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Notes

Hiatus distributions and mass extinctions at the Cretaceous/Tertiary boundary

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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 migrated 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 extraterrestrial (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 played 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 synchronicity.

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 2‰ to 3‰ difference in $\delta^{13}\text{C}$ 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 chronostratigraphic study of lowermost Tertiary biostratigraphic markers has indicated that

correlations based on some standard biozone-defining taxa (e.g., *S. pseudobulloides* FAD, *S. triloculinoides* FAD) could incorporate age differences of as much as 250,000 yr (MacLeod and Keller, unpublished). These results provide strong grounds upon which to question previous, biostratigraphically based, temporal-completeness estimates for K/T boundary sections and cores.

CHRONOSTRATIGRAPHIC-OCEANOGRAPHIC MODEL

Even within the depositionally favorable environments of the deep sea, hemipelagic and

pelagic sequences often contain intervals of either temporally condensed or expanded sediment accumulation as well as both local and global hiatuses of varying duration (Moore et al., 1978; Keller and Barron, 1983, 1987). Additionally, recent global stratigraphic surveys have demonstrated that both local variations in depositional setting (e.g., neritic vs. bathyal) and eustatic sea-level change can dramatically affect realized levels of temporal completeness in the marine sequences (Vail et al., 1977; Schindel, 1980, 1982; Sadler, 1981; Keller and Barron, 1983, 1987; Anders et al., 1987; Haq et al., 1987; Keller et al., 1987; Loutit et al., 1988). Because those K/T boundary sequences that have been 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., 1988), 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 segments 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

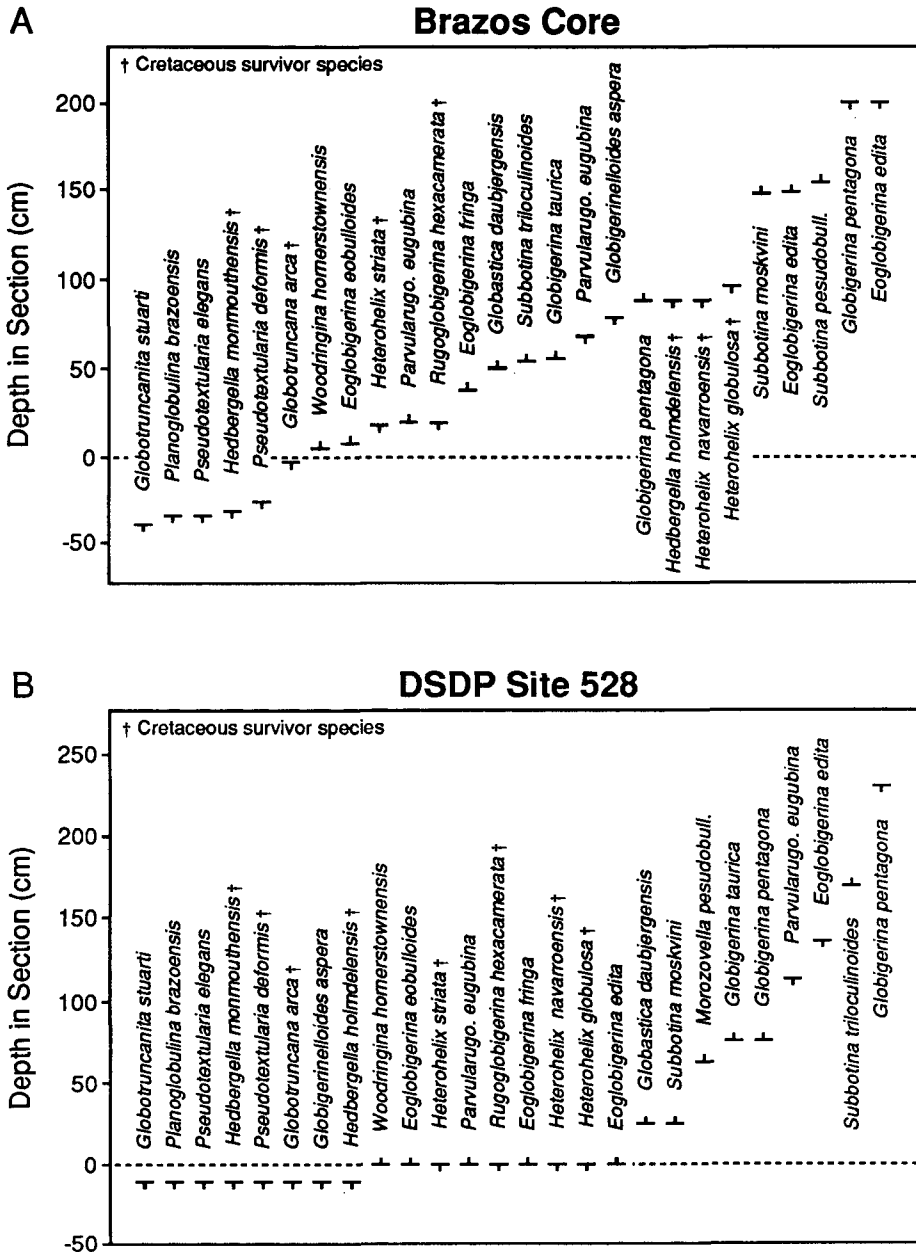


Figure 1. Patterns of biostratigraphic datum occurrence across K/T boundary at middle-neritic (A) and deep-sea (B) boundary sequence illustrating more discontinuous nature of deep-sea biostratigraphic record. Bar with lower tick mark represents last-appearance datum (LAD); bar with upper tick mark represents first-appearance datum (FAD). Brazos core data from Keller (1989a); Deep Sea Drilling Project (DSDP) Site 528 data from D'Hondt (1989).

TABLE 1. SELECTED EARLY TERTIARY PLANKTIC FORAMINIFERAL DATUM LEVELS FOR COMPOSITE, NERITIC, AND DEEP SEA SECTIONS

Datums	Composite (CRU)	Middle Shelf - Upper Slope				Deep Sea	
		El Kef (cm)	Brazos-1 (cm)	Brazos-CM4 (cm)	Brazos Core (cm)	Site 528 (cm)	Site 577 (cm)
1. <i>Eoglobigerina fringa</i> FAD	7	7	20	5	38	0	-
2. <i>Woodringina hornerstownensis</i> FAD	17	22	9	5	5	0	-
3. <i>Eoglobigerina edita</i> FAD	20	62	85	-	149	0	-
4. <i>Parvularugoglobigerina eugubina</i> FAD	54	57	100	35	20	0	-
5. <i>Globigerina taurica</i> FAD	91	137	-	105	55	75	62
6. <i>Subbotina moskvini</i> FAD	111	400	-	105	148	23	50
7. <i>Globastica daubjergensis</i> FAD	113	262	-	85	50	23	21
8. <i>Subbotina pseudobulloides</i> FAD	122	350	-	135	155	60	122
9. <i>Globigerina pentagona</i> FAD	145	302	-	125	88	75	122
10. <i>Parvularugoglobigerina eugubina</i> LAD	400	500	170	100	68	113	39

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.

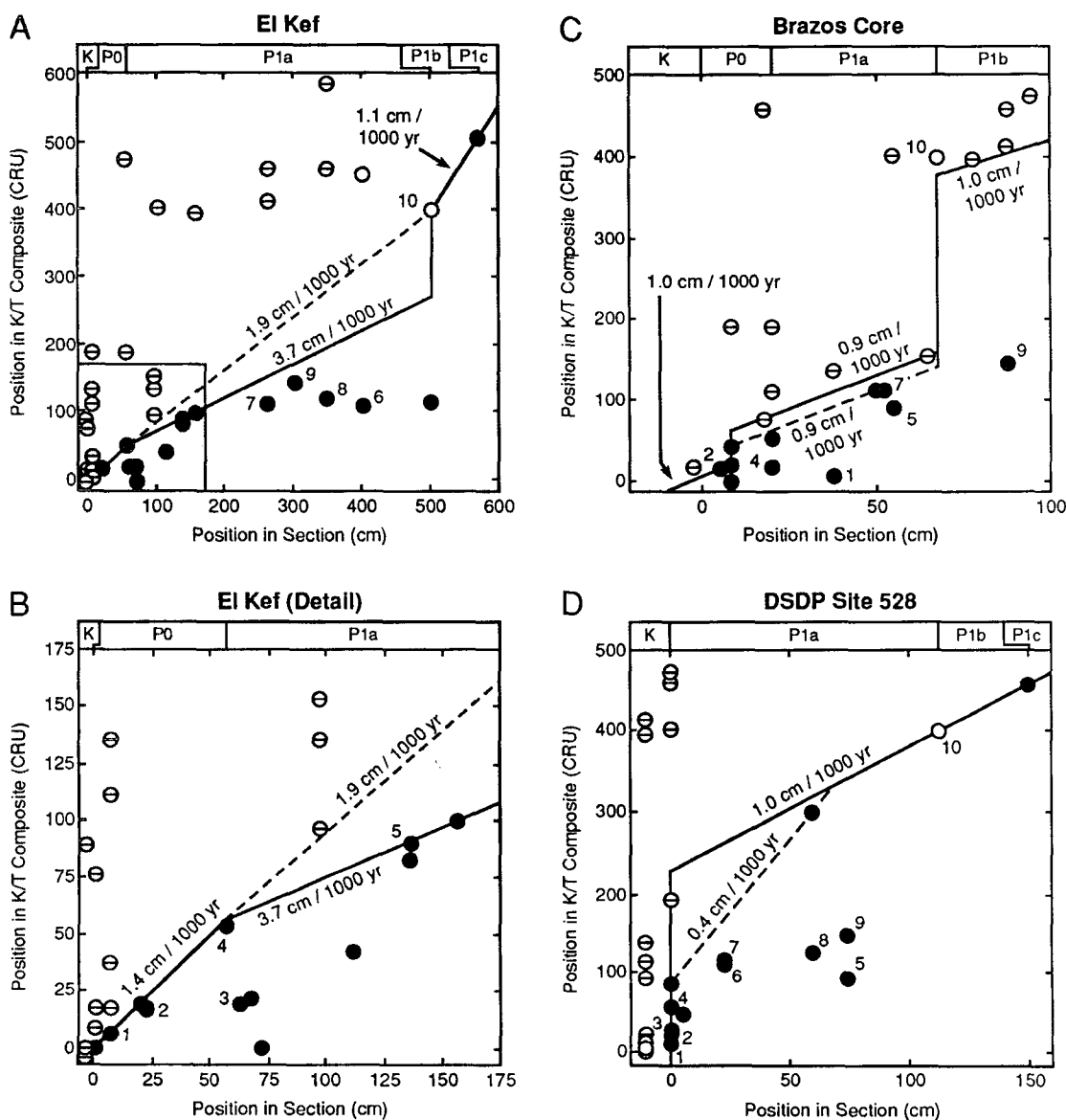


Figure 2. Graphic correlations with K/T composite. A: El Kef, 0-600 cm. B: El Kef (detail), 0-175 cm. C: Brazos core. D: DSDP Site 528 (D). O = last-appearance datum (LAD) of Tertiary taxa, Θ = LAD of Cretaceous survivor taxa, \bullet = first-appearance datum (FAD). Datum numbers refer to following biostratigraphic events: 1 = *Eoglobigerina tringa* FAD, 2 = *Woodringina hornerstownensis* 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 in-

cised 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 Braggs 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 chronostratigraphic 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

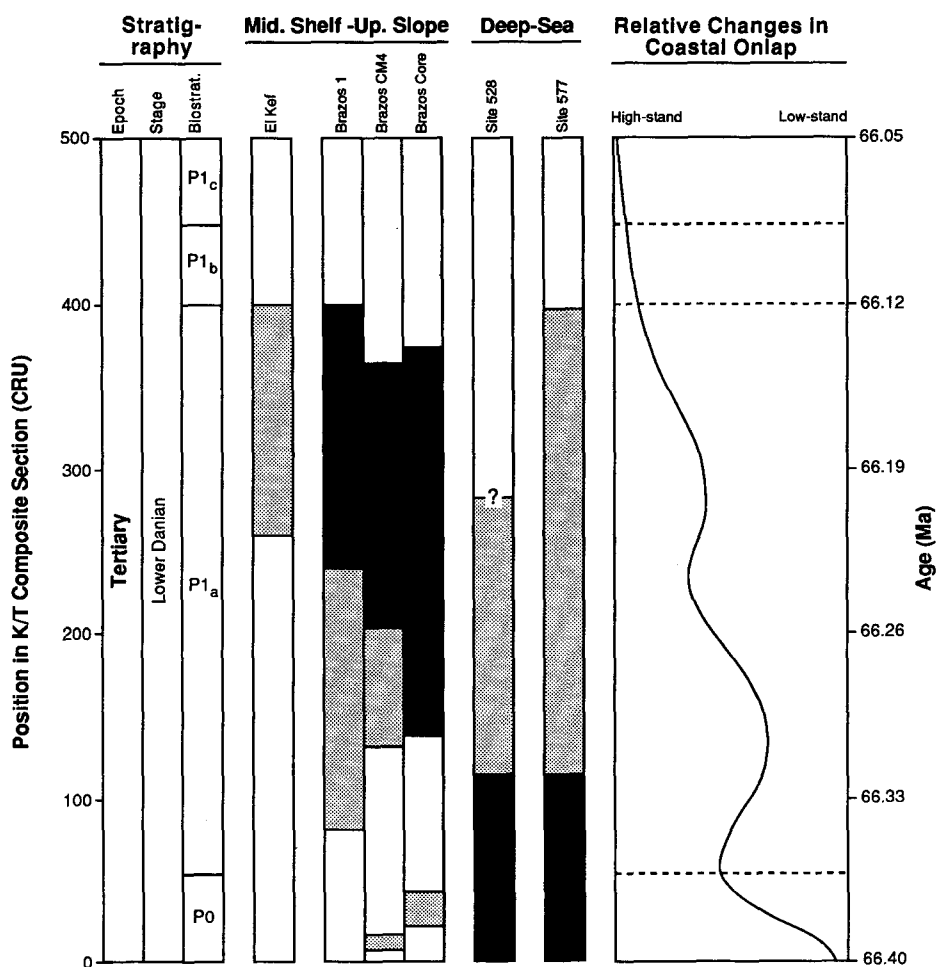


Figure 3. Extent and temporal distribution of lower Paleocene intrazonal hiatuses for sequences from El Kef, Tunisia; Brazos River, Texas; DSDP Site 528, Walvis Ridge, southeastern Atlantic; and DSDP Site 577, Shatsky Rise, western Pacific, plotted alongside K/T sea-level curve of Brinkhuis and Zachariasse (1988). White zones identify intervals of time present under both best-case and worst-case correlation models; patterned zones identify intervals of time present under best-case correlation model but missing under worst-case model; black zones identify intervals of time missing under both best-case and worst-case correlation models (see Fig. 2). CRU = composite reference units. Biostratigraphic zonation from Keller (1988a).

of marine productivity at the K/T boundary (Hsü 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 ~25 000 to 30 000 yr (Barrera and Keller, 1990). Finally, differences in the distribution of Ir anomalies (single vs. multiple) between deep-sea 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 deep-sea K/T boundary sequences—are, most likely, artifacts of a temporally incomplete deep-sea stratigraphic record.

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