Global distribution of late Paleogene hiatuses

G. Keller, T. Herbert, R. Dorsey, S. D'Hondt, M. Johnsson, W. R. Chi
Department of Geological and Geophysical Sciences, Princeton University, Princeton, New Jersey 08544

ABSTRACT

Six global late Paleogene hiatuses (PHa to PHe) have been identified from deep-sea sequences. These hiatuses occurred at the middle/late Eocene boundary, late Eocene, Eocene/Oligocene boundary, late early Oligocene, late Oligocene, and Oligocene/Miocene boundary horizons.

Paleodepth distribution of hiatuses shows hiatus maxima characterized by major mechanical erosion below 4800 m, at mid-depth between 2000 and 3000 m, and in shallower water above 1600 m paleodepth. The geographic distribution and paleodepth of these hiatus maxima suggest that flow paths of major water masses and currents are the principal cause. Widespread short hiatuses due to carbonate dissolution or nondeposition occurred primarily during global cooling trends or climatic instability and appear to correlate to sea-level transgressions or onlap sequences. These hiatuses may have been caused by basin-shelf fractionation of carbonates.

INTRODUCTION

The sedimentary record of the marine depositional environment is interrupted by numerous hiatuses that are random neither in geographic nor in temporal distribution. Many of these oceanic hiatuses appear to be of global extent (Rona, 1973; Van Andel et al., 1975, 1977; Moore et al., 1978; Thiede et al., 1981; Keller and Barron, 1983; Ehrmann and Thiede, 1985) and are produced by mechanical or chemical erosion on the ocean floor. In an earlier study we found that widespread Neogene hiatuses appear generally related to flow paths of bottom-water masses that are intensified during periods of global cooling and lower eustatic sea levels (Keller and Barron, 1983, 1987). Geographically more restricted hiatuses occurred on oceanic rises and plateaus and along the slopes of continental margins. These hiatuses may have been caused by mass wasting due to slumping and boundary currents. In general, the amount of sediment removed by hiatuses is determined by the sediment flux to the ocean floor. In high-fertility regions that have high sediment flux, hiatuses tend to be short because of nondeposition or chemical erosion (carbonate dissolution). In regions of low sediment flux, hiatuses tend to be caused by chemical and mechanical erosion and are more extensive, removing sediment spanning several millions of years.

Keller and Barron (1983, 1987) have identified seven short global deep-sea hiatuses during the Miocene and one in the early Pliocene on the basis of sediment and faunal analyses of high-fertility regions. This report extends the study into the middle Eocene.

Six global deep-sea hiatuses have been identified as occurring between the latest middle Eocene and the late Oligocene (24–42 Ma) on the basis of quantitative planktonic foraminiferal analysis (Keller, 1983a, 1983b, 1985, 1986), coccolith, radiolarian, and diatom stratigraphy of over a dozen deep-sea sections in high-fertility regions of the Atlantic, Pacific, and Indian oceans. The global and temporal distribution of these hiatuses was determined from continuously cored deep-sea sections of the Deep Sea Drilling Project (DSDP) that were reexamined on the basis of multiple microfossil stratigraphies. The durations of hiatuses at each DSDP site were calculated from sediment-accumulation-rate curves based on multiple microfossil stratigraphy. The paleodepth of hiatus formation was determined by means of the paleodepth backtracking method of Sclater et al. (1985).[1]

STRATIGRAPHY

The stratigraphy of middle Eocene through Oligocene deep-sea sediments and hiatuses has been discussed in detail (Keller, 1983a, 1983b, 1985, 1986). The stratigraphic position of these hiatuses is illustrated in Figure 1, along with the eustatic sea-level and coastal onlap curves of Haq et al. (1986), the oxygen-isotope curves of Keigwin and Keller (1984) and Keigwin and Corliss (1986), the standard microfossil zonations, and correlation to the paleomagnetic stratigraphy based on Berggren et al. (1985). Paleogene hiatus (PH) events PHa to PHe are marked as the shortest duration that could be determined from regions of high sediment flux and are assumed to approximate the duration of the erosive events.

We have standardized sea-level, carbonate, and oxygen-isotope curves to the Berggren et al. (1985) time scale. Considering errors of conversion from one time scale to another and errors in dating of events, we assume an error margin of ±0.15 m.y. In addition, there is our assumption that the sediment deposited immediately above a hiatus dates the cessation of the hiatus event. This probably adds another ±0.1 m.y. to the error margin. Thus, we assume that a total error margin of ±0.25 m.y. accounts for the combined uncertainties in ages derived from biostratigraphy, magnetostratigraphy, correlation to the sea-level curves, and uncertainty in the cessation of hiatus events.

The youngest Paleogene hiatus PHa occurred near the Oligocene/Miocene boundary cool event between about 24 and 25 Ma (Keller, 1983b; Keigwin and Keller, 1984) and removed sediment at the base of planktonic foraminiferal *Globorotalia kugleri* Zone (N4a) and the top of *Globigerina ciperoensis* Zone (P22c; Keller and Barron, 1983; Keller, 1983b). In many deep-sea sections, erosion extends to the upper *Globorotalia opima* Zone (P21b). In some sections, the top of another hiatus is near the Zone P22a/P21b boundary interval, and the base is in the lower half of Zone P21b. This indicates that a second hiatus occurred, tentatively identified as PHaa, because of common overlap of erosion from PHa (Fig. 1).

Paleogene hiatus PHb occurred in the late early Oligocene in the lower part of *Globorotalia opima* Zone (Subzone P21a); in many places it eroded sediments downward to the upper *Globigerina ampliapertura* Zone (P20). Hiatus PHc occurred at the Eocene/Oligocene boundary but appears to be geographically less extensive and more restricted to higher latitudes. The latest Eocene PHd event is primarily a dissolution or nondeposition event of about 0.7-m.y. duration (37.5–38.2 Ma) and marks the top of the *Globigerapsis semiinvoluta* Zone and the base of the *Globorotalia cerroazulensis* Zone. In equatorial regions that have high sedimentation rates, a second dissolution/nondeposition event occurred in the lower part of the *Gl. cerroazulensis* Zone coincident with deposition of two closely spaced microtektite layers (Keller et al., 1987). The middle/late Eocene hiatus PHe ranged from the base of the *G. semiinvoluta* Zone to the top of the *Truncorotaloides rohri*

Note: Additional material for this article is Supplementary Data 8712, available on request from the GSA Documents Secretary (see footnote 1).

[1]Paleodepth data and ages of individual hiatuses PHa to PHe, GSA Supplementary Data 8712, are available on request from Documents Secretary, Geological Society of America, P.O. Box 9140, Boulder, CO 80301.

Zone (39.5–40.5 Ma), but in many places it removed the entire *T. rohri* Zone (Fig. 1).

PALEOCEANOGRAPHY

Causes of Hiatus Formation

Eustatic sea-level changes, the coastal onlap-offlap curve, and the benthic foraminifer oxygen-isotope paleotemperature curve can provide some clues to the nature and possible driving forces of deep-sea hiatus events. Figure 1 illustrates that within the uncertainties of dating and correlation, the cessation of late Paleogene hiatuses correlates with global cooling episodes or periods of climatic instability in the oxygen-isotope curve, which is also noted in faunal assemblages that are generally of low diversity and that lived in cool environments. This would suggest that deep-sea hiatuses are primarily related to intensified oceanic circulation driven by increased bottom-water production during episodes of global cooling. Such a relation was

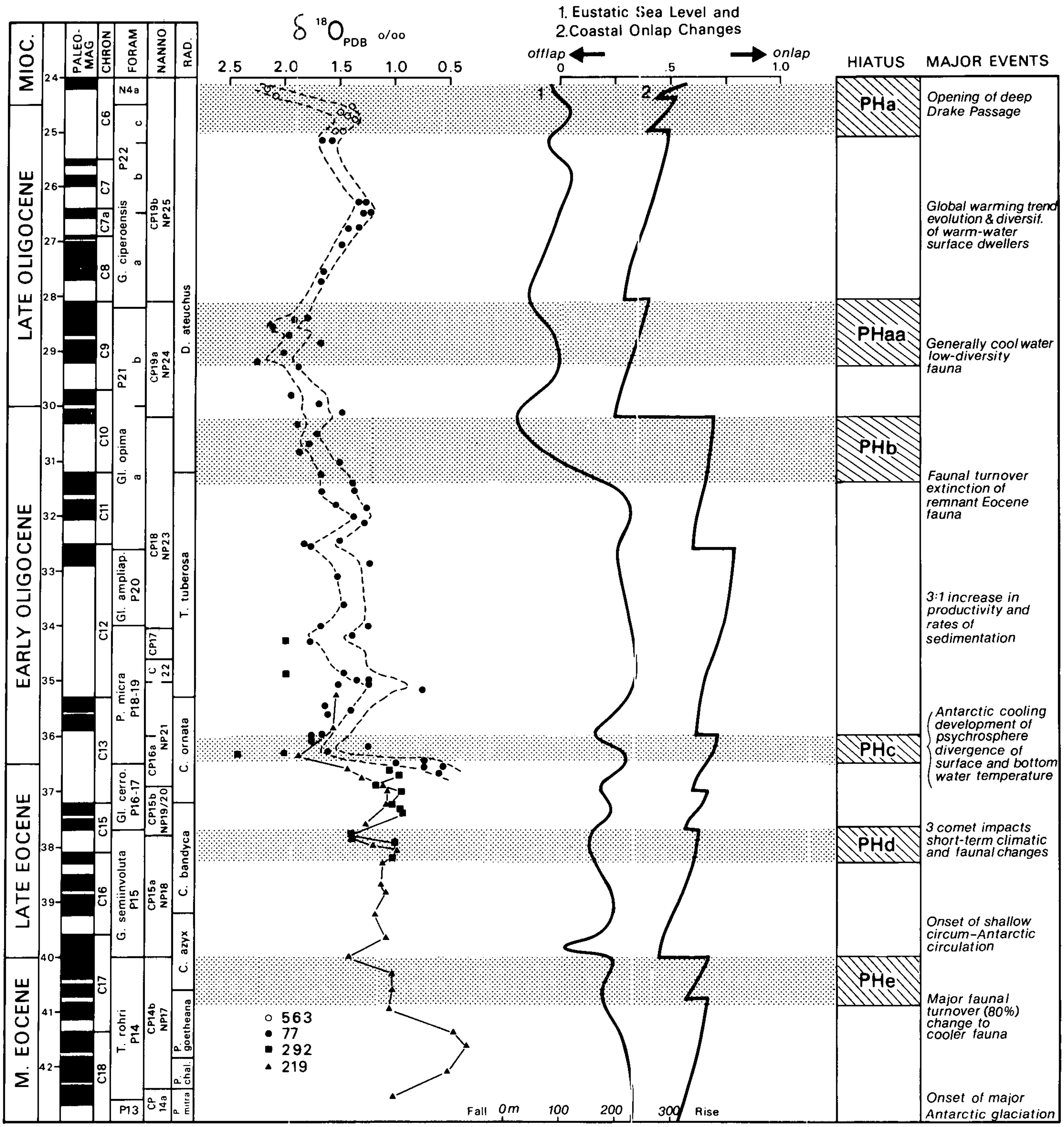

Figure 1. Middle Eocene through Oligocene multiple microfossil biostratigraphy and paleomagnetic stratigraphy (Berggren et al., 1985), oxygen-isotope record (Keigwin and Keller, 1984; Keigwin and Corliss, 1986), eustatic sea level and coastal onlap changes (Haq et al., 1986), global Paleogene hiatuses (PH) a to e, and major events. Note correlation between hiatus events, changes in coastal onlap-offlap curve, and climatic cooling episodes apparent in oxygen-isotope record.

observed for most of the Neogene hiatuses that also correlate with sea-level lowstands and high carbonate deposition (Keller and Barron, 1983, 1987).

On the contrary, most of the late Paleogene hiatus events appear to correlate with coastal onlap, immediately preceding coastal offlap, and carbonate dissolution (Keller et al., 1987) (Fig. 1). Similarly, McGowran (1986) observed a correlation between hiatuses and sea-level transgressions in late Paleogene sequences of Australia. This suggests a different mechanism for hiatus formation and possibly multiple causal factors. Within our assumed error margin of ±0.25 m.y., however, it is not unequivocally clear whether erosion temporally precedes sea-level falls or simply removes sediment deposited prior to coastal offlap. If it is the latter, then deep-sea hiatuses are related to glacio-eustatic sea-level falls. But, if deep-sea hiatuses precede coastal offlap, as is strongly indicated for hiatuses PHa, PHaa, PHc, and PHd, which are predominantly dissolution and nondeposition events in the deep sea, a different mechanism for erosion must be invoked. A plausible mechanism is Berger's (1970) basin-shelf fractionation model, which proposes enhanced deposition of carbonate on shelves during coastal onlap leading to sediment starvation and hence increased carbonate dissolution at depth (see also Hay and Southam, 1977). However, major mechanical erosion frequently associated with hiatuses PHb and PHe suggests intensified bottom currents as a result of changing flow paths and/or as a result of initiation of circum-Antarctic circulation during PHe time (Kennett and Watkins, 1976) or onset of major Antarctic glaciation during PHb time (Keigwin and Keller, 1984).

Thus, at least three mechanisms of hiatus formation can be recognized in late Paleogene deep-sea sequences: (1) hiatuses caused by sediment starvation in the deep sea during sea-level rises or coastal onlap (basin-shelf fractionation); (2) hiatuses caused by global cooling, increased bottom-water production, and hence intensified bottom-water flow; and (3) hiatuses caused by major changes in the flow paths of currents as a result of opening or closing of passageways.

Faunal Record

Major faunal and paleoceanographic events are also associated with hiatuses and cooling trends (Fig. 1). The middle/late Eocene boundary event PHe is marked by expansion of cooler water assemblages and a major extinction event among warmer water species involving 80% of the individuals of the population, or 23% of the species population (Keller, 1983a, 1985, 1986). The widespread mechanical erosion at this time, particularly around Antarctica, marks the onset of at least shallow circum-Antarctic circulation (Kennett and Watkins, 1976; Loutit and Kennett, 1981; McGowran, 1978). The latest Eocene PHd event (primarily a dissolution event) is associated with the extinction of the *Globigerapsis* group, or about 50% of the individuals of the population, and three comet impacts during an interval of about 1 m.y. (Keller et al., 1983, 1987; Keller, 1986). The first comet impact occurred near the top of the *G. semiinvoluta* Zone, and two closely spaced impacts occurred in the lower part of the *Gl. cerroazulensis* Zone. Both the *G. semiinvoluta* Zone impact and the two *Gl. cerroazulensis* Zone impacts are associated with carbonate dissolution and/or nondeposition and short hiatuses. It is therefore possible that the PHd event constitutes two short events.

The Eocene/Oligocene boundary PHc event coincides with a major drop in bottom-water temperatures, marking the development of the psychrosphere, or two-layer ocean with warm surface waters and cold bottom waters (Shackleton and Kennett, 1975; Keigwin, 1980). Before this time, surface- and bottom-water temperatures were nearly the same, indicating that major Antarctic bottom-water production did not start prior to the Eocene/Oligocene boundary. The faunal changes, however, are less dramatic; four planktonic foraminiferal species that constitute less than 10% of the individuals of the population became extinct at this time (Corliss et al., 1984; Keller, 1986).

The early/late Oligocene boundary PHb event, which is correlatable to the major sea-level drop of Vail and Hardenbol (1979), appears geographically less widespread than other hiatus events and occurred in deep as well as shallower waters. This hiatus event is associated with a major faunal turnover; namely, the extinction of the remaining Eocene survivors (*Globigerina linaperta, G. angiporoides, G. eocaena, G. galavisi*) and evolution of new species (Keller, 1983a, 1986). The early late Oligocene PHaa event is associated with faunas of generally cool conditions and low diversity and the decline and extinction of *Globorotalia opima*. A major bottom-water event is indicated at the Oligocene/Miocene boundary PHa event. This hiatus correlates with a short-lived cold event (Keigwin and Keller, 1984; Miller et al., 1985) and widespread erosion, and it may mark the opening of the deep Drake Passage and subsequent changes in circum-Antarctic circulation and deep-water circulation in the Pacific, Atlantic, and Indian oceans (Keller and Barron, 1983; Sclater et al., 1985).

Thus, each of the late Paleogene hiatus events is associated with a time of major faunal turnover representing instability in the oceanic realm, either as a result of global climatic fluctuations or oceanic circulation changes.

PALEOBATHYMETRY OF HIATUS DISTRIBUTIONS

We have reconstructed the paleodepth at which hiatuses formed at individual site locations by using the method of Sclater et al. (1985) for paleodepth backtracking. In general, there appears to be little difference in either geographic distribution or paleodepth of hiatuses PHa to PHe, indicating that the same oceanographic forcing factors were responsible for all hiatuses during late middle Eocene through Oligocene time and that the same basic oceanic circulation patterns prevailed.

The paleobathymetry of hiatus occurrences during the middle Eocene through Oligocene are summarized and illustrated in Figures 2, 3, and 4 for oceanic regions that show different paleodepth distributions of hiatuses in the Atlantic, Pacific, and Indian oceans. Hiatus intervals are categorized as (1) no hiatus present, (2) dissolution or nondeposition events having generally less than 0.5 m.y. missing, (3) short hiatuses restricted to particular hiatus events PHa to PHe, and (4) "megahiatuses" spanning two or more hiatus events. In most cases, however, megahiatuses mark sediment removal for the entire Oligocene to middle Eocene interval studied. These hiatuses are included here for completeness, although it cannot be determined which particular hiatus event(s) contributed to the erosion.

We have plotted the hiatus distributions separately for the western and eastern North Atlantic and South Atlantic (Fig. 2). In the western North Atlantic, the bulk of hiatuses is found at two depth intervals: 4500–5400 m and 1600–3000 m paleodepths. Similar paleodepths of erosion were observed by Ehrmann and Thiede (1985).

In the eastern North Atlantic a deep hiatus maximum with 54% megahiatuses occurred between 3400 and 4800 m paleodepths in the Bay of Biscay. Hiatus maxima in the Hatton Rockall area are present between 600 and 1800 and between 2000 and 3000 m paleodepths, with 52% and 65% megahiatuses, respectively. A shallow hiatus maximum (< 1200 m) is also observed in the Norwegian Sea. Erosion occurred at all depths in the Rio Grande Rise and Walvis Ridge areas, maxima in megahiatuses being between 4200 and 4800 m and between 1400 and 2000 m paleodepths (Fig. 2).

Paleodepths of hiatuses are highly variable between different regions (Fig. 3). The east equatorial Pacific shows hiatuses between 2000 and 5400 m paleodepths and megahiatuses primarily below 4800 m. A similar deep hiatus maximum (4800–6000 m) is present in the west equatorial Pacific, along with an intermediate depth hiatus maximum between 2400 and 3400 m.

In the northwestern Pacific, hiatus maxima are present between 5200 and 5800, 3800 and 4600, 1800 and 2600, and 800 and 1600 m paleodepths. These maxima consist predominantly of megahiatuses and may represent a combination of mass wasting due to slumping and current scour.

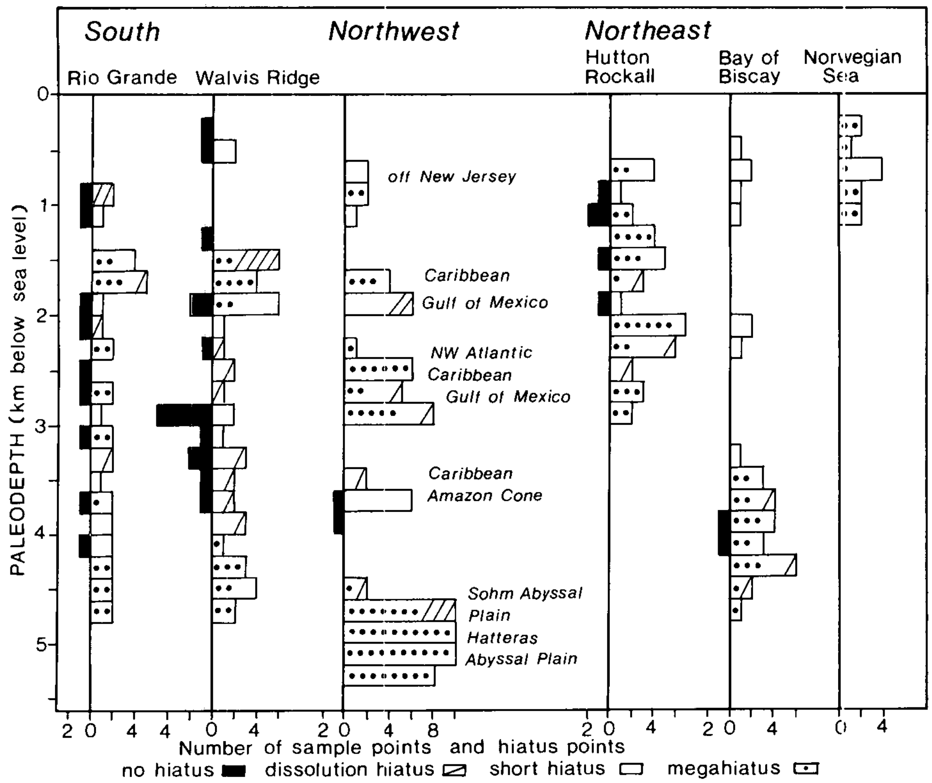

Figure 2. Paleodepth distribution of middle Eocene through Oligocene hiatuses PHa to PHe (PH = Paleogene hiatus) in Atlantic Ocean. Deep-sea sections without hiatuses during PHa to PHe events are plotted to left. Hiatuses are classified as (1) dissolution hiatus caused by nondeposition, generally spans less than 1.0 m.y.; (2) short hiatus restricted to specific intervals PHa to PHe; (3) megahiatus, spans two or more hiatus intervals and in many cases has removed Eocene and/or Oligocene sediments.

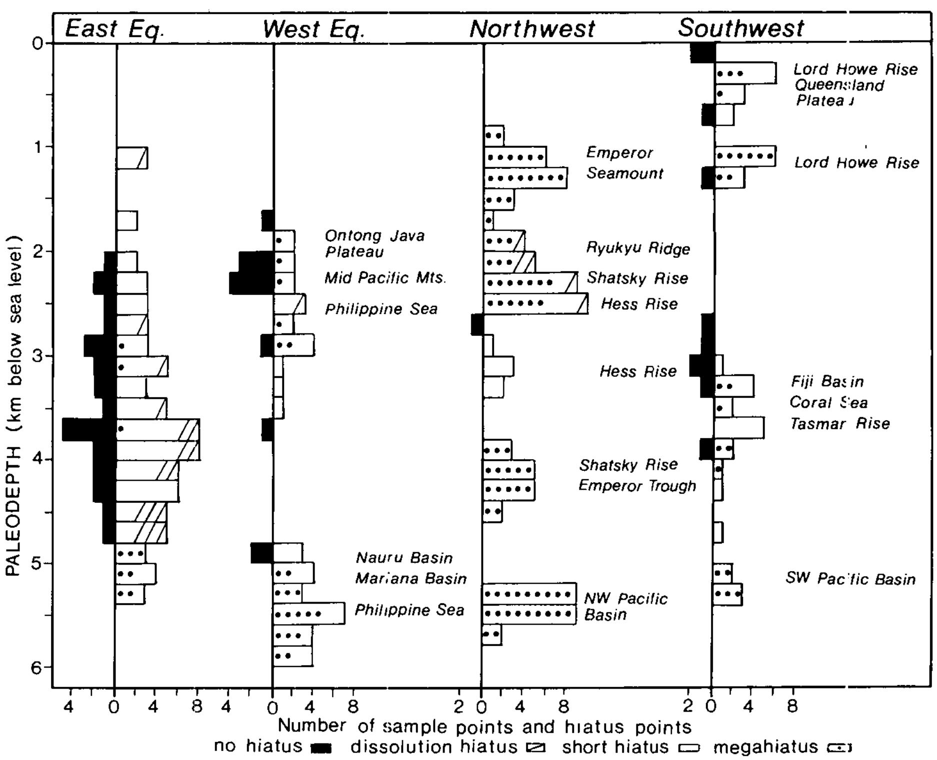

Figure 3. Paleodepth distribution of middle Eocene through Oligocene hiatuses PHa to PHe in Pacific Ocean. See Figure 2 for explanation.

In the southwest Pacific a deep hiatus maximum occurred between 5000 and 5400 m paleodepth, similar to erosion observed in the equatorial and northwest Pacific. A second maximum with 87% hiatuses (33% megahiatuses) occurred between 3200 and 4000 m, and a shallow hiatus maximum was present between 200 and 1400 m paleodepths (Fig. 3).

Paleodepths of hiatus distributions in the western and eastern Indian Ocean are very dissimilar, as shown in Figure 4. The eastern Indian Ocean shows a deep hiatus maximum between 4000 and 5800 m paleodepths where no sediment of middle Eocene to Oligocene is present. Hiatus maxima also occurred between 2200 and 2600 and between 800 and 1400 m paleodepths. In the western Indian Ocean, hiatuses occurred at all depths, the hiatus maxima being between 3800 and 4600 and between 600 and 1200 m paleodepths. Less strong erosion, indicated by absence of megahiatuses, occurred at paleodepths between 1800 and 2600 m.

SUMMARY AND DISCUSSION

Six widespread middle Eocene through Oligocene hiatuses PHa to PHe have been documented from the world ocean. The apparently global distribution of these hiatuses provides easily recognizable datum planes in stratigraphic correlations for both seismic stratigraphy and biostratigraphy.

The paleobathymetry of hiatus formation illustrated in Figures 2, 3, and 4 shows that hiatus maxima occurred at specific depths. It is also apparent that paleodepths of hiatus maxima and minima vary between, and sometimes within, ocean basins. Nevertheless, there is an overriding

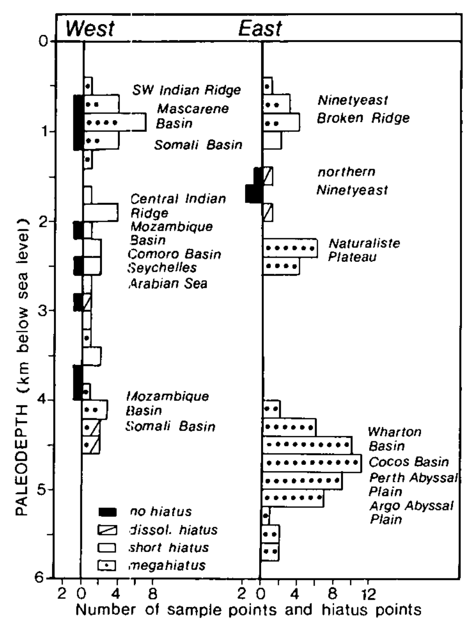

Figure 4. Paleodepth distribution of middle Eocene through Oligocene hiatuses PHa to PHe in Indian Ocean. See Figure 2 explanation.

trend in hiatus maxima to occur in deep (below 4000 m), intermediate (~2000–3000 m), and shallow (< 1600 m) paleodepths. The deep hiatus maxima appear to be related to bottom current flow and deposition below the carbonate compensation depth (CCD), as indicated by the deepest carbonate section not containing a hiatus. This depth level for the CCD is consistent with that of Van Andel et al. (1977) and Hsü and Wright (1985).

The geographic distribution of hiatuses shows megahiatuses, or major mechanical erosion, primarily restricted to flow paths of currents and water masses as, for instance, in the eastern Indian Ocean, northwest and northeast Atlantic, and Rio Grande Rise regions. These same regions also show hiatus maxima during the Neogene (Keller and Barron, 1987), indicating that similar water-mass flow already existed during the late Paleogene.

Short hiatuses and nondeposition hiatuses in high-productivity regions provide the fine tuning of the hiatus record and allow correlation with the stable isotope and coastal onlap-offlap curves. Our correlations indicate that late Paleogene hiatuses largely occur during global cooling trends or periods of climatic instability. Moreover, four of six hiatuses appear to correlate with coastal onlap sequences. This implies multiple causes for hiatus formation.

A plausible mechanism for deep-sea hiatus formation, and particularly dissolution/nondeposition hiatuses associated with coastal onlap, is Berger's (1970) model of basin-shelf fractionation of carbonates. In this model a sea-level transgression or coastal onlap results in increased carbonate deposition on shelves leading to carbonate starvation and, hence, dissolution in the deep sea. Implicit in this model is diachroneity of hiatus formation in the deep sea and along continental margins. Hiatuses along margins form during sea-level lowstands, whereas in the deep sea they form during sea-level highstands. It has yet to be tested whether such diachroneity is present in the hiatus record.

Carbonate dissolution in the deep sea may also occur during sea-level lowstands and cool climates. Mechanisms such as temperature change, however, cannot be directly invoked because the ocean will act to buffer changes in carbonate saturation on a time scale of the residence time of the $CO_3^{=}$ ion (~8000 yr; Broecker and Peng, 1982). Hence, any increase in corrosiveness toward carbonate of deep-water masses probably results from increased levels of CO_2 and nutrients which, in turn, are related to increased upwelling during cooling episodes.

It may be difficult to determine whether dissolution or nondeposition hiatuses are caused by carbonate starvation or by increased levels of CO_2 and nutrients. Correlation of hiatuses to the oxygen-isotope, sea-level, and carbonate curves yields clues. Our data suggest that carbonate starvation was the prevalent cause of deep-sea hiatus formation during the late Paleogene, whereas during the Neogene, increased levels of CO_2 and nutrients predominated (Keller and Barron, 1987). This may reflect a change from oceanic circulation relatively free from glacially influenced deep-water production during the late Paleogene to one dominated by polar ice caps during the Neogene.

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