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Changing depth distribution of hiatuses during the Cenozoic

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Abstract. The differential effects of climate change, sea level, and water mass circulation on deposition/erosion of marine sediments can be constrained from the distribution of unconformities in the world's oceans. I identified temporal and depth patterns of hiatuses ("hiatus events") from a large and chronologically well constrained stratigraphic database of deep-sea sediments. The Paleogene is characterized by few, several million year long hiatuses. The most significant Cenozoic hiatus event spans most of the Paleocene. The Neogene is characterized by short, frequent hiatus events nearly synchronous in shallow and deep water sediments. Epoch boundaries are characterized by peaks in deep water hiatuses possibly caused by an increased circulation of corrosive bottom water and sediment dissolution. The Plio-Pleistocene is characterized by a gradual decrease in the frequency of hiatuses. Future studies will focus on the regional significance of the hiatus events and their possible causes.

1. Introduction

While it is well accepted that the Cenozoic stratigraphic record on continental margins is punctuated by numerous gaps [e.g., *Vail et al.*, 1977; *Miller et al.*, 1990], many studies have also identified regional unconformities in deep-sea sediments [*Keller and Barron*, 1983; *Osborn et al.*, 1983; *Keller et al.*, 1987; *Barron*, 1989; *Aubry*, 1991, 1995; *Ramsay et al.*, 1994]. This paper presents the results of a study of the distribution of hiatuses during the Cenozoic and is based on chronologically well constrained Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) sections. Compared to previous compilations of hiatus distribution in the DSDP stratigraphic record [e.g., *Moore et al.*, 1978], this curve has a better resolution (0.5 m.y.), contains more recent holes with better recovery, and is based on a more reliable and updated biochronology (biostratigraphy and magnetostratigraphy) [*Berggren et al.*, 1995b].

Among the various causes of hiatuses (erosion, dissolution, corrosion, and nondeposition), the rate of sediment supply versus dissolution (corrosion) of sediments, which is controlled by fluctuations in the calcite compensation depth (CCD) as well as shallow to deep water sediment fractionation [*Berger*, 1970], is a very significant factor for hiatuses in deep-water sediments. This relationship has been discussed in detail by *Keller and Barron* [1987].

I have decided to avoid the temptation to speculate about the causes of the hiatuses shown in this study because of the generic presentation of the data in this study. However, I have included in this paper two published curves of sea level fluctuations: the sea level curve of *Haq et al.* [1987] and the benthic oxygen isotope curve of *Miller et al.* [1987]. These curves will be mainly used to suggest possible uses of the hiatus curve and introduce the future developments of this study.

2. Methodology

The data presented here were obtained from 166 globally distributed DSDP and ODP holes included in the Neptune database (Figure 1)[*Lazarus et al.*, 1995]. The chronology of each hole is based on biostratigraphic and magnetostratigraphic data published in the DSDP Initial Reports and ODP Scientific Reports (*Lazarus et al.* [1995] for Neogene DSDP holes). Graphic correlation [*Shaw*, 1964; *Lazarus*, 1992] was used to construct age versus depth plots for each hole and to obtain a combined chronology. Calibrated biostratigraphic and magnetostratigraphic events were used to draw a line of correlation using criteria defined to minimize subjective bias and guarantee consistency. Local biostratigraphic calibrations and reliable events (i.e., synchronous within the accuracy of the method [*Spencer-Cervato et al.*, 1994]) were used for Neogene sections. Locally calibrated events of siliceous plankton (diatoms and radiolarians [*Baldauf and Barron*, 1991; *Caulet*, 1991; *Harwood and Maruyama*, 1992]) augmented by biozonations [*Fenner*, 1984; *Sanfilippo et al.*, 1985; *Sanfilippo and Nigrini*, 1995, also unpublished data, 1995], and biochronological events of calcareous plankton (foraminifera and calcareous nannoplankton [*Berggren et al.*, 1995a, b]) were used to constrain the stratigraphic correlation of Paleogene sections. All events and biozone boundaries were calibrated to the timescale of *Berggren et al.* [1995b].

Stratigraphic unconformities were identified by biostratigraphic and magnetostratigraphic events clustered in a narrow depth interval (from less than one sample spacing up to a maximum of one core length for each inferred event) in intervals of continuous core recovery. One hundred and thirteen holes showed evidence of at least one hiatus, and close to 300 hiatuses in all were recognized in these holes (Table 1)[1]. The holes included in this study were drilled in a broad range of depths, both on shelves and in deep-sea areas (Figure 1) with the majority of holes (77%) between 1000 and 4000 m present-day depth. These sites represent a random subset of the DSDP and ODP holes drilled thus far ($\chi^2 = 9.68$; DF = 6; $p < 0.05$). Hiatuses are equally distributed through the whole depth range of the studied holes (79% of holes with hiatuses are between 1000 and 4000 m depth; $\chi^2 = 1.33$; DF = 6; $p < 0.05$). However, shallow water sediments (shallower than

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[1] Table 1 is available electronically at World Data Center A for Paleoclimatology, NOAA/NGDC, Boulder, Colo. (e-mail: paleo@mail.ngdc.noaa.gov; URL: http://www.noaa.gov/paleo).

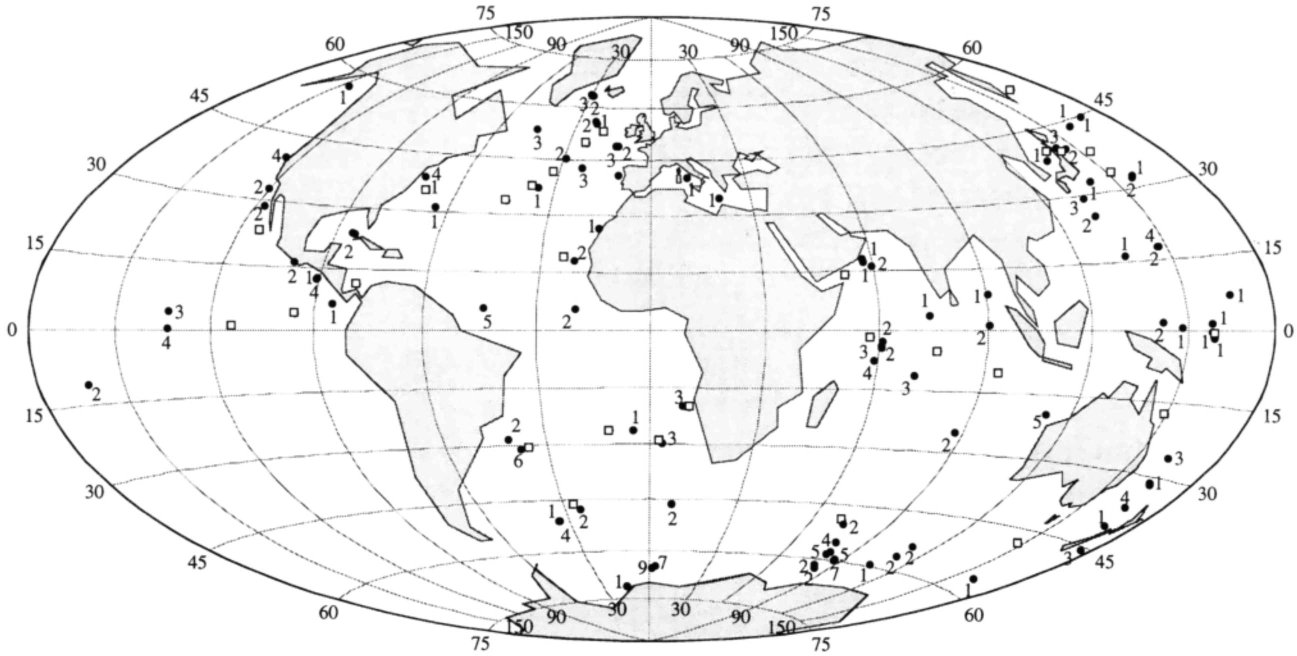

Figure 1. Map of location of Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) holes in the Neptune database. Dots show holes where hiatuses were recorded, and the numbers represent the number of hiatuses at that location. Squares mark holes where no hiatuses were found. Note the higher number of hiatuses recorded at high latitudes and on continental shelves.

1000 m) are underrepresented in the DSDP and ODP holes and are, therefore, also not well represented in this dataset.

Sedimentation hiatuses can be caused by mechanical erosion, by dissolution (corrosion) or by nondeposition. However, other "artificial" causes of hiatuses (e.g., core recovery) are considered first.

Apparent hiatuses or an extended duration of hiatuses can be caused by incomplete recovery of sediments during coring [*Aubry*, 1995]. To test if hiatuses were more frequent in poorly recovered holes, I have compared the percentage recovery versus the number of hiatuses recorded in each hole. The lack of correlation ($r^2 = 0.009$) indicates that incomplete recovery is not an apparent cause for the hiatuses. However, sediment can be lost at core breaks in continuously cored sections, and losses of up to 12% are reported [*deMenocal et al.*, 1991; *Farrell and Janecek*, 1991]. Particular care was used to avoid placing a hiatus near or during an interval of no recovery. Multiple evidence was required in order to identify a hiatus (e.g., missing biozones and/or magnetic reversals reported by the author(s) of the report and agreement of more than one biostratigraphic report). Moreover, hiatuses shorter than the average sample spacing of the bulk of the DSDP and ODP biostratigraphic data included in Neptune (0.18 m.y. [*Spencer-Cervato et al.*, 1994]) were not considered. However, the possibility that some of the hiatuses identified in this work are artificial or artificially lengthened cannot be excluded. For this reason, I have chosen to analyze and correlate a large number of holes with different recovery rates and a global distribution. This integrated approach is intended to minimize any bias [*Aubry*, 1995].

To obtain a temporal distribution of hiatuses, I calculated the number of the holes which recorded each hiatus using a 0.5 m.y. sampling interval. The choice of the time interval was a conservative estimate based on the reliability of the age model (±0.37 m.y. [*Spencer-Cervato et al.*, 1994]). The results are plotted in Figure 2b. The frequency of hiatuses (percentage hiatuses in sections analyzed; Figure 2c) was calculated to eliminate the bias of the uneven distribution of sections through the time interval analyzed [see *Moore et al.*, 1978](higher number in the late Miocene-Pliocene; Figure 2a). I consider this statistical distribution as an estimate of the relative importance of hiatus events through time, regardless of causal mechanisms. While both data sets were evaluated, it is the pattern of hiatus frequencies that will be mainly discussed in this paper. The data presented in this study, the oxygen isotope curve [*Miller et al.*, 1987] (Figure 2e) and the sea level curve [*Haq et al.*, 1987] (Figure 2d), are all calibrated to the *Berggren et al.* [1995b] timescale.

Deep water sediment hiatuses can be caused by dissolution/corrosion linked to shallower CCD and intermediate and deep circulation changes [e.g., *Keller and Barron*, 1983; *Mayer et al.*, 1986]. Deep water hiatuses, however, can also be caused by erosion by deep water currents linked to climate changes or nondeposition [*Ramsay et al.*, 1994]; *Keller and Barron* [1983] identify deep-sea erosional hiatuses (attributed to glacio-eustatic sea level lowstands) and dissolution hiatuses (during sea level highstands, caused by shallower CCD) that remove previously deposited sediments. Two contrasting models have been presented to explain deep water hiatuses: increased deep water production and corrosiveness during glacial periods [*Keller and Barron*, 1983] or nonglacial (deglaciated or decreased glaciation in Antarctica) intervals [*Ramsay et al.*, 1994]. While dissolution can be sometimes identified in seismic lines [e.g., *Mayer et al.*, 1986], no direct means of distinguishing between erosion, nondeposition, and corrosion has been found yet. The concen-

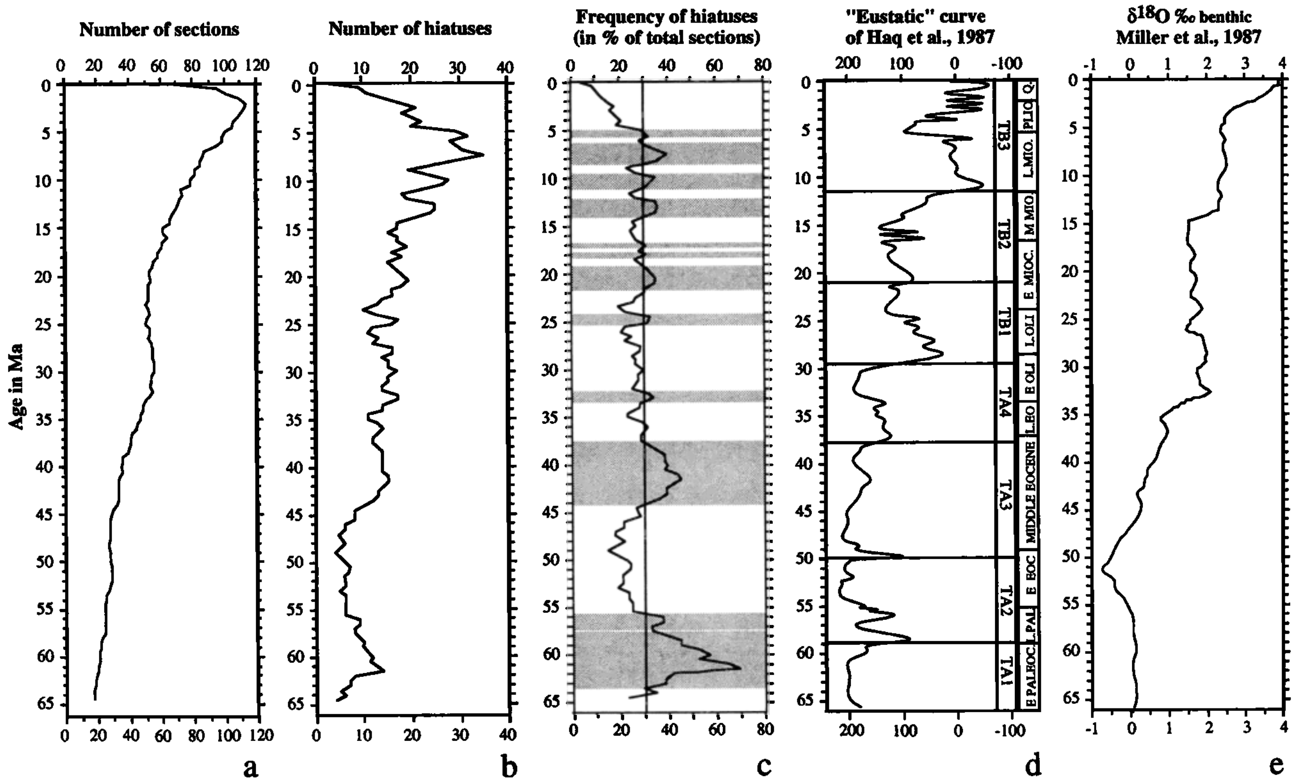

Figure 2. (a) Number of Cenozoic DSDP and ODP sections per 0.5 m.y. in the Neptune database. (b) Number of hiatuses recorded in the Neptune database during the last 65 m.y. (this study). (c) Curve of the frequency of hiatuses (this study). The vertical line represents the average frequency (30%). Shaded intervals mark periods characterized by a higher than average frequency of hiatuses (hiatus events). (d) "Eustatic" sea level curve of *Haq et al.* [1987]. (e) Benthic foraminifera oxygen isotope curve [*Miller et al.*, 1987].

tration of cosmogenic isotopes at hiatuses can potentially enable us to distinguish between nondeposition and erosion/corrosion (G. Ravizza, personal communication, 1997). The results from this study could be used to identify locations and intervals suitable for testing this method; however, no published studies are available at the present.

3. Results

On average, 30% of the sections analyzed contain any particular hiatus. In the hiatus frequency curve (Figure 2c), various hiatus events can be identified as intervals with higher than average hiatus frequency (>30%)(shaded intervals in Figure 2c). They occur within two intervals from the base of the Paleocene. The first interval (65-25 Ma) shows sparse hiatus events of long duration (several million years). Within this interval one sustained peak in hiatuses, spanning most of the Paleocene and peaking at 62 Ma, is recorded in up to 70% of the sections analyzed. This hiatus is the most significant one in the Cenozoic. The second interval (25-0 Ma) shows a higher frequency of several short hiatuses. The last 4 Ma are characterized by a sharp decline in the occurrence of hiatuses.

4. Discussion

Correlation of "wiggly" lines at stratigraphic scale can be fortuitous, and much of the correlation may represent coincidence. *Miall* [1991] has argued that stratigraphic resolution may not be sufficiently accurate to either uniquely identify or reveal the cause of unconformities that define stratigraphic sequences. *Miller et al.* [1996], on the other hand, have shown that this correlation is possible locally, even at a resolution of 0.5 m.y. Because the resolution of *Haq et al.*'s [1987] record is ~1 m.y. or worse [*Browning et al.*, 1996] and the benthic isotopic record of *Miller et al.* [1987] is also a low-resolution record, future, more detailed analysis of this data set will be limited to the 10^6- to 10^7 year scale events. As a starting point to determine the validity of this data set and to identify what needs to be tested next, I have limited the discussion in this paper to a very short analysis of global patterns of the temporal extent of hiatuses.

To help in the interpretation of the record, I have estimated the paleo-water depth for the base of each hiatus in this dataset [*Sclater et al.*, 1985] (Table 1). Simple backtracking calculations were used to calculate paleodepth for sites on oceanic crust. On the basis of a comparison with published data, precision for Neogene sediments is ~100 m [*Sclater et al.*, 1985], while it decreases to a few hundred meters at best for the Paleogene. For details on the method, see *Sclater et al.* [1985].

Paleodepth estimates for sites on continental shelves, or in forearc or intra-arc basins, were not attempted, and present-day water depth was used instead. This approximation should not sensibly affect the data. Paleodepth intervals for this study (0-2000 m, 2000-3000 m, and deeper than 3000 m) were selected to include all continental shelf data into the shallow water category, and I expect water depth to have been within this depth range also in the past. Depths in forearc and intra-arc basins fall largely into the deepest category.

The subdivision of hiatuses in water depth intervals (Figure 3) shows that the early Paleocene hiatuses occurred in the shallowest water groups (on continental shelves or young oceanic crust; Figures 3a and b). The CCD was shallow during the Paleocene-Eocene (~3500 m [*van Andel*, 1975]) which might have caused widespread dissolution of carbonate sediment. Therefore it is reasonable to expect that many, if not all, of the hiatuses recorded between 2000 and 3000 m paleodepth are due to sediment corrosion associated with a shallow CCD. However, it is still not clear what might have caused the shallow water hiatuses in the early Paleocene.

The 6 m.y. long hiatus centered around 42 Ma is recorded mainly in shallow and intermediate water sediments. Isotopic evidence [*Browning et al.*, 1996] sets at this time the beginning of the development of the Antarctic ice cap. It is hypothesized here that increased deep water circulation and corrosion associated with global cooling could have caused widespread hiatuses in deep-sea sediments at this time. However, more detailed comparisons with deep water circulation records is necessary to confirm this hypothesis.

The Oligocene-Miocene boundary (25-24 Ma) is marked by a peak in intermediate and deep water hiatuses and a minimum in shallow water hiatuses. This interval is characterized by increased bottom water circulation following the opening of the Drake Passage [*Barker and Burrell*, 1982; *Tucholke et al.*, 1976]. This suggests that the shallow water and deep water systems were decoupled.

Short and frequent hiatuses characterize the Neogene (Figure 2c). In the early Miocene a hiatus event is recognized between 21 and 19 Ma, followed by two shorter hiatus events between 18 and 17 Ma. These correspond to the NH1a and NH1 events of *Keller and Barron* [1987], and were interpreted by them to correlate with a sea-level lowstand, high carbonate dissolution in deep-sea sediments and polar cooling.

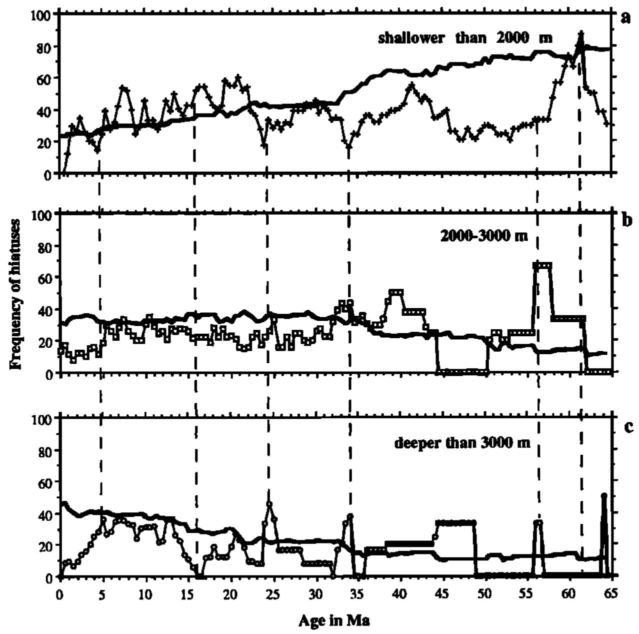

Figure 3. The lines with symbols represent the frequency of hiatuses recorded at various paleodepth intervals: (a) shallower than 2000 m, (b) between 2000 and 3000 m, and (c) deeper than 3000 m. The continuous lines represent the percentage of sections in the Neptune database in that interval of paleo-water depth.

The early middle Miocene (16 to 15 Ma) is marked by the absence of deep-water hiatuses followed by a progressive increase (Fig. 3c). This correlates with reduced AABW production [*Ramsay et al.*, 1994] followed by a bottom water temperature drop [*Miller et al.*, 1987] preceding ice growth [*Kennett*, 1985; *Vincent et al.*, 1985], and an increase in corrosive AABW production [*Ramsay et al.*, 1994].

The middle Miocene to late Pliocene (13-2 Ma) is characterized by frequent, temporally well-defined hiatus events of 1 to 2 m.y. duration that correlate with NH3 to NH8 events of *Keller and Barron* [1987]. These are mainly recorded in shallow water, while deep water hiatuses show a plateau.

The late Pliocene to Recent part of the hiatus curve shows a rapid drop in number and frequency of hiatuses that inversely correlates with the cooling indicated by the benthic oxygen isotopes. This could be caused by several factors, including the better recovery of younger sediments and therefore a lower chance of recording artificial hiatuses. Alternatively, this can indicate that sediment erosion and corrosion is time dependent and thus that there has been insufficient time to create hiatuses in the youngest sections. However, this smooth drop can also be an artefact of the time interval chosen for this analysis, which masks the high-frequency cycles of Quaternary glacio-eustatic sea level change [e.g., *Raymo et al.*, 1989] possibly characterized by short (<0.5 m.y.) hiatuses, not recorded in this study. Higher-resolution studies are thus needed to explain this pattern.

5. Conclusions and Future Studies

The geographic distribution of hiatuses in deep-sea sediments (Figure 1) shows that they are widespread both on continental shelves and in deep-sea basins but that they are more common at high latitudes and on continental margins. Hiatuses in Paleogene sections are few but several million years long. Neogene sediments are characterized by frequent, short (maximum of 2 m.y. long) hiatuses. It is apparent from this study that various modes of depth distribution of hiatuses exist. I suggest that these different modes are linked to different causes. Previous works have mainly concentrated on the effects of cooling, deep water production, dissolution, and/or erosion for the formation of hiatuses. This study represents a comprehensive, yet preliminary, overview of hiatus frequency in deep-sea sediments. Future studies will attempt to determine the geographic distribution of hiatuses within ocean basins (e.g., latitudinal distribution of hiatuses versus latitudinal distribution of DSDP and ODP holes in the database and western versus eastern margins to identify the temporal evolution of oceanic gyre circulation) and to compare them to detailed records of deep water circulation [e.g., *Wright and Miller*, 1993]. The depth distribution of hiatuses in mid-ocean and aseismic ridge sites versus continental shelf and slope sites must be also analyzed separately. These areas should be affected differently by sea level changes.

Finally, I plan to assemble a curve of hiatuses occurring in deep water (>2,000 m) carbonate-rich sediments. This hiatus curve could potentially represent a more detailed update of the Cenozoic CCD curve of *van Andel* [1975].

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