Hiatus distributions and mass extinctions at the Cretaceous/Tertiary boundary

Norman MacLeod and Gerta Keller


Email alerting services  
click [www.gsapubs.org/cgi/alerts](http://www.gsapubs.org/cgi/alerts) to receive free e-mail alerts when new articles cite this article

Subscribe  
click [www.gsapubs.org/subscriptions/](http://www.gsapubs.org/subscriptions/) to subscribe to *Geology*

Permission request  
click [http://www.geosociety.org/pubs/copyrt.htm#ga](http://www.geosociety.org/pubs/copyrt.htm#ga) to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes
Hiatus distributions and mass extinctions at the Cretaceous/Tertiary boundary

Norman MacLeod, Gerta Keller
Department of Geological and Geophysical Sciences, Princeton University, Princeton, New Jersey 08544

ABSTRACT

Much disagreement over the interpretation of data bearing on various Cretaceous/Tertiary (K/T) extinction scenarios results from a failure to view these data within their appropriate stratigraphic context. Combined biostratigraphic and chronostratigraphic analyses of K/T boundary sequences have revealed systematic differences in patterns of sediment accumulation within continental-shelf and deep-sea depositional settings. Although virtually all deep-sea boundary sequences are marked by intervals of nondeposition or hiatus formation during the latest Cretaceous and earliest Tertiary, many continental shelf-slope sequences appear to be temporally complete over this same interval. This differential pattern of sediment accumulation can be related to the latest Maastrichtian-earliest Danian sea-level rise, during which deep-sea sediment-accumulation rates would be expected to drop as the locus of sediment deposition can be related to the latest Maastrichtian-earliest Danian sea-level rise, during which deep-sea sediment-accumulation rates would be expected to drop as the locus of sediment deposition moved across the continental shelf. Our data suggest that the abrupt shifts in carbon-isotope abundances, single-peak Ir anomalies, and apparently instantaneous mass extinctions of marine plankton—which are routinely reported from deep-sea K/T boundary sequences and used to support a causal relation between Late Cretaceous bolide impacts and K/T mass extinctions—may be artifacts of a temporally incomplete (or extremely condensed) deep-sea stratigraphic record.

INTRODUCTION

After more than 10 years, the intense debate over causal mechanisms for mass extinctions at the Cretaceous/Tertiary (K/T) boundary appears to have reached an impasse. Neither the advocates of terrestrial (volcanism, mantle plume, global cooling, sea-level rise) nor extra-terrestrial (impact, extinction periodicity) hypotheses have been able to achieve a consensus within the scientific community because neither group can successfully account for certain problematical data. For example, the impact hypothesis, as advocated by Alvarez et al. (1980, 1982, 1984), focuses on the incidence of anomalously high concentrations of Ir and other platinum-group elements at various K/T boundary sites, but ignores the role that long-term environmental changes may have in reducing both the diversity and geographic distribution of species prior to the impact. Likewise, the recently proposed mantle-plume hypothesis (Loper and McCartney, 1986, 1988; Courtillot and Besse, 1987) provides a plausible explanation for Ir enrichment and global environmental forcing, yet it fails to address the implications of shocked quartz in a number of K/T boundary sequences.

We believe that much of this confusion can be attributed to a general lack of appreciation for the complexity of the marine environments within which these K/T boundary sediments were deposited as well as an oversimplified approach to chronostratigraphic inference. Observations from more than 50 different stratigraphic sequences, representing a large number of terrestrial and marine depositional settings, have been cited in support of numerous alternative hypotheses. Incredibly, almost all of these studies assume that the stratigraphic records preserved at each of these localities are temporally complete, despite the fact that the discontinuous nature of sediment accumulation (especially during intervals of eustatic sea-level fluctuation) is well known. Therefore, it is with good reason that many earth scientists and oceanographers have remained skeptical of various catastrophic extinction scenarios in that they are based on as yet undemonstrated levels of extinction synchrony.

In order to provide the necessary chronostratigraphic and oceanographic context for interpreting K/T boundary data, we have integrated lithostratigraphic, biostratigraphic, and chronostratigraphic observations from 15 densely sampled K/T boundary sections and cores (including El Kef, Tunisia; Brazos River, Texas; Caravaca, Agost, and Sopelana, Spain; Lattengebirge, Germany; Hor Hahar, Sinai, Ben Gurion, Ein Mor, and Zofar, Israel; and DSDP Sites 528 and 577). These results are reported in their entirety in MacLeod and Keller (unpublished; preprints available upon request). Herein, we demonstrate inherent differences in the biostratigraphic and chronostratigraphic records of the four most complete boundary sequences known from both deep-sea (DSDP Site 528, southeastern Atlantic, and DSDP Site 577, western Pacific) and outer-neritic and upper-slope (El Kef, Tunisia, and Brazos River, Texas) depositional environments. In addition, we propose a comprehensive chronostratigraphic-oceanographic model that accounts for many apparent physical (e.g., lithologic, mineralogic, geochemical) and biological (e.g., taxic patterns of first and last occurrences) inconsistencies among the different K/T boundary sequences.

BIOSTRATIGRAPHY VS. CHRONOSTRATIGRAPHY

During the past decade, intensive, high-resolution micropaleontological studies of the K/T boundary have led to the refinement of K/T biostratigraphic zonations (see Smit, 1982; Berggren and Miller, 1988; Keller, 1988). Among microfossil groups, planktic foraminifera continue to offer the most detailed fossil record available for biostratigraphic correlation. However, just as the various K/T boundary sections differ in the extent to which they have recorded lithostratigraphic and geochemical anomalies, many also exhibit differences in the distribution of biostratigraphic datums.

Figure 1 illustrates one aspect of this biostratigraphic variability for two boundary sequences representing different marine environments. Boundary sequences deposited on continental shelves or the upper parts of continental slopes (e.g., Brazos core in Texas [Keller, 1989b], Caravaca and Agost in Spain [Canudo, 1990], and El Kef in Tunisia [Keller, 1988a]) display a more or less continuous distribution of biostratigraphic datums across the K/T boundary with little evidence for the geologically instantaneous planktic foraminiferal mass extinction often observed in deep-sea cores. The earliest Tertiary fauna of these middle-shelf to upper-slope sections often includes eight to ten species that are also present in the underlying latest Cretaceous faunas. Because these Cretaceous species are rarely found above the K/T boundary in deeper-water settings, they are often identified as reworked constituents of older deposits. This explanation is no longer tenable in all cases for the following reasons: (1) there is little independent physical evidence of reworking in the majority of outcrop sections; (2) if major sediment mixing had occurred in these sections, we would expect to see other reworked Cretaceous species in addition to the survivor fauna; and (3) recent stable-isotope analyses of faunas collected at Brazos River, Texas (Barrera and Keller, 1990), have shown that at least two Cretaceous survivor species (H. globulosa and G. cretacea) exhibit a 20 excursion of 7^13C between Maastrichtian and Danian populations. These data indicate that at least some Cretaceous species survived well into the early Tertiary. In contrast, deep-sea sequences such as Deep Sea Drilling Project (DSDP) Sites 528...
(Fig. 1B) and 577 usually exhibit a large discontinuity in the distribution of biostratigraphic datums coincident with the K/T boundary. Most paleontologists have come to associate this deep-sea pattern of planktic foraminiferal turnover with catastrophic mass-extinction scenarios.

Along with these discrepancies in the distribution of biostratigraphic datums, the relative sequence or rank order of taxic first-appearance datums (FADs) and last-appearance datums (LADs) among the various boundary sequences is often highly variable (Table 1). A quantitative correlation analysis in Figure 2 can be used to test various extinction hypotheses encompass a wide variety of marine depositional environments and because large fluctuations in eustatic sea level did occur during the K/T transition (Haq et al., 1983), it is reasonable to expect that at least some of the observed faunal differences might result from characteristic variations in the temporal fidelity of the K/T boundary stratigraphic record.

Figure 2 illustrates temporal completeness—sediment-accumulation rate models for boundary sequences from El Kef (Tunisia), the Brazos River (Texas), and DSDP Site 528 (Walvis Ridge, southeastern Atlantic). In these graphic correlation diagrams (see Shaw, 1964; Edwards, 1983, 1989), the observed occurrences of individual biostratigraphic datums have been plotted against the expected composite datum sequence (see Table 1). On the basis of these event distributions, lines of correlation can be drawn that map each section onto the K/T composite, quantify relative rates of sediment accumulation (slopes of the lines of correlation), and provide information on the lithostratigraphic position and relative duration of depositional hiatuses (vertical segments). As shown in Figure 2, the middle-to outer-neritic boundary sequences at El Kef and Brazos River appear to contain a virtually complete record of sediment accumulation through the K/T transition. In contrast, biostratigraphic data from the deep-sea boundary sequence at Site 528 reveal that a sizable portion of the overlying basal Tertiary, including all of the planktic foraminiferal biozone P0, is either missing or extremely condensed (data from D'Hondt, 1989). Furthermore, distributions of biostratigraphic datums in the sequences at El Kef and in the Brazos core sections reveal that even though all planktic foraminiferal biozones are present, they may still contain depositional hiatuses within Zones P0 and P1a.

The relative chronostratigraphy provided by graphic correlation analysis in Figure 2 can be related to K/T geochronology by a regression analysis of the predicted positions of radiometrically dated events within the K/T composite on the radiometric dates themselves (radiometric
TABLE 1. SELECTED EARLY TERTIARY PLANKTIC FORAMINIFERAL DATUM LEVELS FOR COMPOSITE, NERITIC, AND DEEP SEA SECTIONS

<table>
<thead>
<tr>
<th>Datums</th>
<th>Composite (CRU)</th>
<th>Middle Shelf - Upper Slope</th>
<th>Deep Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>El Kef (cm)</td>
<td>Brazos-1 (cm)</td>
</tr>
<tr>
<td>1. Eoglobigerina fringa FAD</td>
<td>7</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>2. Woodringina hornestownensis FAD</td>
<td>17</td>
<td>22</td>
<td>9</td>
</tr>
<tr>
<td>3. Eoglobigerina edita FAD</td>
<td>20</td>
<td>62</td>
<td>85</td>
</tr>
<tr>
<td>4. Parvularugoglobigerina eugubina FAD</td>
<td>54</td>
<td>57</td>
<td>100</td>
</tr>
<tr>
<td>5. Globigerina taurica FAD</td>
<td>91</td>
<td>137</td>
<td>-</td>
</tr>
<tr>
<td>6. Subbotina moskvini FAD</td>
<td>111</td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td>7. Globastica daubjergensis FAD</td>
<td>113</td>
<td>262</td>
<td>-</td>
</tr>
<tr>
<td>8. Subbotina pseudobulloides FAD</td>
<td>122</td>
<td>350</td>
<td>-</td>
</tr>
<tr>
<td>9. Globigerina pentagona FAD</td>
<td>145</td>
<td>302</td>
<td>-</td>
</tr>
<tr>
<td>10. Parvularugoglobigerina eugubina LAD</td>
<td>400</td>
<td>500</td>
<td>170</td>
</tr>
</tbody>
</table>

Note: FAD = First Appearance Datum. LAD = Last Appearance Datum. CRU = Composite Reference Units. All boundary section datum levels given in centimeters above the K/T boundary (as defined by the first appearance of Tertiary taxa). Datum numbers are the same as those shown in Fig. 2. Complete Early Tertiary Composite Reference Section available upon request from the authors.

Figure 2. Graphic correlations with K/T composite. A: El Kef, 0-600 cm. B. El Kef (detail), 0-175 cm. C: Brazos core. D: DSDP Site 528 (D). O = last-appearance datum (LAD) of Tertiary taxa, 6 = LAD of Cretaceous survivor taxa, • = first-appearance datum (FAD). Datum numbers refer to following biostratigraphic events: 1 = Eoglobigerina fringa FAD, 2 = Woodringina hornestownensis FAD, 3 = Eoglobigerina edita FAD, 4 = Parvularugoglobigerina eugubina FAD, 5 = Globigerina taurica FAD, 6 = Subbotina moskvini FAD, 7 = Globastica daubjergensis FAD, 8 = Subbotina pseudobulloides FAD, 9 = Globigerina pentagona FAD, 10 = Parvularugoglobigerina eugubina LAD.

Lines of correlation: solid = “worst case” correlation model in which variations in sediment-accumulation rates and hiatus durations have been maximized, dashed = “best case” correlation model in which variations in sediment-accumulation rates and hiatus durations have been minimized, inclined = interval of net sediment accumulation, vertical = lithologic position (X axis) and relative temporal duration (Y axis) of depositional hiatus. CRU = composite reference units. Biostratigraphic zonation above each plot is that of Keller (1988a, 1989a).
data from Berggren et al., 1985; MacLeod and Keller, unpublished). Figure 3 summarizes the resulting temporal-completeness estimates for the El Kef and Brazos River sections along with those from DSDP Sites 528 and 577. These estimates reveal that from the K/T boundary through the earliest Tertiary, continental-shelf and upper continental-slope sequences contain substantially more complete temporal records than coeval intervals in the deep sea. Furthermore, the correlation of these K/T hiatus-distribution patterns to the early Tertiary sea-level curve of Brinkhuis and Zachariasse (1988) suggests a causal connection between these environmentally mediated patterns of sediment accumulation and the latest Maastrichtian–early Tertiary sea-level rise.

Recent studies of sequence stratigraphy (Haq et al., 1987, 1988; Donovan et al., 1988) have shown that the uppermost Cretaceous drop in sea level culminated just before the K/T boundary and was followed by a sea-level rise that may have amounted to as much as 130 m. The transgression accompanying this highstand in sea level would have dramatically affected deep-sea sediment-accumulation patterns by reducing the amount of terrigenous clastic sediment and organic carbon delivered to the ocean basins as the locus of sediment deposition migrated across the continental shelf. Moreover, the results of sediment starvation in deep-ocean basins during sea-level highstands are often magnified by an increase in carbonate dissolution leading to the formation of condensed intervals or hiatuses (see Vail et al., 1977; Haq et al., 1987). Shelf sequences, however, would be characterized by elevated rates of sediment accumulation during these same transgressive episodes. Observed K/T hiatus distributions for middle-neritic–upper-slope and deep-sea sequences conform well to this general model.

Highstand sediment-accumulation patterns reverse during sea-level lowstands as incised valleys are cut into the newly deposited shelf sediments in response to lowering of the base level (Posamentier and Vail, 1988). These incised valley systems can result in depositional bypassing of the continental shelves and thus can renew sediment delivery to the deep sea. With this regressive pattern in mind, it is interesting to note that early Tertiary hiatus development in the neritic sequences of El Kef and Brazos River occurs during an interval of sea-level instability superimposed on the overall transgressive trend (Fig. 3).

Donovan et al. (1988) noted a similar hiatus-distribution pattern at the Bragg's K/T boundary section in Alabama, and argued that the multiple Ir anomalies found within this section coincide with parasequence boundaries (maximum flooding surfaces). Our data suggest that such parasequence-influenced depositional patterns may be characteristic features of the earliest Tertiary marine record in other relatively shallow depositional settings.

**DISCUSSION**

Combined biostratigraphic and chronostatigraphic analyses of K/T boundary sequences have revealed systematic differences in patterns of sediment accumulation characterizing neritic and deep-sea depositional environments. Nearly all deep-sea K/T boundary sequences are marked by intervals of nondeposition or hiatus formation from the uppermost Maastrichtian through the lower Danian as a result of sediment starvation in deep ocean basins during a prolonged transgressive event. In contrast, many continental-shelf and upper-slope sequences appear to contain a temporally complete record of sediment accumulation throughout this same interval. Recognition of these differences in the nature of the marine stratigraphic record can resolve much of the continuing controversy regarding the rate of environmental change across the K/T boundary.

The apparently sudden extinction at the K/T boundary of virtually all planktic foraminiferal species has always been the primary evidence supporting a causal connection between the effects of a large bolide impact and K/T mass extinctions. However, these abrupt changes in the composition of the planktic foraminiferal fauna are confined to deep-sea sequences. Our analyses demonstrate that K/T boundary stratigraphic records within deep-sea basins are either condensed or temporally incomplete. In the coeval (but lithostratigraphically expanded) neritic and upper-slope settings at El Kef (Tunisia), Caravaca and Agost (southern Spain), and Brazos River (Texas), the same foraminiferal species record an extended faunal turnover that begins well below the K/T boundary and spans a time interval of between 200,000 and 400,000 yr (Keller, 1988a, 1988b, 1989a, 1989b; Canudo, 1990).

In addition, our biostratigraphic data also suggest that the sudden shift in carbon-isotope ratios reported from many deep-sea boundary sequences and used to infer the abrupt collapse...
of marine productivity at the K/T boundary (Hsi, et al., 1982; Zachos and Arthur, 1986; Arthur et al., 1987) may be the expected result of an interval of nondeposition or hiatus production (Scholle and Arthur, 1980; Loutit et al., 1988). At Brazos River, where a lithostratigraphically expanded record of this time interval is present, the carbon-isotope shift has been observed to occur gradually over a time span of −25000 to 30000 yr (Barrera and Keller, 1990). Finally, differences in the distribution of Ir anomalies (single vs. multiple) between deepsea and shelf and slope settings may also be related to the intrinsically different patterns of sediment accumulation that characterize these different depositional environments. Although we do not dispute the physical evidence (e.g., shocked quartz) supporting the occurrence of a bolide impact during the K/T transition (see Bohor et al., 1984, 1987), the only direct evidence for a causal link between this event and organismal extinctions comes from the deep sea. It now seems clear that the apparent mass extinction in marine plankton, the sudden shift in carbon-isotope values, and the single-peak Ir abundance anomalies—all of which characterize deepsea K/T boundary sequences—are, most likely, artifacts of a temporarily incomplete deepsea stratigraphic record.

REFERENCES CITED


ACKNOWLEDGMENTS

Supported by National Science Foundation Grant OCE 88-11732 to Keller and the Tuttle Fund of the Department of Geological and Geophysical Sciences, Princeton University. We thank Katharina van Salis Perch-Nielsen for stimulating discussion on K/T boundary stratigraphy and S. D’Hondt for allowing us to use unpublished thesis data. We also thank Walter Alvarez and two anonymous Geology reviewers for critically reading and commenting on the original manuscript.

Manuscript received June 21, 1990
Revised manuscript received December 10, 1990
Manuscript accepted December 18, 1990

GEOLOGY, May 1991

Printed in U.S.A.