The Eocene/Oligocene Boundary Event in the Deep Sea

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Abstract. *Analysis of middle Eocene to early Oligocene calcareous and siliceous microfossils shows gradual biotic changes with no massive extinction event across the Eocene/Oligocene boundary. Biotic changes in the late Paleogene appear to reflect changing paleoclimatic and paleoceanographic conditions and do not support suggestions of a catastrophic biotic event caused by a bolide impact at the Eocene/Oligocene boundary.*

The Eocene/Oligocene boundary is of interest to geologists in large part because of numerous associated geological events, including major changes in sedimentation patterns and chemistry of the oceans (*1*), biogeographic distributions (*2*), as well as a dramatic global climatic cooling (*3–5*). Reports of an iridium anomaly in the latest Eocene and its suggested association with extinctions in the marine and terrestrial record due to a bolide impact have led to the extension of a catastrophe scenario proposed for the Cretaceous/Tertiary boundary to account for the Eocene/Oligocene event (*6–9*). Our study of planktonic and benthic foraminifera, calcareous nannoplankton, and planktonic diatom data from four Deep Sea Drilling Project (DSDP) sites (*10*) from the Atlantic, Indian, and Pacific oceans suggests that no catastrophic extinction event occurred, but rather that sequential mid-Paleogene faunal and floral changes were a response to changing oceanographic and climatic conditions.

Calcareous Microfossils

Analysis of calcareous microfossils and of oxygen isotopic measurements from DSDP sites 219, 292, and 363 (Figs. 1 to 3) provided ranges of individual species for each fossil group (*11*), the number of first and last appearances of taxa for each sample, and the number of species per sample, which is presented as an approximate measure of species diversity (*12*). Site 219 (9°1.75′N, 72°52.67′E) is located on the Laccadive-Chagos Ridge in the northern Indian Ocean at a depth of 1764 m (*13*); site 292 (15°49.11′N, 124°39.05′E) is located on the Benham Rise in the western Pacific at 2943 m (*14*); and site 363 (19°38.75′S, 9°2.8′E) is located on the Walvis Ridge in the southeastern Atlantic at 2248 m (*15*). At the Eocene/Oligocene boundary (~36.6 million years ago), the paleolatitudes and paleodepths of these sites, respectively, were 3°S and 1100 m (*16*, *17*); 0° and 1500 m (*18*); and 30°S and 2000 m (*19*).

At site 292 (Fig. 1), the benthic foraminiferal oxygen isotopic data show relatively constant values preceding and following an approximate 1 per mil enrichment in ^{18}O beginning at the Eocene/Oligocene boundary (*5*). The planktonic foraminiferal isotopic data show a substantially smaller enrichment, ~0.3 per mil, from the late Eocene to early Oligocene. The number of first and last appearances is generally low (fewer than five) throughout the sequence, with peaks of benthic foraminiferal first and last appearances and a peak in planktonic foraminiferal first appearances in the late Eocene. The benthic foraminiferal species diversity is relatively constant, but planktonic foraminifera and calcareous nannoplankton diversities vary, possibly as a result of increased calcium carbonate dissolution. The diversity in all three groups is relatively constant across the Eocene/Oligocene boundary. Microtektites are found preceding the Eocene/Oligocene boundary (located at 321 m) at 351 m in the *Globigerinatheka semiinvoluta* zone (*20*) and between 332 and 335 m (*21*) within the *Globorotalia cerroazulensis* zone; no major biotic changes are associated with the tektites.

Benthic foraminiferal $\delta^{18}O$ from site 363 (Fig. 2) increases by 1.0 per mil near the middle to late Eocene boundary and at the Eocene/Oligocene boundary with generally constant values in the early Oligocene (*22*). Planktonic foraminiferal $\delta^{18}O$ shows an increase of approximately 1.0 per mil from the late Eocene to the early Oligocene, which may result from cooling surface waters at this temperate location. First appearances are found in the Eocene for all three groups, but are rare in the early Oligocene, and there are last appearances throughout the sequences. The planktonic and benthic foraminiferal diversities are generally constant, with a low diversity among planktonic foraminifera at the top of core 8 coinciding with severe calcium carbonate dissolution. Calcareous nannoplankton show relatively constant diversity in the late Eocene, but exhibit a decrease in species number after the Eocene/Oligocene boundary.

Benthic foraminiferal $\delta^{18}O$ at site 219 (Fig. 3) increases by about 1.0 per mil within the *Truncorotaloides rohri* zone in the late middle Eocene and by 0.7 per mil across the Eocene/Oligocene boundary. Planktonic foraminiferal oxygen isotope values are nearly constant in the *T. rohri* zone and show an enrichment of about 0.3 per mil in the late Eocene. First appearances are nearly constant throughout the interval with small peaks of first appearances per sample (*4–8*) in all groups in the early *T. rohri* zone and of benthic foraminifera in the earliest Oligocene. Last appearances are found throughout, with the last appearance of 28 benthic foraminiferal species concentrated in the early Oligocene. Because of the sporadic occurrence of rare benthic foraminifera, the number of last appearances in the early Oligocene is probably overestimated, but since no Oligocene material was recovered above core 15, we are unable to evaluate this possibility at this location. Also, the number of last appearances reflects a combination of extinctions and migrations due to changing environmental conditions. Of the six

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sites considered in our on-going study this is the only one to show such an event among benthic foraminifera. Other detailed studies of Paleogene deep-sea benthic foraminifera have documented only gradual changes across the Eocene/Oligocene boundary (*23–25*). The diversity of the foraminifera is nearly constant, whereas the calcareous nannoplankton diversity, constant in the Eocene, is reduced by about 50 percent in the early Oligocene.

Planktonic Diatoms: Site 366

Planktonic diatoms were not well preserved at sites 219, 292, and 363, and additional well-preserved siliceous material from sites 167, 366, and 511 was studied. Data from site 366 (Fig. 4) (*26*) are typical of the diatom results. Site 366, located at 5°40.7′N, 19°5.1′W with a present-day water depth of 2853 m, was located about 10° south of its present position 36.6 million years ago (*19*). The oxygen isotopic data, based on analysis of bulk carbonate (*26*), show an enrichment of about 1 per mil in the early Oligocene. Species numbers rise in the late Eocene, followed by a decrease in the early Oligocene. The low species numbers in core 6 and upper part of core 7 are probably due in part to opal dissolution. First and last appearances occur throughout, with last appearances outnumbering the first appearances in the early Oligocene.

Estimate of Evolutionary Change

The number of extinctions per million years for each of the fossil groups (Figs. 1 to 4) was calculated in order to evaluate the faunal and floral records (Fig. 5) (*27, 28*). With the exception of the 35.5 million-year-old data point from site 219, the number of benthic foraminiferal extinctions ranges from 0 to 4, with most intervals having between 0 and 2 extinctions. The number of extinctions per million years of planktonic foraminifera ranges from 0 to 9, of calcareous nannoplankton from 0 to 3, and of planktonic

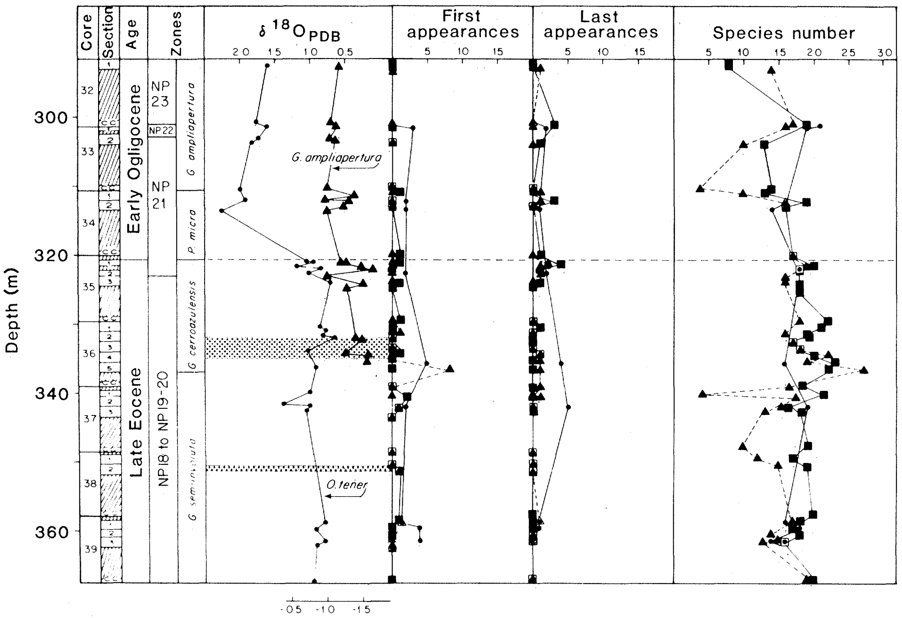


Fig. 1. Summary of stratigraphic (*33, 35*), isotopic (*5*), and faunal and floral data from site 292 in the Pacific Ocean. The sediment consists of foraminiferal nannofossil chalks. The first and last appearance data and the species number per sample are shown for benthic foraminifera (●), planktonic foraminifera (▲), and calcareous nannoplankton (■). The dashed line indicates the location of the Eocene/Oligocene boundary at 36.6 million years. Isotopic scale for benthic foraminiferal data (●) is shown at the top and for planktonic foraminiferal data (▲) is shown at the bottom. Locations of microtektite occurrences (*20, 21*) are stippled and are shown with oxygen isotopic data. Abbreviation: NP, nannoplankton zones.

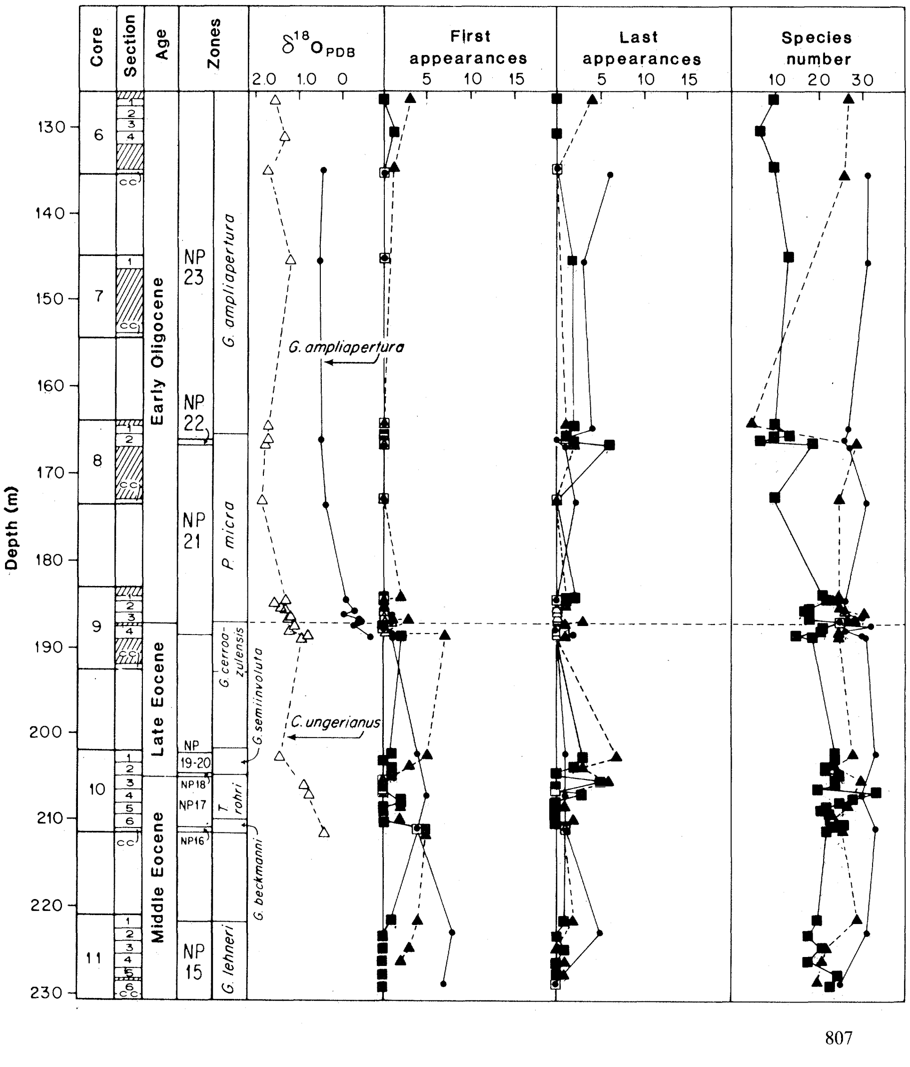


Fig. 2. Summary of stratigraphic (*33, 35*), isotopic (*22*), and faunal and floral data from site 363 in the Atlantic Ocean. The sediments are foraminiferal-nannofossil ooze or chalks. Symbols are the same as in Fig. 1. Benthic foraminiferal isotopic data are shown as open triangles, and planktonic foraminiferal data are shown as closed circles. Hatched sections indicate coring gaps. Abbreviations: NP, nannoplankton zones; and cc, core catcher.

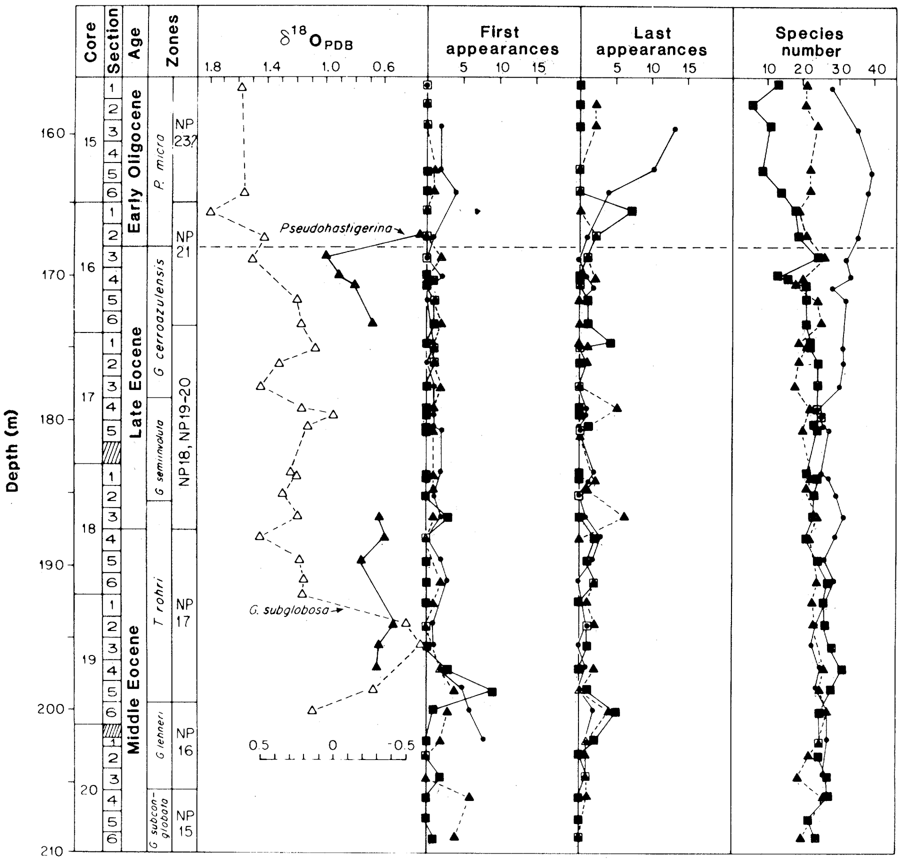


Fig. 3. Summary of stratigraphic (*33*, *35*), isotopic (*22*), and faunal and floral data from site 219 in the Indian Ocean. Symbols are the same as in Fig. 1. Isotopic scale for benthic foraminiferal data (△) is shown at the top and for planktonic foraminiferal data (▲) at the bottom. Hatched sections indicate coring gaps; NP, nannoplankton zones.

diatoms from site 366 from 1 to 8. Values of the net change or turnover (first appearances minus extinctions) for samples at the four sites (Fig. 6) are generally between 5 and −5 per million years, and positive and negative values are found throughout the sequences with a trend of generally negative values in the early Oligocene.

The data in Figs. 5 and 6 show changes of benthic and planktonic taxa across the Eocene/Oligocene boundary, but the magnitude of these faunal and floral changes is similar to that found throughout the middle Eocene–early Oligocene interval, reflecting a sequence of faunal and floral changes during the mid-Paleogene. These patterns are not restricted to low-latitude sites but are also found in high-latitude sites 277, 511, and 549 (*29*), where paleoclimatic changes are documented to be greater (*5*, *22*).

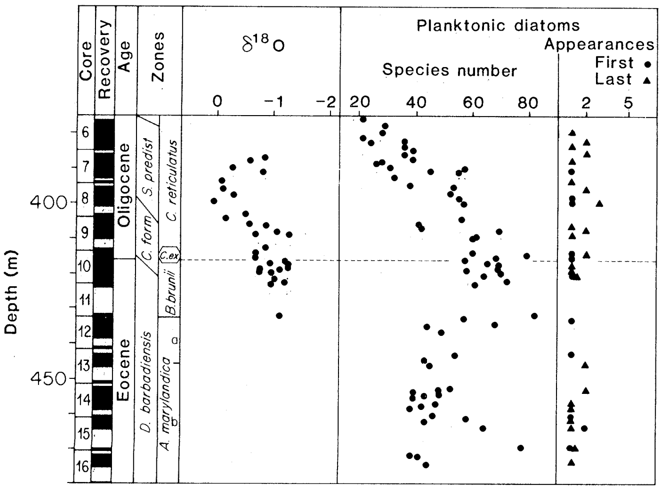


Fig. 4. Summary of stratigraphic, isotopic, and planktonic diatom data for site 366 (*26*). The number of species in each sample is shown. A comparison of the first and last appearance data with the species number data shows that many samples had no first or last appearance events.

Discussion

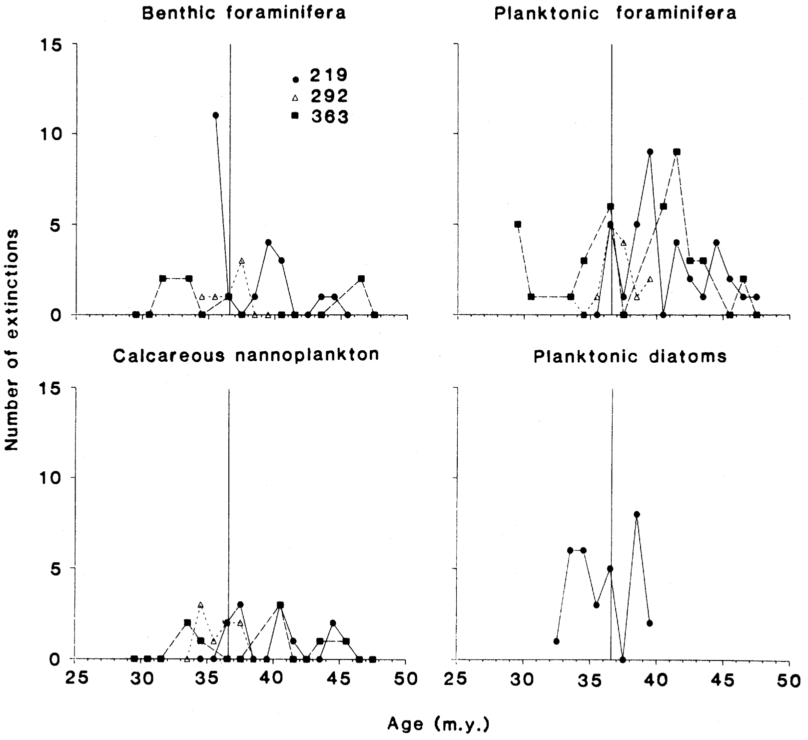
The absence of catastrophic change in the deep-sea benthic data at the Eocene/Oligocene boundary is consistent with work showing a gradual faunal turnover of benthic foraminifera in the middle Eocene to early Oligocene interval (*23*–*25*). The major faunal change in benthic foraminifera is associated not with the Eocene/Oligocene boundary but rather with (i) the progressive restriction during the middle to late Eocene of abyssal Eocene taxa to greater depths; (ii) the replacement in the early late Eocene of the abyssal assemblage by increasingly abundant, bathymetrically wide-ranging and stratigraphically long-ranging taxa; and (iii) the extinction of several abyssal taxa (for example, *Nuttallides truempyi*, *Clinapertina* spp., *Abyssamina* spp., *Alabamina dissonata*, and *Aragonia* spp.). These faunal changes are interpreted as a depth migration by deep-water Eocene assemblages which were derived from relict Cretaceous and Paleocene forms after a major taxonomic turnover at the Paleocene/Eocene boundary (*23*, *30*). Viewed in this manner, the Paleogene faunal changes may be seen as a series of threshold events contributing to the evolution of the modern deep-water benthic foraminiferal fauna (*31*).

Previous estimates of evolutionary change in planktonic foraminifera (*32*) show a steady decline in evolutionary turnover beginning in the early Eocene and continuing in the middle and late Eocene. The rate accelerated near the top of the Eocene with several well-known and biostratigraphically important taxa becoming extinct (for example, *Hantkenina* and *G. cerroazulensis*). Yet this scenario must be seen against the background of a sequential series of extinctions and appearances of other planktonic foraminifera that occurred continuously during the late Eocene, as shown in our data. Major planktonic foraminiferal assemblage changes during middle Eocene to Oligocene time, recorded in material from the Atlantic, Indian, and Pacific oceans (*10*), include three changes between the middle Eocene and early Oligocene rather than one catastrophic event (*33*), suggesting that climatic coolings occurred in a series of threshold events with the transition between events marked by rapid cooling, as indicated in the ^{18}O record. These coolings are indicated by the replacement of warm middle Eocene faunas by successively cooler faunas of lower diversity consisting of species of simple morphology (*34*).

A survey of the distribution of calcareous nannoplankton from the middle Eocene to early Oligocene from various DSDP sites shows that, with the exception of the discoasters, a much greater qualitative difference exists between middle and late Eocene assemblages than between late Eocene and early Oligocene assemblages (*35, 36*). At equatorial sites, three species became extinct near the Eocene/Oligocene boundary: *Discoaster saipanensis, Discoaster barbadiensis*, and *Reticulofenestra reticulata*. The last appearance of the latter two taxa was time-transgressive, occurring as early as early late Eocene in high latitudes. These time-transgressive last appearances suggest that the geographic distributions of these species were gradually reduced because of changing environmental conditions until they became extinct at the Eocene/Oligocene boundary at low latitudes. The calcareous nannoplankton data indicate that extinctions occurred in a sequential, step-like manner over an interval of several million years (*37*). The extinctions of *D. barbadiensis* and *D. saipanensis*, while temporally close, are not simultaneous and precede those of the late Eocene extinctions of the planktonic foraminiferal taxa *G. cerroazulensis* and *Hantkenina* spp.

Although no extinction event is seen in the planktonic diatom data, a distinct change in the diatom composition occurs in low-latitude sites (sites 77B, 167, 366, 369A) in the earliest Oligocene and is associated with the oxygen isotope enrichment (Fig. 4). Relatively large and robust low- to mid-latitude species of the genus *Cestodiscus*, which were of minor qualitative importance during the late Eocene (5 to 20 percent), increase to 60 to 80 percent in the early Oligocene. A second floral turnover occurs in the Oligocene in planktonic foraminiferal zones P20 and P21, with the evolution of and quantitative increase of cosmopolitan species of the genera *Synedra, Rossiella*, and *Rocella*.

Our faunal and floral data from the three oceans do not rule out a possible influence of a bolide impact near the Eocene/Oligocene boundary, but the data show that it is not necessary to invoke an extraterrestrial event (or events) to account for the observed biotic changes. These changes in the deep sea had been interpreted to be of an abrupt (that is, catastrophic) nature because of the precipitous benthic foraminiferal oxygen isotopic change at the boundary (*4*). Detailed oxygen isotopic studies from throughout the world oceans show that surface and deep waters experienced a series of sharp coolings during the Paleogene, with the cooling at the Eocene/Oligocene boundary being part of this sequence of events (*3, 4*). This sequential climatic cooling is seen in the land record as well (*38*). Hence, the Eocene/Oligocene boundary event should not be regarded as an isolated event, but rather as part of the evolution of the Paleogene ocean in



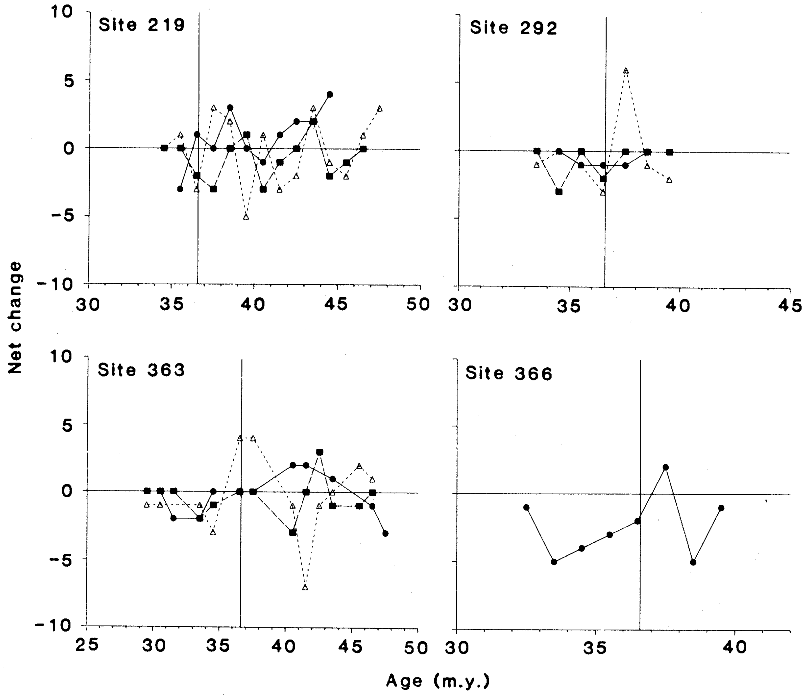


Fig. 5 (top right). The number of extinctions per million years for benthic foraminifera, calcareous nannoplankton, and planktonic foraminifera from analysis of sites 219, 292, and 363, and for planktonic diatoms from site 366. The Eocene/Oligocene boundary is shown as a vertical line at 36.6 million years (m.y.). Fig. 6 (bottom right). The net change (first appearances minus extinctions) of benthic foraminifera (●), planktonic foraminifera (△), and calcareous nannoplankton (■) per million years for sites 219, 292, and 363, and for planktonic diatoms in site 366 is shown. The Eocene/Oligocene boundary is shown as a vertical line at 36.6 million years (m.y.).

which biotic changes occurred in response to a series of worldwide climatic events that marked the transition from a warm, perhaps ice-free, climate to a colder climate with more polar ice, stronger pole-equator temperature gradients, and more vigorous surface and deep-water circulation.

On the basis of our study of DSDP sites from three oceans, we find no evidence for a simultaneous and massive extinction event at the Eocene/Oligocene boundary or at any time during middle Eocene to middle Oligocene time. These findings are similar to results from paleontological and paleobiogeographic studies of European and North American mammalian fossils that show no catastrophic event at the Eocene/Oligocene boundary, but instead indicate a turnover spanning the late Eocene and early Oligocene (*39*). These observations argue against a bolide impact having a major influence on the earth's biosphere near the Eocene/Oligocene boundary.

Catastrophism, although a viable working hypothesis in the interpretation of some geologic events, is not reflected in the geologic record across the Eocene/Oligocene boundary. Rather, we interpret the sequence of changes found in the deep-sea benthic fauna and in the planktonic fauna and flora within the middle Eocene–early Oligocene interval as responses to complex interactions of changing paleoceanographic and paleoclimatic conditions.

References and Notes

1. G. R. Heath, *Geol. Soc. Am. Bull.* **80**, 689 (1969); Tj. H. van Andel, G. R. Heath, T. C. Moore, Jr., *Geol. Soc. Am. Mem. 143* (1975); T. C. Moore, Jr., Tj. H. van Andel, C. Sancetta, N. Pisias, *Micropaleontology* **24**, 113 (1978).
2. B. U. Haq and G. P. Lohmann, *Mar. Micropaleontol.* **1**, 119 (1976); J. P. Kennett, *ibid.* **3**, 301 (1978); C. Sancetta, *ibid.* **4**, 363 (1979).
3. S. M. Savin, R. G. Douglas, F. G. Stehli, *Geol. Soc. Am. Bull.* **86**, 1499 (1975); A. Boersma and N. J. Shackleton, *Init. Rep. Deep Sea Drill. Proj.* **39**, 911 (1977); C. Vergnaud-Grazzini, C. Muller, C. Pierre, R. Letolle, J. P. Peypouquet, *ibid.* **48**, 475 (1979); B. Buchardt, *Nature (London)* **275**, 121 (1978); K. G. Miller and W. B. Curry, *ibid.* **296**, 347 (1982); C. Cavelier, *Sci. Geol. Mem. Strasb. 54* (1979).
4. N. J. Shackleton and J. P. Kennett, *Init. Rep. Deep Sea Drill. Proj.* **29**, 743 (1975); J. P. Kennett and N. J. Shackleton, *Nature (London)* **260**, 513 (1976).
5. L. D. Keigwin, Jr., *Nature (London)* **287**, 722 (1980).
6. J. A. O'Keefe, *ibid.* **285**, 301 (1980).
7. R. Ganapathy, *Science* **216**, 885 (1982).
8. W. Alvarez, F. Asaro, H. V. Michel, L. W. Alvarez, *ibid.*, p. 886.
9. F. Asaro, L. W. Alvarez, W. Alvarez, H. V. Michel, *Geol. Soc. Am. Spec. Pap.* **190**, 517 (1982).
10. The DSDP sites studied include 77B, 277, and 292 from the Pacific Ocean, 219 and 253 from the Indian Ocean, 363 from the Atlantic Ocean, and Eureka borehole E68-128 from the Gulf of Mexico. Planktonic diatoms were studied from sites 77B and 167 in the Pacific Ocean and sites 366, 369A, and 511 in the Atlantic Ocean. Sites 292, 219, and 363 contain apparently continuous sequences across the Eocene/Oligocene boundary.
11. Sediment samples of 25 to 35 cm^3 were disaggregated in hot Calgon solution, sieved wet over a 63-μm sieve, and then dry sieved over a 150-μm sieve. The >150-μm size fraction was used for the planktonic and benthic foraminiferal analyses. A sample size of 300 specimens was attempted with the benthic foraminifera, although in some cases a smaller sample size (between 100 and 300 specimens) was used because of scarcity of benthic foraminifera and time considerations. If benthic foraminifera were abundant in a sample, a random split was made with a modified Otto microsplitter to obtain 300 specimens for counting. Certain genera of benthic foraminifera were not considered because of poor preservation (*Lenticulina* and *Stilostomella*) or because they contained a number of rare species that occurred sporadically (*Fissurina, Fursenkoina, Lagena, Oolina, Orthomorphina*, and *Pleurostomella*). Agglutinated foraminifera and miliolids were rare and were not considered. An examination of these genera in our samples shows that their exclusion does not significantly change the results of the study. For the quantitative calcareous nannoplankton data, smear slides were made from raw sediment, and counts of at least 300 specimens were made. Additional specimens were examined for the determination of the first and last occurrences.
12. The number of first and last occurrences in a particular sample may be artificially enhanced by coring gaps and possible hiatuses, as indicated by a comparison of the relative length of the fossil zones. A direct correspondence between the first and last occurrences and species number does not exist because the species number of a fossil group within a site is much higher than in any particular sample. For example, last occurrences could increase, first occurrences could remain constant, and species number could remain constant rather than decrease because of the presence of rare species found sporadically within the sequence.
13. R. B. Whitmarsh *et al.*, *Init. Rep. Deep Sea Drill. Proj.* **23**, 539 (1974).
14. D. E. Karig *et al.*, *ibid.* **31**, 67 (1975).
15. H. M. Bolli *et al.*, *ibid.* **40**, 183 (1978).
16. J. G. Sclater, D. Abbott, J. Thiede, in *Indian Ocean Geology and Biostratigraphy*, J. R. Heirtzler *et al.*, Eds. (American Geophysical Union, Washington, D.C., 1977), pp. 25–59.
17. Paleodepths were determined by the back-tracking method [W. H. Berger and E. L. Winterer, *Spec. Publ. Int. Assoc. Sedimentol. 1* (1974), p. 11.
18. J. G. Sclater, R. Anderson, G. Bell, *J. Geophys. Res.* **76**, 7888 (1971).
19. J. G. Sclater, S. Hellinger, C. Tapscott, *J. Geol.* **85**, 509 (1977).
20. G. Keller, S. D'Hondt, T. L. Vallier, *Science* **221**, 150 (1983).
21. B. P. Glass and J. R. Crosbie, *Bull. Am. Assoc. Pet. Geol.* **66**, 471 (1982).
22. For isotope results, see L. D. Keigwin, Jr., and B. H. Corliss, in preparation. Isotope methods follow those in L. D. Keigwin, Jr. [*Earth Planet. Sci. Lett.* **45**, 361 (1979)], with the following modifications: samples were sonicated in methanol, benthic foraminifera were crushed in methanol before roasting at 370°C, and all volatiles were condensed with liquid nitrogen as they were produced in H_3PO_4.
23. R. C. Tjalsma and G. P. Lohmann, *Micropaleontol. Spec. Publ. 4* (1983), p. 90.
24. K. G. Miller, W. B. Curry, D. R. Ostermann, *Init. Rep. Deep Sea Drill. Proj.*, in press; R. G. Douglas and F. Woodruff, in *The Oceanic Lithosphere*, C. Emiliani, Ed. (Wiley-Interscience, New York, 1981), p. 1233.
25. B. H. Corliss, *Nature (London)* **282**, 63 (1979); *Mar. Micropaleontol.* **6**, 367 (1981).
26. Calcareous nannoplankton zones are from D. Bukry [*Init. Rep. Deep Sea Drill. Proj.* **41**, 689 (1978)], planktonic diatom zones are from J. M. Fenner (*Micropaleontology*, in press), and oxygen isotope data, based on the analysis of bulk carbonate, are from C. Vergnaud-Grazzini and D. R. Lointier [*Rev. Geol. Geogr. Phys.* **22**, 63 (1980)]. The planktonic diatom data are based on a count of 2000 diatom valves. Samples were weighed and prepared by boiling in equal amounts of 10 percent HCl and 30 percent H_2O_2, and a 0.5 percent solution of sodium pyrophosphate was used in the gravitational separation of diatoms from clay particles. A statistically random distribution of diatoms on the cover slip was achieved following the methods outlined by R. W. Battarbee [*Limnol. Oceanogr.* **18**, 647 (1973)]. The first and last appearance events in Fig. 4 are evolutionary rather than migrational events.
27. The first and last occurrences in our data reflect both evolutionary and ecologic changes. Estimates for the number of real evolutionary events for each group were made from a comparison of events in our DSDP cores and other studies with compatible taxonomies. The estimates of planktonic foraminiferal and calcareous nannoplankton evolutionary events are more accurate than the benthic foraminiferal estimates since there has been much more biostratigraphic work done on the planktonic foraminifera and calcareous nannoplankton.
28. The time scale used to calculate ages is that of W. A. Berggren, D. V. Kent, and J. J. Flynn [in *Geochronology and the Geological Record*, N. J. Snelling, Ed. (Special Paper, Geological Society of London, London, in press)]. The early/middle Eocene boundary is dated at 52 million years (m.y.), the middle/late Eocene boundary at 40 m.y., the Eocene/Oligocene boundary at 36.6 m.y., and the early/late Oligocene boundary at 30 m.y. The foraminiferal and calcareous nannoplankton zones and associated ages used to calculate ages for samples are: (i) site 219, the top of *G. cerroazulensis* zone at 36.6 m.y., the top of NP17 at 40 m.y., and the top of *Globigerinatheka subconglobata* zone at 46 m.y.; (ii) site 292, the top of NP22 at 34.6 m.y., the top of *G. cerroazulensis* zone at 36.6 m.y., and the top of *G. semiinvoluta* zone at 37.6 m.y.; and (iii) site 363, the top of *Pseudohastigerina micra* zone at 34 m.y., the top of *G. cerroazulensis* zone at 36.6 m.y., and the bottom of *G. semiinvoluta* zone at 41.3 m.y.
29. Benthic foraminifera (*25*), planktonic foraminifera (*33*), and calcareous nannoplankton (*35*) from site 277, planktonic diatoms (*26*) from site 511, as well as data from site 549 [S. W. Snyder, C. Muller, K. G. Miller, *Geology* **12**, 112 (1984)], all indicate that there was no catastrophic change at the boundary.
30. D. Schnitker, *Int. Rep. Deep Sea Drill. Proj.* **48**, 377 (1979).
31. B. H. Corliss and L. D. Keigwin, Jr., *Bull. Am. Assoc. Pet. Geol.* **67**, 443 (1983); W. A. Berggren and F. M. Gradstein, *Geol. Soc. Am. Spec. Publ.*, in press.
32. W. A. Berggren, *Micropaleontology* **15**, 351 (1969); R. C. Thunell, *Nature (London)* **289**, 670 (1981).
33. G. Keller, *Mar. Micropaleontol.* **7**, 463 (1983).
34. J. H. Lipps, *Evolution* **24**, 1 (1970).
35. M-P. Aubry, in preparation. The DSDP sites studied include 77B, 232, 253, 277, 292, 363, and 366.
36. B. U. Haq [*Mar. Geol.* **15**, M25 (1973)] has also shown that there is a marked decline in diversity in the early late Eocene, with a continual and gradual decline into and throughout the Oligocene.
37. M-P. Aubry, *Bull. Am. Assoc. Pet. Geol.* **67**, 415 (1983).
38. J. A. Wolfe, *Am. Sci.* **66**, 694 (1978).
39. J.-L. Hartenberer, *Bull. Mus. Nat. Hist.* **132**, 49 (1973); B. Sige and M. Vianey-Liand, *Newsl. Stratigr.* **8**, 79 (1979); D. R. Prothero, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, in press.
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