sections surveyed (Figure 3). In the eastern equatorial Pacific, relatively few unconformities are present between 1200- and 2000-m paleo- depth in the Guatemala Basin. Sediments in this region are of late Miocene age and younger. In the west equatorial Pacific a hiatus maximum (70% hiatuses) is present at this paleodepth, and erosion occurs primarily in the margin of the Mariana Basin.

The paleodepth distribution at which deep-sea unconformities are formed in the northwest Pacific is controlled primarily by ocean floor topography, in particular, the position of Hess Rise, Shatsky Rise, and Emperor Seamount (Figures 2 and 3). Maxima in hiatus occurrence range across all depths. However, there are similarities to the equatorial Pacific that suggest the same currents and/or water mass boundaries at work. The deep maximum in deep-sea unconformities, which is probably related to bottom water activity and deposition below the CCD, occurs below 5000-m paleodepth. A second maxima in deep-sea hiatus occurrence is found between 3800- and 4600-m similar to the maximum found at this paleodepth in the equatorial Pacific (Table 2). However, unlike the equatorial Pacific, an intermediate depth (4600-5000 m) with few unconformities separates the two deep hiatus maxima in the northwest Pacific. Moreover, there is no pronounced minimum in unconformities in the northwest Pacific corresponding to the minimum in hiatus occurrence found between 3400- and 3800-m in the equatorial regions. Two hiatus maxima at intermediate and shallow paleodepths of 2000-3600 m and 1000-1800 m, respectively, occur on the Shatsky Rise, Hess Rise, and Emperor Seamount regions and correspond to maxima at similar depths in the equatorial regions (Figure 3).

Hiatus formation in the southwest Pacific shows two maxima at depths between 2600- and 3600-m and 3800- and 4600-m, where 91% and 87% of the sections, respectively contain unconformities. The high percentage of sections containing megahiatuses, 90% and 100%, respectively (Table 2), indicates strong bottom current scour. A third maximum in hiatus occurrence is present in shallow waters between 200- and 1400-m paleodepth with 89% of the sections containing hiatuses (Figure 3). A minimum in hiatus distribution is present between 1400- and 2200-m paleodepth, where short hiatuses are present in only 13% of the sections. Sedimentation at these depths occurred on Lord Howe Rise and Ontong Java Plateau.

Atlantic Ocean

Paleodepth distribution of hiatuses in the Atlantic has been plotted separately for the western and eastern regions of the north and south Atlantic (Figure 4). In the northeastern Atlantic a maximum in the formation of deep-sea unconformities is present between 4000- and 4600-m paleodepth in the Biscay Abyssal Plain and Cape Verde region, where 65% of the sections contain hiatuses (44% megahiatuses, Figure 4, Table 2). A minimum in hiatus development is present between 3200- and 3800-m paleodepth. A second hiatus maximum with 66% hiatuses (37% megahiatuses) is present at intermediate depths between 2000- and 3200-m paleodepth, and a shallow interval with 93% hiatuses occurs between 600- and 1600-m paleodepth. These hiatus maxima appear to be related to flow paths of north Atlantic deep thermohaline currents (NADW) from the Norwegian-Greenland Sea across the deepening Faeroe-Shetland Ridge. Initiation of the Norwegian-Greenland Sea overflow (NADW) into the deep north Atlantic is believed to have occurred by late Eocene to early Oligocene time [Miller and Tucholke, 1983]. Increased production of NADW during Miocene global cooling phases would have intensified the abyssal circulation resulting in increased hiatus formation in the northeast Atlantic.

Hiatus distribution in the western North Atlantic, including the Gulf of Mexico and the Caribbean Sea, is not well defined at intermediate or shallow depths because of the paucity of deep-sea sections with published biostratigraphies. Two deep maxima in hiatus occurrence are present between 3600- and 4200-m and 4400- and 5200-m paleodepth where 91% and 94% of the deep-sea sections, respectively, contain unconformities. Megahiatuses (86%) occur predominantly below 4400-m paleodepth. Erosion at these depths is probably related partly to Antarctic Bottom Water Flow (AABW) and partly to NADW [Tucholke and Mountain, 1986]. At shallower depths between 800- and 2000-m and 2800- and 3400-m, numerous unconformities appear to be present in the Caribbean Sea and Gulf of Mexico, respectively.

The paleodepth distribution of deep-sea unconformities is plotted separately for the Walvis Ridge area in the southeastern Atlantic, the Falkland Plateau, and Rio Grande Rise regions in the southwestern Atlantic. Throughout the Miocene and Pliocene, erosion was greater in the southwestern region reflecting current flow paths over the Falkland Plateau and through the Vema Channel in the Rio Grande Rise region.

A deep maximum in hiatus formation occurs between 3600- and 4800-m paleodepth in the Hunter and Vema channels and the Brazil Basin (Figure 4), where 89% of all deep-sea sections contain hiatuses. Major sediment removal (megahiatuses) by current scour apparently occurred in all sections. A second hiatus maximum (100% hiatuses) occurs between 2400- and 3200-m paleodepth in the Falkland Plateau region, where major physical erosion occurs in all sections. Less erosion is evident on the Rio Grande Rise and Malvinas Escarpment between 1000- and 2200-m, where 74% of the sections contain hiatuses, but only 11% of these are megahiatuses.

The Walvis Ridge area in the southeastern Atlantic experienced considerably less erosion than the Rio Grande Rise area. A hiatus maximum appears to be present only below 3600-m paleodepth with 63% hiatuses but only 44% megahiatuses. Few hiatuses are present at shallower depths.

Indian Ocean

The paleodepth distributions of hiatuses in the eastern and western Indian Ocean are widely different due to topography and flow paths of Antarctic Bottom Water (AABW). The western Indian Ocean maintained relatively continuous sedimentation interrupted by few short hiatuses (NH1 to NH8), and megahiatuses are rare (Figure 5). As in the Pacific and Atlantic, a deep hiatus maximum (75% hiatuses) occurred between 3400- and 4600-m paleodepth and was most severe in the Somali Basin and Arabian Abyssal Plain. This maximum is most likely related to AABW flow [Johnson, 1985]. Two shallower maxima also appear to be present between 2200- and 3400-m and 600- and 1400-m paleodepth in the Central Indian Ridge region, the Gulf of Aden, and Mascarene Basin. The shallow hiatus maximum may be related to thermohaline circulation from the Red Sea and Arabian Sea which at present is found at these depths [Wyrtki, 1973; Johnson, 1985].

In contrast to the western Indian Ocean, megahiatuses, which frequently remove the Upper Cretaceous to Miocene sediments, predominate in the eastern Indian Ocean and indicate mechanical erosion and transport of sediments by powerful currents. A deep-hiatus maximum with a bimodal distribution similar to the Pacific and Atlantic lies below 3400-m paleodepth with hiatuses in 96% of the sections (Figure 5). The deeper part of this maximum occurs below 4400-m paleodepth in the Perth Abyssal Plain, Cocos and Wharton basins, with hiatuses in 93% of the sections (90% megahiatuses). The shallower part of this deep maximum (hiatuses in 93% of the sections) occurs between 3400- and 4200-m paleodepth on the Southeast Indian Ridge. A hiatus maximum at intermediate depths occurs between 2200- and 3000-m and is restricted to the Naturaliste Plateau (93% megahiatuses, Figure 5, Table 2). Minimal erosion occurs between 1400- and 2200-m paleodepth. A shallow hiatus maximum occurs between 600- and 1400-m paleodepth restricted to the Ninetyeast Ridge and Broken Ridge (Figure 5, Table 2).

These three deep-, intermediate- and shallow-hiatus maxima appear to be characteristic of the Pacific, Atlantic and Indian oceans and are likely to be related to global oceanic circulation patterns as discussed below.

DISCUSSION

Our data suggest that widespread erosional hiatuses are generally related to flow paths of bottom water masses and boundary currents, whereas geographically restricted hiatuses occur on oceanic rises and plateaus and along the slopes of continental margins. Identifying the cause of erosion in specific geographic regions is difficult.

The paleobathymetry of unconformity formation illustrated in Figures 3-5 clearly shows that maximum erosion/dissolution occurs at specific depths separated by intervals of relatively little erosion. It is also apparent that paleodepths of unconformity maxima and minima vary between, and sometimes within, ocean basins. Nevertheless, there is an overriding trend in hiatus maxima to occur in deep (below 3800 m) (Figure 6), intermediate (2000-3000 m), and shallow (< 1500 m) paleodepths (Figure 7). The most intense erosion in all ocean basins occurs below 3800-m paleodepth. Megahiatuses predominate at these depths, indicating active mechanical and chemical erosion of slowly accumulating sediments which lie near or below the CCD. This deep maximum in unconformities generally has a bimodal distribution with maximum erosion below 4400 m and a second peak between 3800- and 4400-m paleodepth. The lack of a peak in hiatus formation in Atlantic sections below 4400-m paleodepth reflects the paucity of sections collected below that depth in the Atlantic. The hiatus peak below 4400-m paleodepth appears to be related to deposition below the CCD (Figures 2-5). This depth level for the CCD is consistent with Van Andel et al.'s [1977] depth level for the CCD.

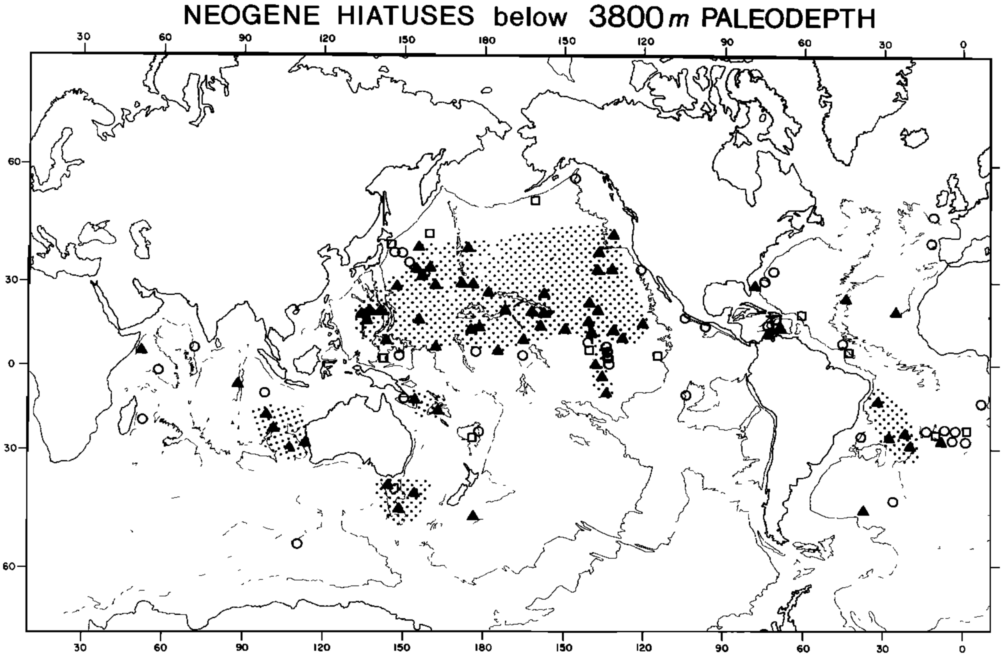

Fig. 6. Distribution of Miocene to early Pliocene hiatuses below 3800-m paleo- depth. Stippled areas mark regions of maximum erosion. See Figure 2 for explanation of symbols.

The second peak in the deep unconformities occurs between about 3800- and 4400-m paleodepth. Mechanical erosion below 3800-m paleodepth is most strongly recorded in the southwest Pacific, southwest Atlantic, northwest Atlantic and eastern Indian Ocean, as illustrated in Figure 6 and corresponds

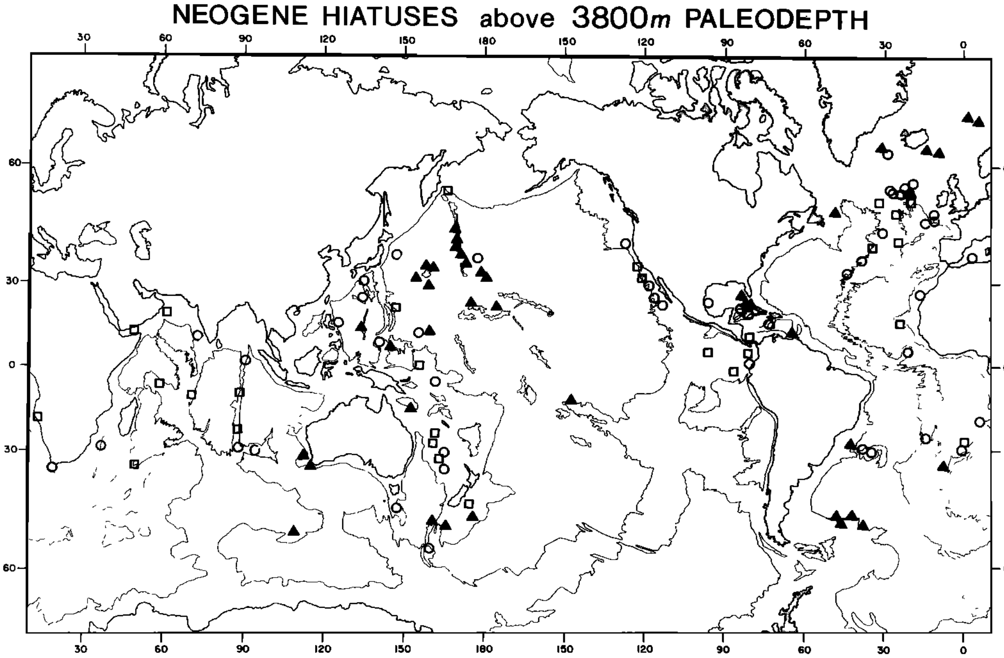

Fig. 7. Distribution of Miocene to early Pliocene hiatuses above 3800-m paleodepth. See Figure 2 for explanation of symbols.

to present-day flow paths of Antarctic Bottom Water. It may therefore be assumed that paths of Antarctic Bottom Water circulation during the Miocene to early Pliocene was similar to the present. A large region of megahiatuses at this paleodepth (below 3800 m) also is present in the central north Pacific and is largely the result of deposition below the CCD and low-organic productivity in the central gyre.

A major hiatus maximum also occurs at mid-depth between about 2000- and 3000-m paleodepth in the Pacific, excepting Lord Howe Rise and Ontong Java Plateau (Figure 3), and in the Atlantic, excepting Walvis Ridge (Figure 4), and in the Indian Ocean (Figure 5). A shallow-hiatus maximum (<1500-m paleodepth) is present in restricted regions, such as Emperor Seamount, Campbell Plateau, and South Tasman Rise in the Pacific, the Norwegian- Greenland Sea in the north Atlantic, and the Ninetyeast Ridge and Broken Ridge in the Indian Ocean. Figure 7 illustrates the geographic distribution of hiatuses at paleodepths shallower than 3800 m. It is evident that megahiatuses at these depths are restricted to seamounts, oceanic rises, and plateaus remote from areas of high biologic productivity. With reduced rates of sedimentation, mechanical erosion in these areas may be caused by mass wasting due to slumping, particularly in the Hess Rise and Shatsky Rise areas of the northwest Pacific. However, erosion at mid-depths in the Southern Hemisphere is likely caused by flowpaths of Circumpolar Deep Water [Ledbetter and Ciesielski, 1986]. Erosion in the Greenland-Norwegian Sea is probably related to North Atlantic Deep Water (NADW) production.

CONCLUSIONS

One of the more dominant factors determining the distribution of deep-sea hiatuses is the rate of sediment supply. Where sediment rates are high, such as in high-fertility regions, unconformities are found only along paths of intense bottom water flow (mechanical erosion) or beneath the CCD. In areas peripheral to high fertility regions, changing patterns of surface water productivity can drastically affect the depth of the CCD and the rate of sediment supply to the seafloor. These areas are especially susceptible to brief erosive events (short hiatuses) triggered by paleoceanographic events, e.g., polar cooling, which affect both fertility patterns and the intensity of flow of deep waters. Regions within the low-fertility central water masses receive reduced sediment supplies, and mechanical erosion along flow paths of deep water masses becomes significant.

The paleodepth distribution of Miocene and early Pliocene deep-sea hiatuses reflect productivity patterns as well as the distribution of deep and intermediate water masses in the various ocean basins. Three deep-sea hiatus maxima occurring at deep (>3800 m), intermediate (3000-2000 m), and shallow (<1500 m) paleodepths are apparent in the Atlantic, Pacific and Indian oceans. We conclude that the paleodepth distribution of Miocene and early Pliocene deep-sea hiatuses suggests that global hiatus maxima occurring at these depths are caused primarily by Antarctic Bottom Water, Circumpolar Deep Water, and North Atlantic Deep Water, respectively. Geographic distribution of deep-sea unconformities indicates that mechanical erosion (megahiatuses) is most severe directly in the paths of these water masses. Mass wasting due to slumping may be the primary factor in erosion of seamounts and oceanic rises. However, paleodepth distributions of hiatus maxima also show some variations within and between oceanic regions which appear to be influenced primarily by ocean floor topography.

Brief intervals of nondepositional or dissolution (short hiatuses) hiatuses in high-productivity regions provide refined dating of the record of widespread deep-sea hiatuses and allow correlation with the carbonate, stable isotope, and sea level curves. Our analyses indicate that Neogene hiatuses prior to 11 Ma generally correlate with sea level lowstands, high carbonate in sediments and cooling episodes. After 11 Ma hiatuses seem to correlate with either cooling episodes, sea level highstands (NH4, NH7, NH8), or lowstands (NH5, NH6), and carbonate dissolution (except for NH5). It is unclear why sea level highstands appear to occur during global cooling episodes. Possible explanations include an increased rate of oceanic crustal spreading causing increased volume of the mid-ocean ridge system, or simply errors in correlation. In any case, hiatus formation during sea level highstands can be explained by Berger's [1970] and Berger and Winterer's [1974] basin-shelf fractionation model. Hiatus formation during sea level lowstands may be related to cooling episodes as a result of both intensified bottom circulation and increased corrosiveness of bottom water. The latter is probably a result of increased levels of CO_2 and productivity related to increased upwelling.

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