How complete are Cretaceous/Tertiary boundary sections? A chronostratigraphic estimate based on graphic correlation

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ABSTRACT

Cogent interpretations of data bearing on the Cretaceous/Tertiary (K/T) extinction controversy depend on the existence of accurate chronostratigraphic models for the various K/T boundary sections. We have employed the graphic correlation technique to summarize biostratigraphic and lithostratigraphic data from 15 intensively sampled K/T boundary sections within a common chronostratigraphic model. Our results indicate that almost all of these sections, along with 13 additional boundary sections not used to construct the model, contain prolonged and in many cases multiple hiatuses. Of these 28 boundary sections, only six were found to contain a continuous record of sediment accumulation across the K/T boundary itself. These six K/T-complete sections are El Kef (Tunisia), Agost (Spain), Caravaca (Spain), and three sections along the Brazos River (Texas).

A comparative analysis of hiatus distributions among these 28 K/T boundary sections also reveals the presence of systematic differences between continental-shelf and deep-sea depositional environments. The lower Danian interval immediately following the K/T boundary, and extending into biochronozones P0 and P1a, is typically missing from the deep sea, whereas boundary sections deposited in shallower middle-neritic to upper-slope environments are in most cases complete across the K/T boundary. These shallow, neritic boundary sections, however, are in many instances disrupted by hiatuses at the P0/P1a boundary and again in the upper part of Zone P1a. These differential patterns of hiatus distribution between deep-sea and continental-shelf depositional settings appear to be linked to sea-level fluctuations. Our data suggest that the apparently sudden mass extinction of planktonic Foraminifera and anomalies in the occurrence of geochemical tracers that are characteristic of the K/T boundary in deep-sea sections may be artifacts of a temporally incomplete deep-sea stratigraphic record.

INTRODUCTION

Much recent controversy concerning the biotic response to environmental events that took place at or near the Cretaceous/Tertiary (K/T) boundary focuses on the question of time resolution. Although few geologists dispute the existence of a major late Maastrichtian–early Danian faunal turnover, estimates as to the time interval encompassed by this turnover range from as little as a few months (Alvarez and others, 1982; Smit, 1982, 1990) to as much as several hundred thousand years (Keller, 1989a, 1989b). Because the sheer magnitude of this discrepancy has hampered attempts to assess alternative causal scenarios, the nature of chronostratigraphic relationships within and among the various K/T boundary sections must be clearly understood by those engaged in making such assessments.

Until now, temporal completeness estimates for individual K/T boundary sections have been based almost entirely on raw biostratigraphic data. Perch-Nielsen and others (1982) have defined a "complete" K/T boundary marine sequence as one that includes "the uppermost Cretaceous coccolith zone of *Micula prinsii* and the so-called (K/T) boundary clay within the planktonic foraminifer zone of *Eoglobigerina fringa* [= *Guembelitria cretacea* Zone or Zone P0], followed by the *Parvularugoglobigerina eugubina* Zone = Zone P1a]." If this definition is used, stratigraphic sections at Caravaca, Spain (Romein, 1977; Smit, 1977, 1979, 1982; Perch-Nielsen and others, 1982); Zumaya, Spain (Percival and Fischer, 1977; Lamolda and others, 1983); Agost, Spain (Smit, 1990); El Kef, Tunisia (Perch-Nielsen, 1979, 1981a, 1981b; Brinkhuis and Zachariasse, 1988; Keller, 1988a, 1988b, 1989a); Lattengebirge, Germany (Herm, 1962; Herm and others, 1981); and Brazos, Texas (Jiang and Gartner, 1986; Keller, 1989a, 1989b) along with DSDP Sites 465 (Boersma, 1981), 528 (D'Hondt and Keller, 1991), and 577 (Gerstel and Thunell, 1986; D'Hondt and Keller, 1991) can all be identified as K/T-complete. It is widely recognized, however, that biostratigraphy, by itself, is an inadequate proxy for chronostratigraphy (see Hedberg and others, 1976). Owing to the possible existence of diachrony within biologically defined stratigraphic horizons and others, the simple occurrence of a zone-defining taxon provides no guarantee that the entire time interval encompassed by that taxon's biozone is necessarily present in any particular stratigraphic section (see Dowsett, 1988, 1989; Hills and Theirstein, 1989; Johnson and others, 1989).

On occasion (for example, Smit, 1977), lithostratigraphic criteria have also been used to infer the temporal completeness of K/T boundary sequences. One common example of this practice is the almost routine identification of the El Haria section at El Kef, Tunisia, as the "most complete" K/T boundary section on the basis of the lithostratigraphic thickness of its *M. prinsii*, *G. cretacea*, and *P. eugubina* biozones along with the relative thickness of the basal Tertiary black clay layer. This argument implicitly assumes strict isochrony for all zone-defining biostratigraphic datums and constancy in the rates of sediment accumulation at all boundary sections irrespective of local differences in depositional environment. Yet, many recent stratigraphic surveys have documented strong relationships between variation in rates of sediment accumulation and depositional setting (Schindel, 1980, 1982; Sadler, 1981; Anders and others, 1987), whereas Vail and others (1977), Haq and others (1987), Keller and Barron (1983, 1987), Keller and others (1987), and Haq (1990) have shown that similar relationships exist between sediment accumulation rates and changes in eustatic sea level. Therefore, neither biostratigraphic completeness nor the relative lithologic thickness of individual boundary sections *per se*, constitutes an appropriate criterion upon which to base accurate estimates of temporal completeness.

In order to provide more robust temporal-completeness evaluations for marine K/T boundary sections, we have undertaken the graphic corre-

lation (Shaw, 1964) of 15 intensively sampled boundary sections from North America, Spain, Europe, North Africa, and Israel, along with deep-sea cores from the southern Atlantic and western Pacific Ocean basins (Fig. 1). By quantitatively integrating both biostratigraphic and lithostratigraphic data from a large number of coeval sections, graphic correlation circumvents many of the problems inherent in the *a priori* assumption of either biostratigraphic isochrony or constant sediment-accumulation rates. This is accomplished by systematically comparing all sections in pairs and resolving inconsistencies in the relative placement of datums as dictated by those comparisons. In addition, the combined biostratigraphic/lithostratigraphic summaries that result from graphic correlation analysis have the advantage of being readily updated as more data become available.

On the basis of results obtained from these analyses, we have constructed a composite standard reference section (CSRS) consisting of a best estimate of the corrected global sequence of 75 latest Maastrichtian through early Danian (Zones P0-P1c) biostratigraphic datums. This K/T-CSRS was then used to infer the chronostratigraphy of these and other boundary sections. In this report, we demonstrate the presence of intrazonal hiatuses, provide a preliminary geochronologic estimate of their temporal duration, and assess the implications that these hiatuses hold for scenarios involving geologically instantaneous mass extinctions, sudden

changes in the productivity of surface waters, and abrupt enrichments or depletions in various isotopic, elemental, and mineral species at the K/T boundary.

METHODS

Biostratigraphic Database

The set of 15 primary boundary sections used to construct the K/T-CSRS includes Brazos River, Texas (Brazos 1, Brazos CM4, and Brazos Core sections); Caravaca, Agost, and Sopelana, Spain; Lattengebirge, Germany; El Kef, Tunisia; and Hor Hahar, Sinai, Ein Mor, Zofar, and Ben Gurion in Israel, along with DSDP Sites 528 and 577 (see references above). Each of these sections contains an abundant, well-preserved, and well-documented planktonic foraminiferal and calcareous nannoplankton biota. Moreover, with the exception of Sopelana and Lattengebirge, the datum levels for which were taken from Rocchia and others (1988) and Herm and others (1981), respectively, all planktonic foraminiferal data were generated by G.K., thereby insuring a consistent planktonic foraminiferal taxonomy.

In all, 68 planktonic foraminiferal and 7 calcareous nannoplankton
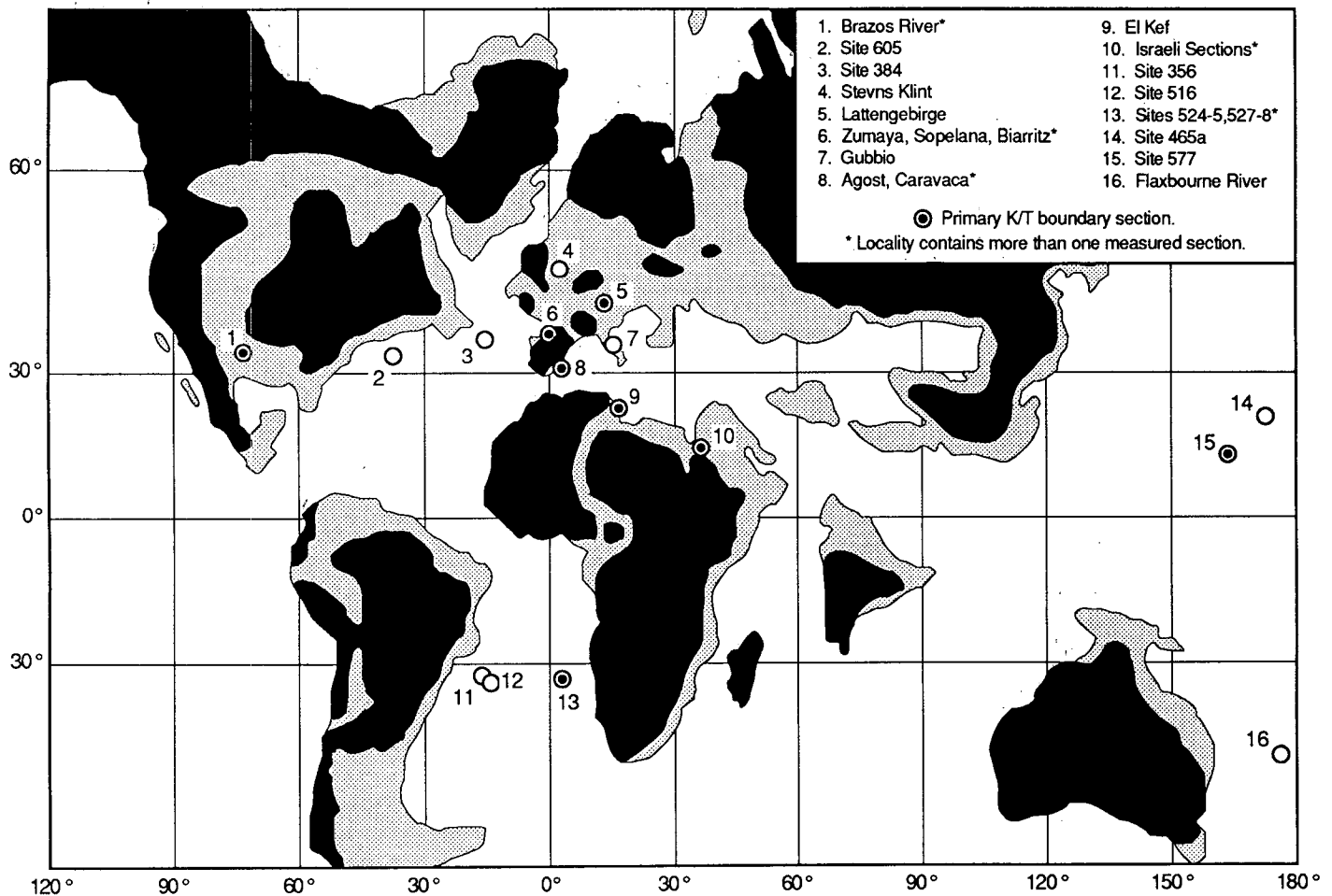

Figure 1. Locations of 28 K/T boundary sections examined in this study, plotted on a paleogeographic reconstruction of continental positions at the time of the K/T boundary (66.4 Ma). White, ocean basins; light stipple, continental platforms; black, inferred extent of terrestrial exposure. Reconstruction based on Denham and Scotese (1987), Stanley (1989), and Ziegler (1990).

TABLE 1. PROJECTION OF BIOSTRATIGRAPHIC EVENT DATUMS ONTO THE K/T COMPOSITE
STANDARD REFERENCE SECTION (K/T-CSRS)

Zone	Rank order	Taxon	Datum*	Depth†
	75	Cruciplacolithus primus	LAD	1000
	74	Eoglobigerina pentagona	LAD	950
	73	Eoglobigerina edita	LAD	950
	72	Morozovella trinidadensis	FAD	750
	71	Towiensus petalosus	FAD	674
	70	Guembelitria cretacea§	LAD	584
Plc	69	Cruciplacolithus primus	FAD	506
	68	Heterohelix globulosa§	LAD	474
	67	Heterohelix navarroensis§	LAD	459
	66	Heterohelix striata§	LAD	459
	65	Morozovella inconstans	FAD	458
	64	Globastica conusa	FAD	453
	63	Subbotina varianta	FAD	448
	62	Globotruncanella caravacaensis§	LAD	413
Plb	61	Hedbergella holmdelensis§	LAD	413
	60	Biscutum parvulum	FAD	406
	59	Pseudotextularia costulata§	LAD	402
	58	Parvularugoglobigerina eugubina	LAD	400
	57	Parvularugo. longiapertura	LAD	400
	56	Globigerinelloides aspera§	LAD	396
	55	Globanomalina compressa	FAD	379
	54	Eoglobigerina trivialis	FAD	297
	53	Globotruncanella subcarinatus§	LAD	190
	52	Pseudotextularia kempensis§	LAD	190
	51	Rugoglobigerina hexacamerata§	LAD	190
	50	Planoglobulina carseyae (s.l.)§	LAD	154
	49	Eoglobigerina pentagona	FAD	145
Pla	48	Globigerinelloides volutus§	LAD	136
	47	Heterohelix glabrans§	LAD	136
	46	Subbotina pseudobulloides	FAD	122
	45	Subbotina triloculinoides	FAD	115
	44	Globastica daubjergensis	FAD	113
	43	Pseudotextularia costata§	LAD	112
	42	Rugoglobigerina rugosa§	LAD	112
	41	Subbotina moskvini	FAD	111
	40	Heterohelix pulchra§	LAD	111
	39	Globanomalina planocompressa	FAD	100
	38	Heterohelix planata§	LAD	97

Rank order	Taxon	Datum*	Depth†	Zone
37	Globigerina taurica	FAD	91	
36	Hedbergella monmouthensis§	LAD	90	
35	Chiloguembelina midwayensisFAD	83		Pla
34	Rugoglobigerina macrocephala§	LAD	77	
33	Markalius inversus	FAD	70	
32	Parvularugo. longiapertura	FAD	54	
31	Parvularugoglobogerina eugubina	FAD	53	
30	Globastica sp.	FAD	43	
29	Pseudotextularia punctulata§	LAD	38	
28	Eoglobigerina eobulloides	FAD	22	
27	Eoglobigerina edita	FAD	20	
26	Biscutum romeini	FAD	20	
25	Globastica conusa	FAD	18	
24	Globotruncana arca§	LAD	18	PO
23	Pseudotextularia deformis§	LAD	18	
22	Rugoglobigerina robusta§	LAD	18	
21	Woodringina hornerstownensis	FAD	17	
20	Rugoglobigerina scotti§	LAD	9	
19	Eoglobigerina fringa	FAD	7	
18	Pseudoguembelina palpebra§	LAD	7	
17	Abathomphalus mayaroensis	LAD	0	
16	Eoglobigerina simplissima	FAD	0	
15	Globotruncana aegyptiaca	LAD	0	
14	Globotruncanita conica	LAD	0	
13	Globotruncanita stuarti	LAD	0	
12	Planoglobulina brazoensis	LAD	0	
11	Pseudotextularia elegans	LAD	0	
10	Racemiguembelina powelli	LAD	0	A. mayaroensis / P. deformis
9	Racemiguembelina intermedia	LAD	0	
8	Racimeguembelina fructicosa	LAD	0	
7	Biantholithus sparsus	FAD	0	
6	Globotruncanella havaensis	LAD	-5	
5	Globotruncanita contusa	LAD	-5	
4	Gublerina cuvilieri	LAD	-5	
3	Planoglobulina multicamerata	LAD	-5	
2	Globotruncana trinidadensis	LAD	-5	
1	Planoglobulina carseyae (s.s.)	LAD	-25	

*LAD, last-appearance datum; FAD, first-appearance datum.
†Projected spatial position given in composite standard reference units (CSRU); K/T boundary, 0.
§Cretaceous survivor taxon.

datum events, extending from the uppermost Cretaceous through Zone Plc, were used in K/T–CSRS construction (Table 1). In order to assemble the planktonic foraminiferal biostratigraphic database, each one of the >1,000 individual samples was washed through a 63-μm screen to remove the fine fraction and then randomly split into an aliquot containing approximately 300 specimens. Each specimen within the aliquot was then identified, counted, and mounted on a microslide for reference. Calcareous nannoplankton datum levels were supplied by Romein (1982), Perch-Nielsen and others (1982), Jiang and Gartner (1986), Rocchia and others (1988), and S. Gartner (1990, personal commun.), with the relatively small number of datums reflecting the present lack of a high-resolution K/T biostratigraphy for this organismal group.

The El Kef, Brazos River, and southeastern Spain sections were sampled continuously at the centimeter scale from 50 cm below the K/T boundary to 1.75 m above the boundary and then at between 2 and 5 samples per meter thereafter (see Keller 1988a, 1988b, 1989a, 1989b). The Israeli sections were sampled at 5-cm intervals from the K/T boundary through a black clay layer located from 1.5 to 3 m above the boundary, with sample spacing gradually increasing to 1 sample every 25 cm thereafter (Keller and Benjamini, 1991). DSDP Site 528 was sampled at 20-cm intervals throughout, except for a 1.5-cm subinterval containing the K/T boundary clay. Two samples were taken within this subinterval (see D'Hondt and Keller, 1991). DSDP Site 577 was sampled at 4-cm intervals from 11 cm below to 42 cm above the K/T boundary and at irregular intervals that did not exceed 1 sample every 60 cm thereafter (D'Hondt and Keller, 1991).

Temporal-completeness estimates were also attempted for 13 additional (secondary) boundary sections, including Stevns Klint, Denmark; Gubbio, Italy; Zumaya, Spain; Biarritz, France; and Flaxbourne River, New Zealand, along with DSDP Site 465 in the western Pacific; Sites 356, 516, 524, 525, and 527 in the South Atlantic; and Sites 384 and 605 in the North Atlantic. These secondary sections were not used to construct the K/T–CSRS, owing to a lack of sufficiently detailed biostratigraphic data and the relative absence of supplemental stratigraphic information (for example, detailed lithostratigraphy, stable isotopic logs, relative-abundance data). Figure 1 shows the locations of these 28 primary and secondary boundary sections on a paleogeographic reconstruction of continental positions at the K/T boundary (66.4 Ma).

Graphic Correlation

Graphic correlation (Shaw, 1964; Miller, 1977; Edwards, 1984) was applied to this biostratigraphic database in order to (i) construct a composite estimate of the datum sequence, (ii) determine correlations between each boundary section and the K/T–CSRS, and (iii) provide a means whereby sediment accumulation rates and hiatus durations could be calculated (via interpolation) from available geochronologic data. Graphic correlation accomplishes these tasks by analyzing the spatial distribution of stratigraphic datum events among all pairs of sections in a quantitative manner (Fig. 2).

Aside from biostratigraphic data, a variety of nonpaleontological but chronostratigraphically informative events (for example, magnetic polarity

reversal horizons, key beds, relative-abundance logs, stable-isotope logs) can be included in any graphic correlation analysis to improve the overall correlation. Because the incorporation of this information often proves crucial in recognizing depositional hiatuses and changes in sediment accumulation rates (see Pisias and others, 1984, 1985; Hazel and others, 1984; Barron and others, 1985; Prell and others, 1986; Edwards, 1989; Hazel, 1989), our biostratigraphic database was coupled with data on the positions of key lithostratigraphic marker beds (for example, the red layer that in many cases, is found at the base of Zone P0), shifts in $CaCO_3$ abundance, changes in $\delta^{13}C$, and abrupt shifts in the relative abundance of both planktonic and benthonic foraminiferal taxa. Consequently, our K/T
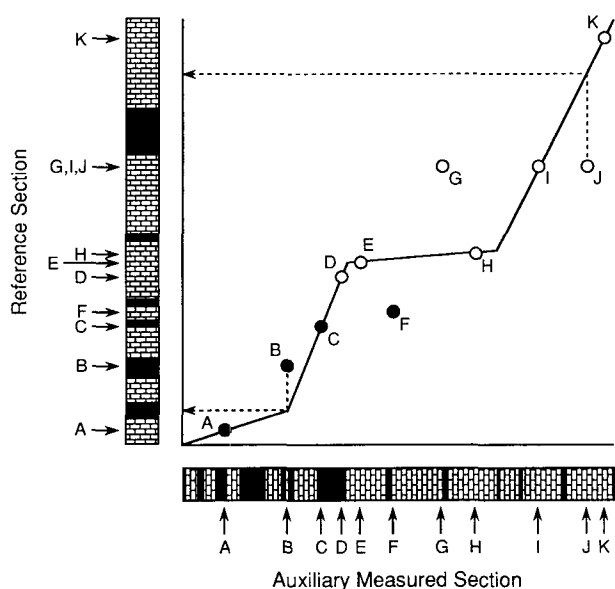

Figure 2. Illustration of the graphic correlation method. Given two stratigraphic sections, each of which contains 11 biostratigraphic datums (filled circles, first-appearance datums or FAD's; open circles, last-appearance datums or LAD's), the correlation between these sections can be expressed as that line which best maps the position of datums in one section onto their corresponding positions in the other. FAD's and LAD's located on or near the line of correlation (LOC) (datums A, C, D, E, H, I, and K) represent events that occur at approximately the same temporal horizon in each section, whereas those located at some distance from the LOC (datums B, F, G, and J) are indicative of intersection temporal diachrony. If the datum sequence on the y axis of such a plot is designated as a "reference" section, LAD's occurring below the LOC (datum J) and FAD's occurring above the LOC (datum B) represent datums that occupy (respectively) lower and higher horizons in the auxiliary section (x axis) than in the reference section (y axis). Because accurate chronostratigraphic correlation requires that only global highest and lowest occurrences be employed in relating depositional sequences to one another, erroneous (nonmaximal) occurrences of these datums in the reference section can be corrected by using a well-constrained LOC to estimate their appropriate positions (dashed lines). After this is done, the reference section becomes a composite estimate of the actual datum sequence or a composite standard reference section (CSRS). By performing several rounds of comparison between the CSRS and a set of auxiliary measured sections, a stable estimate of the global sequence of datums can be made.

boundary correlations are derived from a total stratigraphic database of >100 individual events.

El Kef was selected as the reference section upon which the K/T-CSRS was based. This section presents the longest (>10 m) of the 15 primary measured sections, has no obvious faults or structural complications, contains the largest percentage (83%) of the total datum set, and exhibits the smallest number of co-occurrences between datums. Edwards (1984) has recommended that auxiliary (measured) sections be admitted to the compositing process in order of their information content. This data admission protocol was employed throughout each compositing cycle, following an initial estimation of each boundary section's information content that was made according to the criteria used to select the reference section.

The most critical aspect of any graphic correlation study involves the placement of the line of correlation (LOC) that quantitatively expresses relative rates of sediment accumulation between any two measured sections. Although Shaw (1964) originally advocated the use of least-squares linear regression for this purpose, both Miller (1977) and Edwards (1984) have suggested that the judgment of the stratigrapher play a predominant role in LOC placement. This is sensible advice, particularly in situations in which the stratigrapher is employing a wide variety of data (some of which he or she did not personally collect) to infer the correlation. Besides, not all biostratigraphic datums are equally reliable. For instance, the first- and last-appearance datums of fossil species that constitute arbitrary subdivisions of a continuous morphological series are notoriously difficult to recognize. Similarly, a stratigrapher may suspect that the last few occurrences of a species in any particular section may be due to reworking, especially if these specimens show obvious discolorations, signs of physical abrasion, or a patchy stratigraphic distribution. Because these frequently encountered situations can have a dramatic effect on LOC placement, we consider the advantages gained by reintroducing a degree of stratigraphic/paleontologic judgment to outweigh any losses incurred by slightly increasing the overall idiosyncrasy of the result.

During construction of the K/T-CSRS, LOC placement was further constrained by the following guidelines: (i) that the datum sequence specified by established Upper Cretaceous through lower Danian biostratigraphic zonations (see Smit, 1982; Berggren and Miller, 1988; Keller, 1988a; Canudo and others, 1991; Keller and Benjamini, 1991) was maintained within the initial compositing cycle, and (ii) that correlations among sections located within the same depositional basin exhibit a general consistency. Given these criteria, three compositing cycles were needed to achieve a stable sequence of datum events on the K/T-CSRS (Table 1). As shown by Edwards (1984), datum levels constituting this K/T-CSRS may represent slight over-extensions of the actual stratigraphic ranges of these species. Given the high taxonomic consistency of the biostratigraphic database and the density with which all sections participating in CSRS formation were sampled, however, this sequence must be regarded as the most comprehensive and highly constrained global stratigraphic summary of the K/T transition currently available.

After a stable composite datum sequence has been achieved, the CSRS can be used to evaluate the chronostratigraphy of each boundary section that contributed to its construction. Although we agree that this composite section represents an estimate of the actual datum sequence, we regard a well-constrained estimate to be a more suitable correlation tool than is the a priori assumption of both biostratigraphic isochrony and temporal completeness in any single K/T boundary section. Nevertheless, it is important to take inherent variations in the distribution of LOC-defining datums into account when graphically estimating the temporal completeness of single sections. [Note: such variations can influence CSRS construction, leading to the possible over-extension of species ranges as

mentioned above. These errors, however, can, in theory, be detected either by scanning the compositing history of individual datums and re-evaluating those for which the CSRS positions were markedly changed on the basis of a single (miscorrelated?) section, or by expanding the stratigraphic database.] We have attempted to address this inherent uncertainty in the correlation of individual sections with the K/T–CSRS by developing "best-case" (section as temporally complete and sediment accumulation rates as constant as the majority of the data allow) and "worst-case" (section as temporally incomplete and sediment accumulation rates as variable as the majority of the data allow) alternatives. These best- and worst-case correlation models correspond to Miller's concept of the correlation channel (Miller, 1977, Text-Fig. 3) and provide a crude estimate of the boundaries within which the actual correlation is contained. Although we have tried to keep the number of LOC segments specified by our correlations to an absolute minimum, this should not be taken to mean that we fail to appreciate the dynamic nature of sediment accumulation in marine environments. Rather, we interpret these LOC segments to be representative of average sediment accumulation-rate trends that existed over comparatively long time intervals.

In evaluating these results, it should be kept in mind that reification of the geometric relationships between distributions of event datums in the K/T–CSRS and individual boundary sections is by no means a straightforward matter. CSRS estimation is a *spatial* process with changes in the sequence of datum levels taking place along an axis defined by the reference section. This has two important implications. First, the units of the CSRS are equivalent to the spatial units used to define event levels in the reference section; second, identical spatial distances in different parts of the CSRS may represent different intervals of absolute time. The fact that the CSRS is arrayed along a spatial rather than a temporal axis, however, in no way alters the chronostratigraphic interpretation of these results (Shaw, 1964; Miller, 1977). Discontinuities in the distribution of stratigraphic datum events and changes in the trend of a well-constrained LOC are real phenomena that have clear-cut chronostratigraphic implications regardless of whether we can accurately express them in terms of absolute time. Because causal hypotheses purporting to explain the K/T boundary extinctions are almost always described in terms of years (or some subdivision thereof), however, there exists a compelling need to provide the geological community with independent, theory-neutral estimates of temporal resolutions in K/T boundary sections based on empirical stratigraphic data. In order to meet this need, we have attempted a preliminary calibration of the K/T–CSRS to the widely used Paleogene time scale of Berggren and others (1985).

This calibration was achieved by comparing geochronologic age estimates (as given in Berggren and others, 1985) for the K/T boundary (66.40 Ma), the first-appearance datum (FAD) of *P. eugubina* (66.35 Ma), and the duration of the 29R magnetochron (570,000 yr) to the predicted position of these datums on the K/T–CSRS, using a least-squares linear regression of CSRS position on estimated geochronologic age (Fig. 3). The assumptions implicit in this calibration are that these dates provide the best available age assignments for these stratigraphic events and that the K/T–CSRS datum sequence is, to a first approximation, temporally linear. Although these assumptions are certainly open to question (for example, no attempt has been made to adjust the calibration to reflect the intrinsic error of estimation associated with each age assignment; see caption for Fig. 3), their equivalents are routinely used to evaluate event durations in a large number of geologic and paleontological contexts. Moreover, we believe that these assumptions are reasonable within the context of the present study for several reasons. Our calibration uses all of the available geochronologic data in a rigorous and verifiable manner. Resulting completeness estimates are also (by definition) consist-

ent with the standard geochronologic interpretation of this interval and may be readily modified as more radiometric age determinations are made. Furthermore, empirical analyses of these data indicate that the K/T–CSRS is, indeed, highly linear with respect to their radiometrically based ages despite some uncertainty as to the location of the top of magnetochron 29R in several primary boundary sections (Fig. 3). Irrespective of
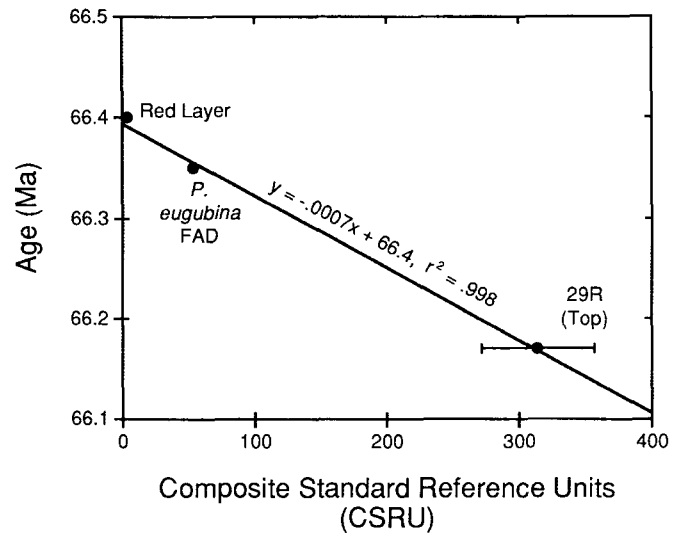

Figure 3. Linear model relating temporal positions of three correlatable events (occurrence of the basal Tertiary red boundary clay, the *P. eugubina* FAD, and the top of magnetochron 29R as given in Berggren and others, 1985) to their predicted positions on the K/T–CSRS (measured in composite standard reference units or CSRU). Age estimates for these three events were obtained by Berggren and others (1985), via interpolation, from their radiometric age calibration of the LaBrecque and others (1977) paleomagnetic reversal sequence. Calibration of the lower Paleogene part of this sequence is based on two radiometric age determinations: (i) an 84.0 Ma date from the Campanian-Santonian boundary (Anomaly 34y) based on K-Ar analysis of bentonites from the western interior of North America by Obradovich and Cobban (1975) and (ii) a 49.5 Ma date for Anomaly 21y based on K-Ar analyses of lavas and tuffs from the western United States by Flynn (1983a, 1983b). Although errors on these dates are substantial (~1.0 m.y.), they do not affect either the age calibration of the magnetic reversal sequence or the age estimates (via interpolation) of individual biostratigraphic events, owing to their similarity of magnitude. Although no attempt was made to take this intrinsic error of absolute age estimation into account within the preliminary calibration model, Berggren and others (1985) indicated that they regard this error to be less than 50,000 yr (as evidenced by their distinction between the K/T boundary at 66.40 Ma and the *P. eugubina* FAD at 66.35 Ma). Uncertainty as to the spatial position of the top of chron 29R on the K/T–CSRS results from differing magnetic sampling densities in the sections from which this datum was obtained, along with variations in the correlation of these sections to the K/T–CSRS. Error bars on the plot represent the entire range of positional estimates for this datum. The transfer function shown is based on a least-squares regression of spatial position (in the K/T–CSRS) on time using the mean of the 29R position data. The very high degree of linearity exhibited by these data is indicated by the large coefficient of determination.
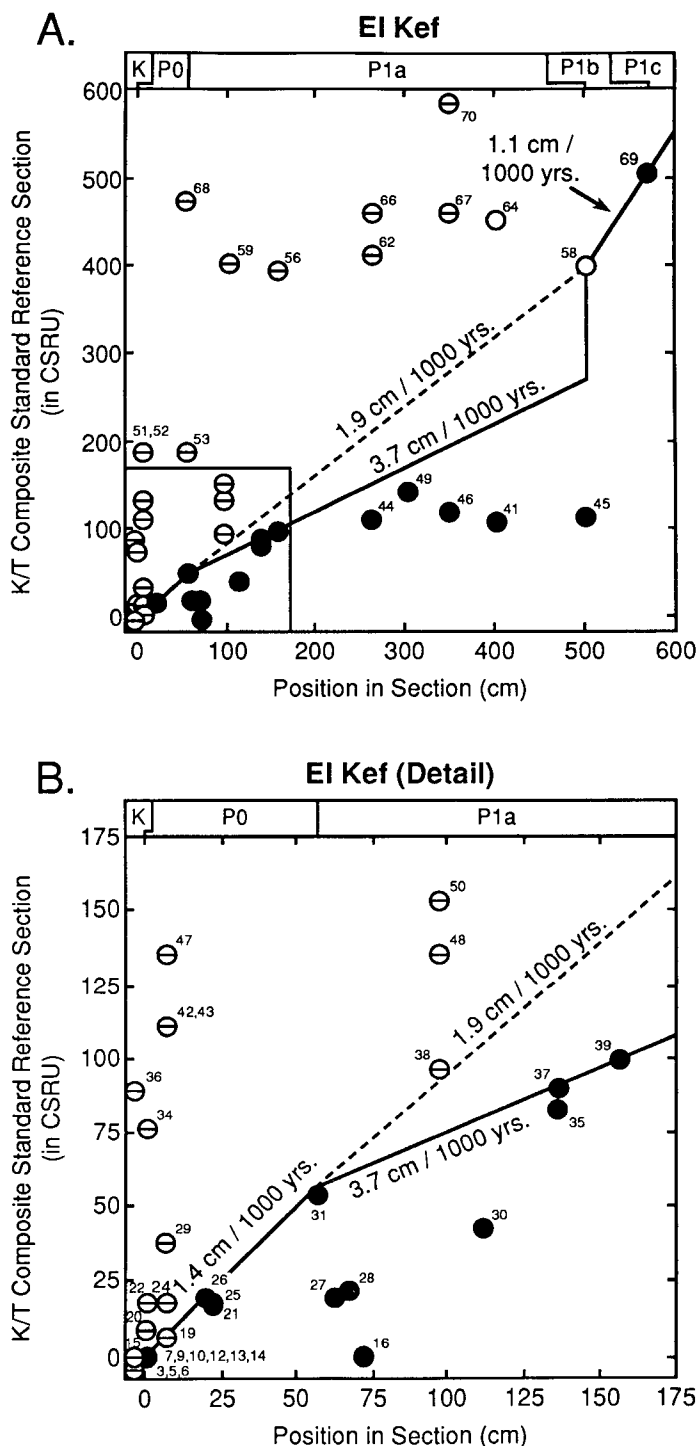
Figure 4. Graphic correlation for the El Kef section with the K/T–CSRS. (A) Distribution of biostratigraphic datums within the first 6 m of the section. (B) Distribution of biostratigraphic datums in the first 1.75 m after the K/T boundary (represented by the square in the lower left-hand corner of part A). Note the widespread diachroneity of biostratigraphic datums in this section when compared to the K/T–CSRS. Circles, LAD's of Tertiary taxa; circles with bars, LAD's of Cretaceous survivor taxa; filled circles, FAD's. Datum numbers refer to datum rank orders given in Table 1. Solid LOC's, worst-case model; dashed LOC's, best-case model (see text). Inclined LOC's define intervals of net sediment accumulation. Vertical LOC's mark the lithologic positions (x axis) and relative temporal durations (y axis) of hiatuses. Biostratigraphic zonation above each plot is that of Keller (1988a, 1989a). Sediment accumulation rates based on preliminary geochronologic calibration of the K/T–CSRS (Fig. 3). Data from Keller (1988a). Biostratigraphic zonation is that of Keller (1989a).

which spatial position is used for this latter datum, the product moment correlation coefficient between these radiometric and spatial age data is never less than 0.96. Last, sediment accumulation rates calculated on the basis of this temporal calibration agree well with expectations derived from the study of equivalent modern depositional environments. Although we emphasize that our spatially based chronostratigraphic interpretations are logically distinct from the preliminary geochronologic calibration of the K/T–CSRS, we believe that our admittedly crude but internally consistent and stratigraphically data-based method for relating spatial separations among event horizons to absolute geologic time is preferable to the unbridled chronostratigraphic speculation that has characterized much of the last decade of K/T boundary controversy.

RESULTS

Cretaceous Planktonic Foraminiferal Survivors

Thirty-five percent of the datum events included in Table 1 are Cretaceous planktonic Foraminifera for which the last-appearance datums (LAD's) have been observed to extend into the lowermost Danian. Most previously published accounts of lower Danian biostratigraphy have attributed the occurrence of these species in unquestionably Danian strata to redeposition rather than *in situ* survivorship. We believe that this traditional explanation is no longer valid in all cases for the following reasons: (i) comparative (graphic) analyses of these biostratigraphic data reveal the survivor fauna to be present in the majority of well-studied, biostratigraphically complete boundary sections; (ii) there is no sedimentological or stratigraphic evidence for significant reworking in K/T boundary sections containing the survivor fauna; (iii) if major sediment mixing had occurred in these sections, we would expect to see other Cretaceous species (for example, *Rugoglobigerina, Globotruncana*), in addition to the characteristic survivor fauna, in lower Danian strata; and (iv) recent stable-isotopic analysis of faunas collected at Brazos River, Texas (Barrera and Keller, 1990), has shown that at least two Cretaceous survivor species (*H. globulosa* and *G. cretacea*) exhibit a $2^{0}/_{00}$ to $3^{0}/_{00}$ $\delta^{13}C$ difference between Maastrichtian and Danian samples. This unique isotopic signature indicates that these Danian specimens could not have been derived from the underlying Upper Cretaceous fauna, but existed in early Danian oceans as extant, living populations. Isotopic analyses of other K/T boundary survivor species are currently underway.

El Kef, Tunisia

Correlation between the K/T–CSRS and the El Haria section near El Kef, Tunisia, is shown in Figure 4. Although this boundary section has been widely recognized as containing the most extensive accumulation of lower Paleocene sediments and the most complete lower Danian planktonic foraminiferal fauna, our results show that a large number of these taxic first and last appearances present within the El Kef sections are diachronous with respect to their positions in other K/T boundary sections. Nevertheless, our data also indicate that the K/T transition at El Kef

may be interpreted both to be temporally complete and to exhibit the highest relative sediment accumulation rate of any section considered in this study.

On the basis of the distribution of 64 biostratigraphic datums contained within the El Kef section (Keller, 1988a), a best-case model can be readily developed in which El Kef is inferred to be both biostratigraphically and temporally complete. This model suggests that sediment accumulation rates remained approximately constant across the K/T boundary and throughout Zone P0, after which they increased slightly. Preliminary geochronologic calibration of the K/T-CSRS suggests that these time-averaged accumulation rates may have been as high as 1.9 cm/1,000 yr. Although this best-case model is consistent with the pattern of biostratigraphic first- and last-appearance datums, the position of the LOC from the Zone P0/P1a boundary to the end of Zone P1a is not well constrained. In addition, this best-case model fails to account for abrupt changes in a variety of other El Kef stratigraphic data (discussed below).

Alternatively, a worst-case correlation model for El Kef suggests that average rates of sediment accumulation may have been much greater during the lower part of Zone P1a (estimated to range as high as 3.7 cm/1,000 yr) and that deposition was truncated by either an intrazonal hiatus or interval of active erosion at the top of this biochronozone. Preliminary geochronologic calibration of this worst-case model indicates that as much as 120,000 yr of sediment accumulation may be missing from the section. This interpretation is based on the assumption that the LAD's of *S. moskvini*, *G. daubjergensis*, *S. triloculinoides*, *S. pseudobulloides*, and *E. pentagona* appear at El Kef close to their global maxima. The El Kef worst-case model also provides an explanation for a variety of other stratigraphic data, including (i) the sudden appearance of foraminiferal specimens >150 μm in 4 separate planktonic lineages (Keller, 1988a); (ii) the abrupt appearance of 3 benthonic foraminiferal species (Keller, 1988b), and sudden changes in the relative abundance of 4 different benthonic foraminiferal species (Keller, 1988b); (iii) abrupt shifts in the paleodepth of deposition and oxygen levels as inferred from ostracode (Peypouquet and others, 1986), dinoflagellate (Brinkhuis and Zachariasse, 1988), and benthonic foraminiferal (Keller, 1988b) data; and (iv) a local CaCO₃ percent abundance maximum (Keller and Lindinger, 1989), all of

which are coincident with the graphically predicted position of an upper Zone P1a hiatus (Fig. 5). This putative hiatus event is also supported regionally by coeval hiatuses in nearby Spanish and Israeli sections (see below).
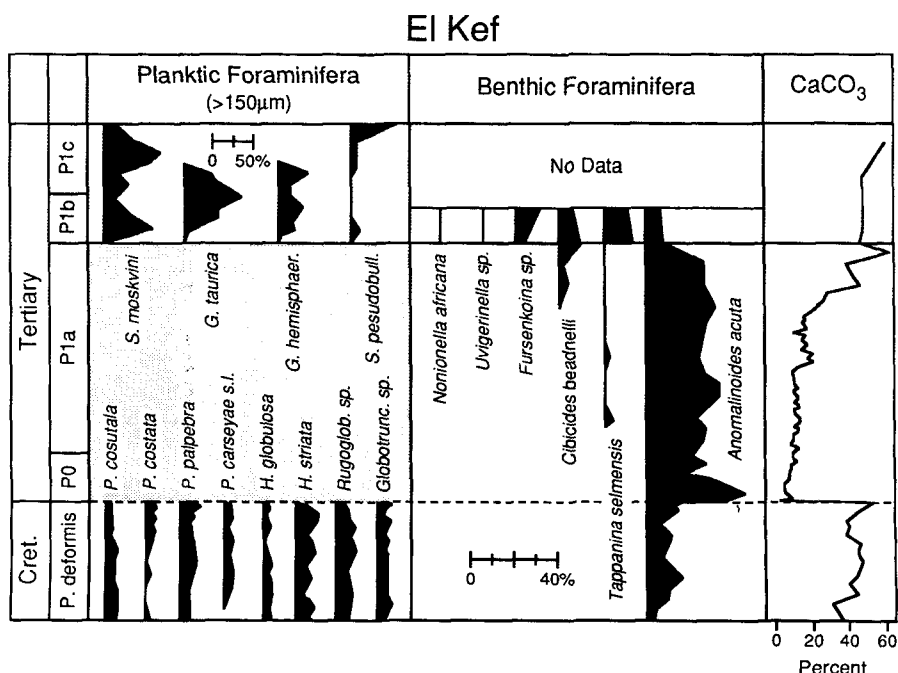
Brazos River, Texas

Correlations between the K/T-CSRS and the Brazos River sections (Brazos 1, Brazos CM4, and Brazos Core) are shown in Figure 6. Graphic correlation of the 44 biostratigraphic datum events present in these sections indicates that each section appears to be missing part of the upper part of Zone P1a and to contain either a short interval of nondeposition or a hiatus within Zone P0. Our biostratigraphically based analyses, however, do indicate that continuous sediment accumulation occurred across the K/T boundary at these Brazos River sections.

In addition to the geometry of LAD and FAD distributions, much physical and paleoecological evidence supports the inference of a Zone P1a hiatus in the Brazos CM4 and Brazos Core sections. At Brazos CM4, Keller (1989a, 1989b) reported "A small unconformity is present 1 m above the K/T boundary marked by sand and glauconite and overlain by silty clay." A similar unconformity was observed by Keller (1989a) 85 cm above the K/T boundary at Brazos Core. Keller's placement of hiatuses at these positions is corroborated by graphic analyses of the biostratigraphic data (Figs. 6B and 6C). This upper Zone P1a hiatus is also characterized by abrupt increases in the relative abundance of *Eoglobigerina* spp. and *G. daubjergensis*, along with the simultaneous disappearance of *H. globulosa*, *H. navarroensis*, *G. aspera*, and *P. carseyae s.l.* (Fig. 7A). Presence of the upper Zone P1a hiatus at Brazos 1, although not necessitated by available biostratigraphic data, is nevertheless inferred on the strength of the evidence from the other two Brazos River sections and their geographic proximity to Brazos 1.

Evidence supporting recognition of a hiatus or interval of nondeposition within Zone P0 in both the Brazos CM4 and Brazos Core sections is provided by the simultaneous appearance of *E. fringa* and *W. hornerstownensis* at Brazos CM4 (Fig. 6B), along with the coincident appearance of *E. fringa*, *E. eobulloides*, and *Globastica* sp. at Brazos Core (Fig. 6C).

El Kef

Figure 5. Relative-abundance data and event-datum distributions supporting recognition of the upper Zone P1a hiatus in the El Kef section. Hiatus level is marked by a solid horizontal line, whereas the K/T boundary is marked by a dashed horizontal line. Stippled pattern indicates the complete absence of any planktonic Foraminifera >150 μm in diameter from this stratigraphic interval. Data from Keller and others (1988a, 1988b), Keller and Lindinger (1989), Peypouquet and others (1986), and Brinkhuis and Zachariasse (1988). Biostratigraphic zonation is that of Keller (1988a).
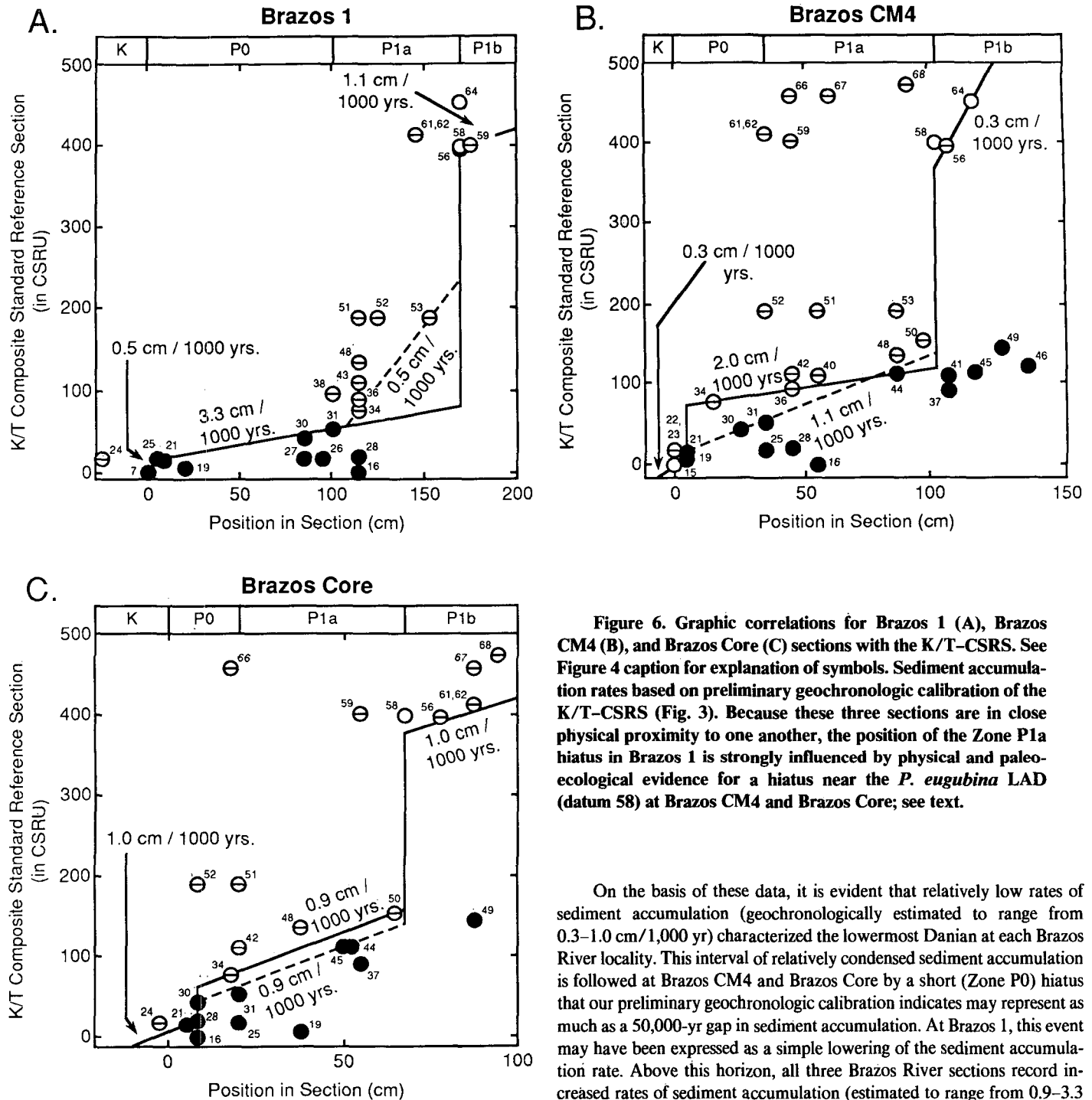
A. Brazos 1

B. Brazos CM4

C. Brazos Core

Figure 6. Graphic correlations for Brazos 1 (A), Brazos CM4 (B), and Brazos Core (C) sections with the K/T–CSRS. See Figure 4 caption for explanation of symbols. Sediment accumulation rates based on preliminary geochronologic calibration of the K/T–CSRS (Fig. 3). Because these three sections are in close physical proximity to one another, the position of the Zone P1a hiatus in Brazos 1 is strongly influenced by physical and paleoecological evidence for a hiatus near the *P. eugubina* LAD (datum 58) at Brazos CM4 and Brazos Core; see text.

On the basis of these data, it is evident that relatively low rates of sediment accumulation (geochronologically estimated to range from 0.3–1.0 cm/1,000 yr) characterized the lowermost Danian at each Brazos River locality. This interval of relatively condensed sediment accumulation is followed at Brazos CM4 and Brazos Core by a short (Zone P0) hiatus that our preliminary geochronologic calibration indicates may represent as much as a 50,000-yr gap in sediment accumulation. At Brazos 1, this event may have been expressed as a simple lowering of the sediment accumulation rate. Above this horizon, all three Brazos River sections record increased rates of sediment accumulation (estimated to range from 0.9–3.3 cm/1,000 yr) followed by a second intrazonal hiatus that includes the upper part of Zone P1a. Age calibration of the K/T–CSRS suggests that the duration of this hiatus might vary from 110,000–220,000 yr, depending on the section and stratigraphic model employed in its estimation.

Caravaca and Agost, Southeastern Spain

At Caravaca and Agost, sediment accumulation from the K/T boundary through lower Zone P0 appears to have proceeded at a lower rate (estimated to be no higher than 0.2 cm/1,000 yr) than is observed at either El Kef or the Brazos River sections (Fig. 8A). In the upper part of

Abrupt changes in the relative abundances of *W. hornerstownensis* (including *W. claytonensis*) and *Guembelitria* sp. also occur at this same horizon (Fig. 7B). Although it seems likely that the Zone P0 hiatus is also present at Brazos 1, the comparatively small number of biostratigraphic datums recorded within Zone P0 hinders a definitive interpretation (Fig. 6A). Nevertheless, extrapolated LOC-segment orientations based on the available Brazos 1 data seem to imply that a marked change in the sediment accumulation did occur at a position that generally corresponds to the Zone P0 hiatus within Brazos CM4 and Brazos Core.

A. Brazos Core
(Upper Zone P1a Hiatus)

B. Brazos Core
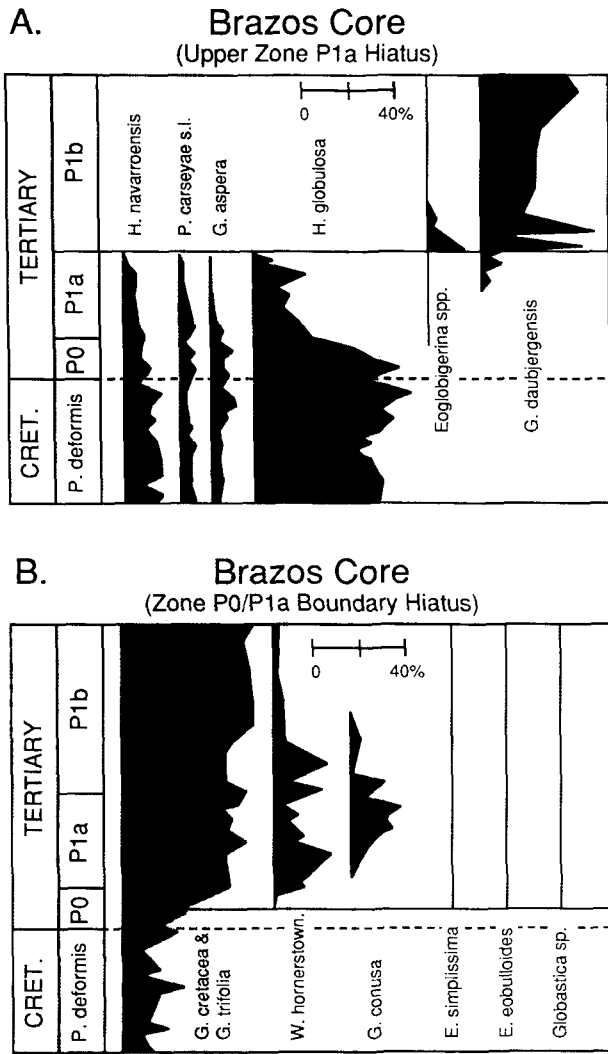### (Zone P0/P1a Boundary Hiatus)

Figure 7. Relative-abundance data and event-datum distributions supporting recognition of the upper Zone P1a (A) and Zone P0/P1a boundary (B) hiatuses in the Brazos Core section. Hiatus levels are marked by solid horizontal lines, whereas the K/T boundary is marked by a dashed horizontal line. See text for discussion. Data from Keller (1989b). Biostratigraphic zonation is that of Keller (1988a).

this zone, however, our graphic correlations suggest two alternative LOC arrangements for each section: a best-case model in which very low sediment accumulation rates persist through the remainder of Zone P0, and a worst-case model in which the sediment accumulation rate increases slightly within the lower part of the zone but, in turn, is truncated by a small hiatus or interval of nondeposition in upper Zone P0 that extends at

Figure 8. Graphic correlations for the Caravaca (A) and Agost (B) sections with the K/T–CSRS. See Figure 4 caption for explanation of symbols. Sediment accumulation rates based on preliminary geochronologic calibration of the K/T–CSRS (Fig. 3). Data from Canudo and others (1991). Biostratigraphic zonation is that of Keller (1989a).

least to the Zone P0/P1a boundary. These geometric discontinuities in the correlation between Caravaca/Agost and the K/T–CSRS are mirrored by either the abrupt appearance and/or sudden changes in the relative abundance of *Guembelitria* (*cretacea* and *trifolia*), *E. cf. edita*, *G. conusa*, and *P. longiapertura* (Fig. 9).

Sediment accumulation rates in these southern Spanish sections undoubtedly increased within the lower part of Zone P1a, after which, again, a relative paucity of FAD's and LAD's allows for both complete and

A. Caravaca

B. Agost

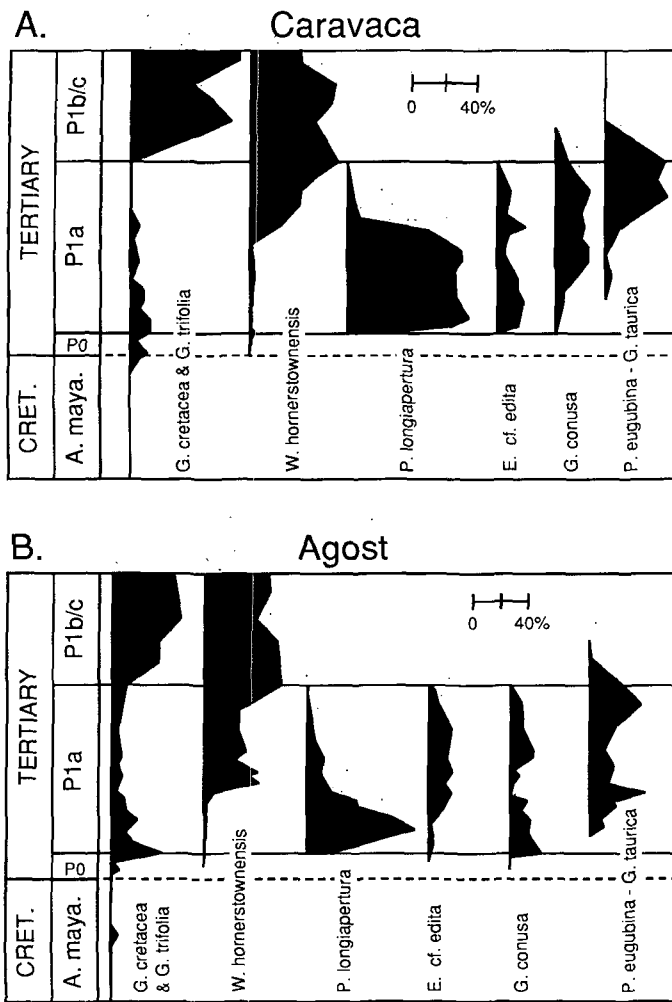## A. Caravaca

B. Agost

Figure 9. Relative-abundance data and event-datum distributions supporting recognition of the upper Zone P1a and Zone P0/P1a boundary hiatuses in the Caravaca (A) and Agost (B) sections. Hiatus levels are marked by solid horizontal lines, whereas K/T boundary is marked by a dashed horizontal line. Data from Canudo and others (1991). Biostratigraphic zonation is that of Keller (1989a).

incomplete sediment accumulation models to be postulated. Recognition of the upper Zone P1a hiatus as well as a short hiatus at the Zone P0/P1a boundary at both Caravaca and Agost is supported by sudden changes in the relative abundances of *G. cretacea*, *G. trifolia*, and *W. hornerstownensis*, along with the simultaneous disappearance of *P. longiapertura*, *E. cf. edita*, and *G. conusa* (see Fig. 9). In both sections, these events coincide with a sharp contact between the black basal boundary clay and overlying marly sediments. Thus, available stratigraphic data for Caravaca and Agost indicate that rates of sediment accumulation were not constant through the lower Danian and that substantial diachrony characterizes these biostratigraphic datum events. Although a best-case interpretation of these data is consistent with the conclusion that Caravaca and Agost both contain complete records of local faunal and environmental changes across the K/T boundary and throughout the lowermost Danian, the very low apparent rates of sediment accumulation called for by these correlations suggest that results of biostratigraphic, paleobiological, or geochemical analyses of samples from these sections will necessarily incorporate much greater degrees of time-averaging than comparable samples from other boundary sections (for example, El Kef, Brazos River).
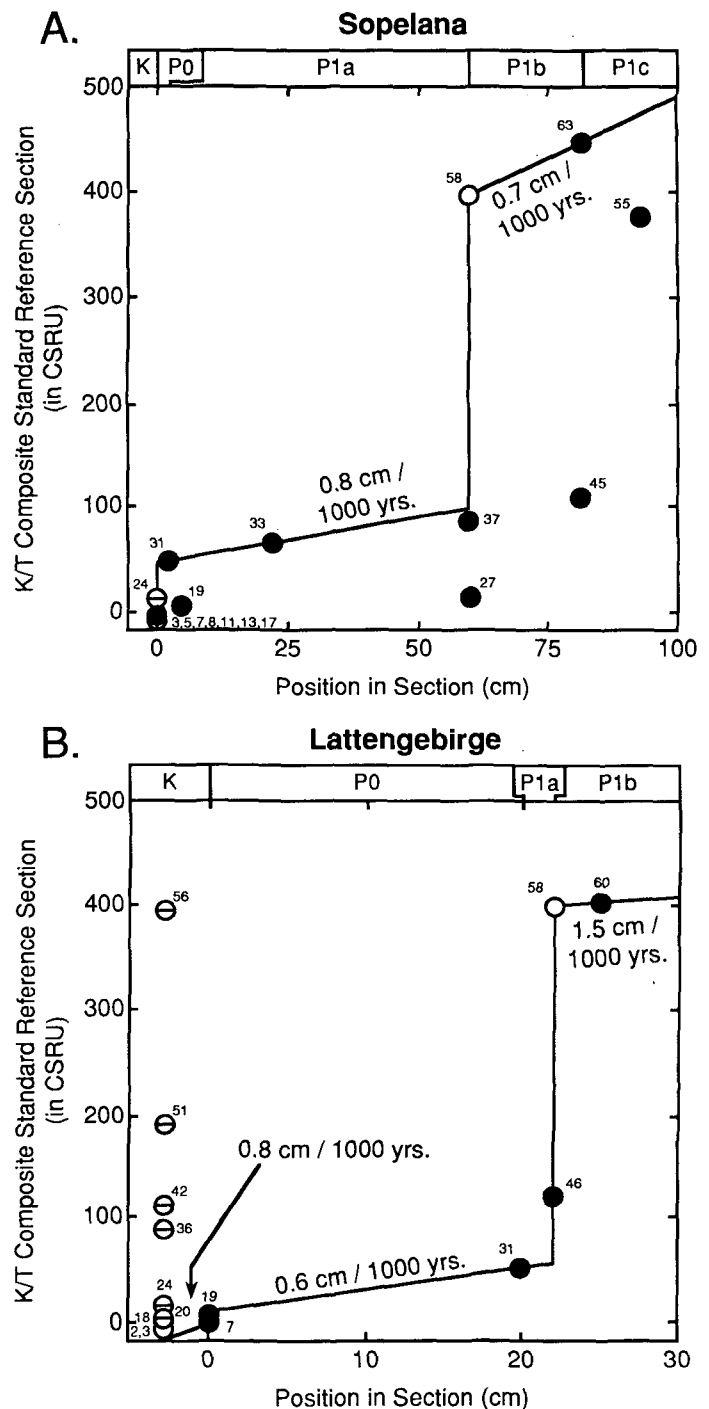
A. Sopelana

B. Lattengebirge

Figure 10. Graphic correlations for the Sopelana (A) and Lattengebirge (B) sections with the K/T-CSRS. See Figure 4 caption for explanation of symbols. Sediment accumulation rates based on preliminary geochronologic calibration of the K/T-CSRS (Fig. 3). Data from Lamolda (1983) and Herm and others (1981), respectively. Biostratigraphic zonation is that of Keller (1989a).

Sopelana, Northern Spain, and Lattengebirge, Germany

Patterns of sediment accumulation and hiatus distribution of Sopelana and Lattengebirge are very similar (Fig. 10) despite the relatively small number of datum events that have been recorded from each. Availa-

ble data from these sections, however, indicate the presence of at least two hiatuses. The first of these occurs just above a 2- to 3-mm red layer that, in many sections, coincides with the biostratigraphically defined K/T boundary. Co-occurrence of this red layer and the FAD of *E. fringa* at Lattengebirge suggests the presence of a very high degree of stratigraphic condensation within Zone P0, as these two datums are separated by 7 composite standard reference units (CSRU). At Sopelana, the red layer is separated from the FAD of *P. eugubina* by only 2 cm, implying the elimination of virtually all of Zone P0 (estimated by Berggren and others, 1985, to be 50,000 yr in duration). Location of the *P. eugubina* FAD 17 cm above the *E. fringa* FAD in the Lattengebirge section indicates that Zone P0 sediment accumulation rates may have been very low. Also, coincidence of the *S. pseudobulloides* FAD and *P. eugubina* LAD at Lattengebirge, and the *G. taurica* and *E. edita* FAD's with the *P. eugubina* LAD at Sopelana, suggests that prolonged depositional hiatuses are present within the upper part of Zone P1a in both of these European sections.

Negev Desert, Israel

Correlations of Israeli K/T boundary sections at Sinai, Zofar, Hor Hahar, Ben Gurion, and Ein Mor (Keller and others, 1990) with the K/T–CSRS are presented in Figure 11. During the Late Cretaceous and early Danian, these sections represented outer-shelf to upper-slope environments that were subject to intermittent coastal upwelling (Shemesh and Kolodny, 1988; Keller and others, 1990). Graphic comparison of biostratigraphic datum levels in these sections to the K/T–CSRS indicates that in addition to a K/T boundary hiatus, both Zone P0/P1a and upper Zone P1a hiatuses are present (Figs. 11 and 12).

Physical evidence supporting our interpretation of this highly fragmented lower Danian stratigraphic record includes the very short lithostratigraphic intervals containing Zones P0 and P1a in these sections, the absence of a distinct basal Tertiary boundary clay, and the abundant tan-colored angular microclasts derived from the underlying Maastrichtian sediments that are common within the gray lower Danian clays. We have observed no microclasts above Zone P1a in any other primary boundary section. These microclasts are most likely redeposited fragments of underlying lithified Maastrichtian sediments and are indicative of active current erosion.

Biostratigraphic evidence for a K/T boundary hiatus in these sections is based on anomalous co-occurrences of *E. edita*, *W. hornerstownensis*, *G. conusa*, *E. fringa*, and *E. eobulloides* FAD's (Fig. 11). The co-occurrence of these datum levels, that are separated by as much as 15 CSRU on the K/T–CSRS, suggests that most of Zone P0 is absent. Preliminary geochronologic estimates for this K/T boundary hiatus range as high as 10,000 yr. At least part of Zone P0 appears to be present in all of these Israeli sections except Hor Hahar, where the co-occurrence of *W. hornerstownensis*, *G. conusa*, *E. edita*, *P. eugubina*, and *P. longiapertura* FAD's implies that sediments assignable to Zone P1a lie directly on upper Maastrichtian strata (Fig. 11C).

Israeli sections at Sinai, Zofar, and Ein Mor also exhibit evidence for a second hiatus at or near the Zone P0/P1a boundary (Figs. 11A, 11B, 11E, and 12) in the form of the co-occurrence of *P. eugubina*, *P. longiapertura*, and *Ch. midwayensis* FAD's. These taxa are separated by as much as 30 CSRU, implying the absence of a substantial time interval (geochronologically estimated to represent as much as 20,000 yr). Strong similarities between this Zone P0/P1a boundary hiatus in the Negev sections and coeval hiatuses at Brazos River, Agost, and Caravaca indicate that the effects of this oceanographic event were worldwide in scope.

Each of the Israeli sections exhibits a third and much longer stratigraphic hiatus corresponding to the upper Zone P1a hiatus observed in sections from Texas, southern Spain, Germany, and Tunisia (Figs. 11 and 12). Biostratigraphic evidence for this hiatus is provided by the co-

occurrence of *S. pseudobulloides*, *S. moskvini*, *G. taurica*, *G. compressa*, *G. pentagona*, and *G. daubjergensis* FAD's along with *P. eugubina* and *G. conusa* LAD's (Figs. 11 and 12). Although the chronologic dimensions of this upper Zone P1a hiatus vary among the Israeli sections, together they define an interval of approximately 160,000 yr.

DSDP Sites 528 and 577

Compared to the K/T boundary shelf sections in Tunisia, Texas, Spain, Germany, and Israel, patterns of sediment accumulation in deep-sea settings such as DSDP Sites 528 (Walvis Ridge) and 577 (Shatsky Rise) are of a decidedly different character (Fig. 13). Whereas varying amounts of Zone P0 sediments are typically present in middle-shelf to upper-slope sections, there is no evidence for the presence of this biozone in either of these two deep-sea sites. Instead, available biostratigraphic evidence strongly supports the recognition of a basal Tertiary hiatus in both cores. This evidence includes the co-occurrence of *E. fringa*, *W. hornerstownensis*, *E. eobulloides*, *E. edita*, P. longiapertura, and *Ch. midwayensis* FAD's (Figs. 13 and 14). On the basis of our K/T–CSRS, co-occurrences of these datums would not be expected until the lower part of Zone P1a (Table 1). This biostratigraphic evidence is augmented by a sharp lithologic contact and an abrupt decrease in the percent abundance of $CaCO_3$ at the K/T boundary in both of these deep-sea cores (D'Hondt and Keller, 1991).

Although the evidence supporting recognition of this K/T boundary hiatus at Sites 528 and 577 is clear, the relatively impoverished planktonic foraminiferal faunas contained within these cores, along with the somewhat coarse sample spacing, greatly encumber our ability to infer the temporal limits of this deep-sea hiatus event. Consequently, the hiatus event limits shown in Figure 13 are based on assumptions of relatively constant sediment accumulation rates determined from a combination of FAD's and LAD's in the overlying strata. These limits should be regarded as approximations that will, it is hoped, be improved through high-resolution restudy of these and other deep-sea sections. On the basis of our present model, though, the basal Tertiary hiatus at Sites 528 and 577 is geochronologically estimated to represent a minimum of 60,000 yr.

Chronostratigraphy of Secondary K/T Boundary Sections

We have also compared published biostratigraphic descriptions of 13 additional K/T boundary sections with the K/T–CSRS in an effort to evaluate their chronostratigraphic fidelity (Fig. 15). The sampling of these sections was done on a much coarser scale than in the 15 primary boundary sections, and the available biostratigraphic database is, for the most part, limited to anecdotal notations of a few basal Tertiary index species. Although this lack of biostratigraphic detail, along with any ancillary stratigraphic data, severely limits our ability to evaluate the chronostratigraphy of these sections, a number of important generalizations can still be made.

Stevns Klint, Denmark. The widely discussed shallow-neritic K/T boundary section at Stevns Klint consists of a basal boundary clay that separates Maastrichtian from Danian limestones. Foraminifera in the 0- to 2-cm-thick basal black clay are dissolved, although a very poorly preserved assemblage is present in the interval from 2–10 cm above the boundary. This fauna contains *Globastica conusa*, *W. hornerstownensis*, and *Eoglobigerina danica* (unpub. data). In the absence of the critical *P. eugubina* datum, this particular assemblage of species could occur anywhere within the P0 through P1c interval (Table 1). No planktonic Foraminifera have been recovered from the interval between 10 and 20 cm above the K/T boundary, although at 25 cm, a well-preserved assemblage containing abundant *G. daubjergensis* and *S. pseudobulloides*, but, again, lacking *P. eugubina*, was found (Hofker, 1960; Cepek and Moorkens, 1979; G. Keller, unpub. data). The faunal record of this upper
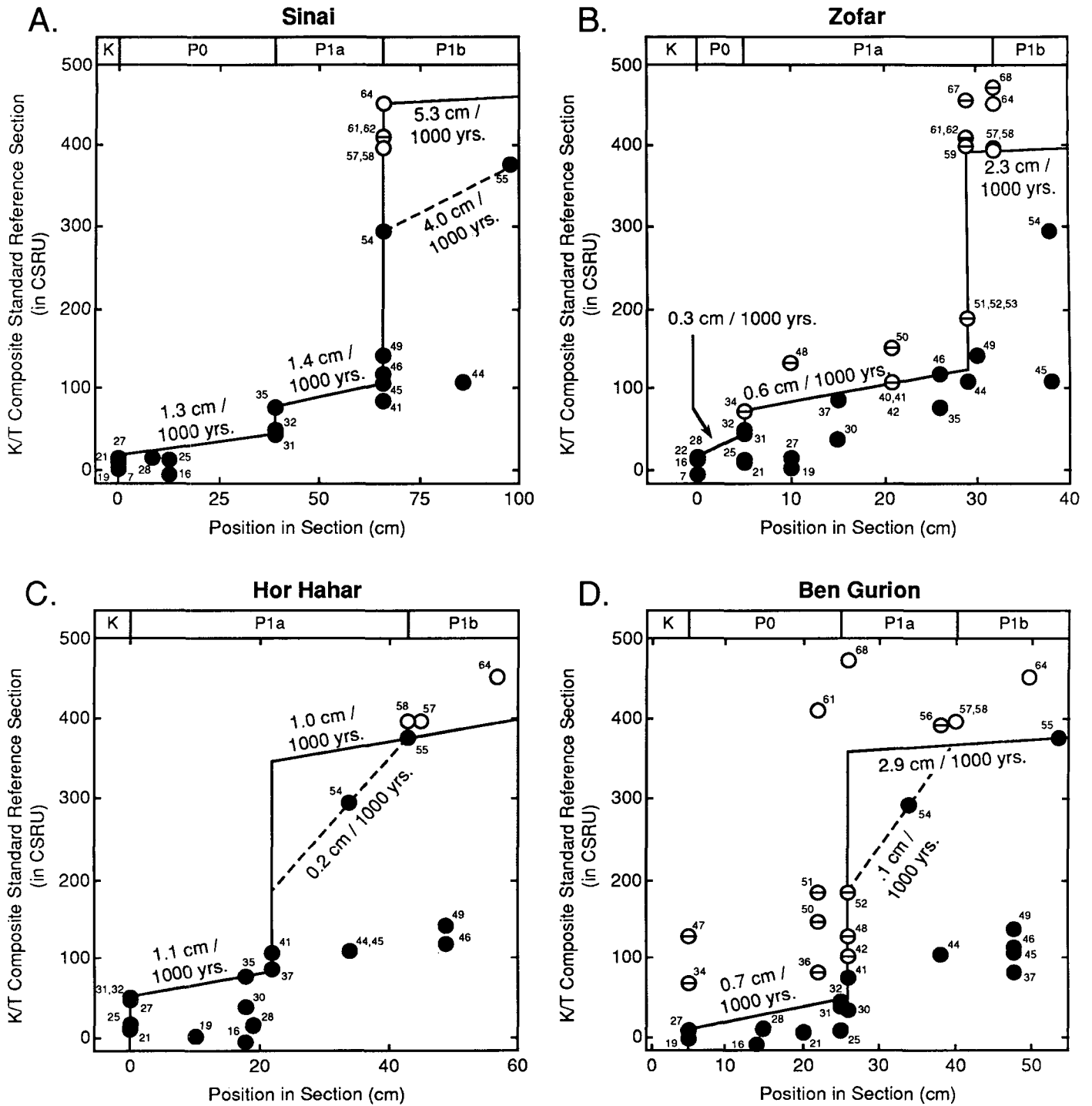
Figure 11. Graphic correlations for the Sinai (A), Zofar (B), Hor Hahar (C), Ben Gurion (D), and Ein Mor (E) sections from the Negev Desert with the K/T-CSRS. See Figure 4 caption for explanation of symbols. Sediment accumulation rates based on preliminary geochronologic calibration of the K/T-CSRS (Fig. 3). Data from Keller and Benjamini (1991). Biostratigraphic zonation is that of Keller (1989a).

interval is characteristic of Zone P1c. If Zone P1a is present at Stevns Klint, it would have to be contained within the 15-cm barren interval. Thus, it seems very likely that a period of either extreme stratigraphic condensation, nondeposition, or hiatus formations is present somewhere within the Zone P0 to P1c interval, although available biostratigraphic data are insufficient to constrain this event more precisely. A basal K/T

hiatus for this section has also been proposed by both Hakansson and Hansen (1979) and Perch-Nielsen and others (1982).

Gubbio, Italy. The K/T boundary section near the town of Gubbio, Italy, has often been described as complete and has been, at various times, proposed as the K/T boundary magnetostratotype (Alvarez and others, 1977; Arthur and others, 1987). This boundary is lithologically marked by
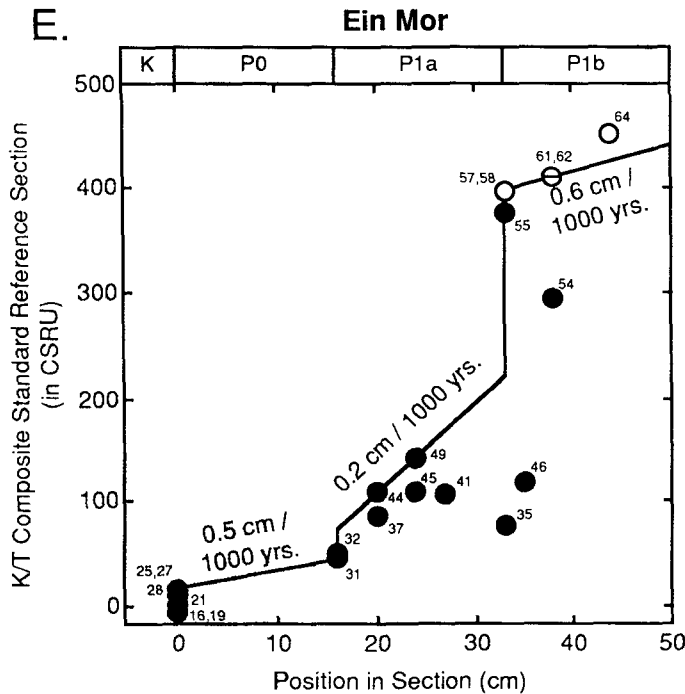
E.

Figure 11. (Continued).

a 0.5- to 1.0-cm red-brown clay layer intercalated between Maastrichtian and Tertiary limestone beds. There is no distinct basal red clay layer, and no Tertiary planktonic Foraminifer have been reported from this clay interval (Smit and ten Kate, 1982). Immediately above the clay layer, Luterbacher and Premoli-Silva (1964) observed both *P. eugubina* and *S. pseudobulloides* FAD's. Virtually all lower Danian planktonic foraminiferal biostratigraphic zonations of the past 10 yr show this datum sequence to be incomplete (Herm and others, 1981; Smit, 1982; Keller, 1988a). Our K/T-CSRS corroborates these findings (Table 1). The simultaneous occurrence of these two lower Danian datums suggests that a hiatus at Gubbio spans all of Zone P0 and extends into at least the lower part of Zone P1a. Contrary to statements by Alvarez and others (1980, 1982, 1990), there is no high-resolution planktonic foraminiferal evidence to suggest that the Gubbio section contains a temporally complete history of K/T boundary events.
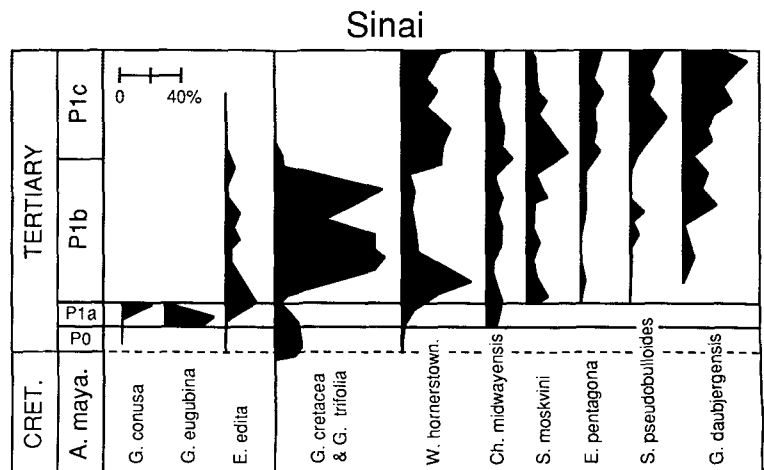
Zumaya, Spain. The K/T boundary section exposed in the coastal cliffs near Zumaya in northern Spain lacks a distinct boundary clay layer,

but a 35-cm-thick, dark silty marl bed is present at the boundary. Herm (1965) reported *P. eugubina* and *W. hornerstownensis* within the basal 3 cm of this bed and the FAD of *S. pseudobulloides* at the 3 cm level, whereas Smit and ten Kate (1982) observed *P. eugubina*, *W. hornerstownensis*, and *E. fringa* throughout the first 10 cm of this bed. Co-occurrence of these species implies the presence of a depositional hiatus spanning Zone P0 and the lowermost part of Zone P1a (Table 1).

Biarritz, France. The section exposed along the coastal cliffs 3 km south of the village of Biarritz consists of upper Maastrichtian pelagic marls and Danian pelagic limestones separated by a 1-cm-thick boundary clay that underlies 40 cm of red-brown marl (Romein and Smit, 1981). No planktonic Foraminifera have been recovered from the boundary clay, but a "*Parvularugoglobigerina eugubina* assemblage" is reported from the overlying marl (Smit and ten Kate, 1982) along with the nannofossil *M. inversus* (Perch-Nielsen, 1979). Absence of the distinctive Zone P0 planktonic foraminiferal fauna implies that this biozone may be missing from the section. In addition, there are no foraminiferal datums constraining the interval above the *P. eugubina* FAD, although Perch-Nielsen (1979) reported the *C. primus* (calcareous nannofossil) FAD 1.5 m above the K/T boundary. On the basis of these data, it is probable that all of Zone P0 and at least the lower part of Zone P1a is missing (Table 1). After examining the Stevns Klint calcareous nannofossil record, Perch-Nielsen and others (1982) concluded that "in the Tertiary part [of Biarritz], sedimentation seems to have been interrupted repeatedly." Our results corroborate this interpretation.

Flaxbourne River, New Zealand. The Flaxbourne River section, considered by some to be the most complete K/T boundary section in New Zealand (Strong and others, 1987), consists of Maastrichtian and Danian pelagic limestones separated by 40–50 cm of laminated calcareous mudstone that, in turn, overlies a 2-cm-thick boundary clay. Although the first Tertiary planktonic Foraminifera are not reported until 30 cm above the boundary clay, the entire interval from the boundary clay to this horizon was assigned to Zone P0 by Strong and others (1987). The fact that no Tertiary species have ever been recovered from this 0- to 30-cm interval, however, renders this assignment arbitrary. These authors also assigned the interval from 30–40 cm above the boundary clay that was found to contain some small Tertiary species (for example, *E. cf. fringa*) to Zones P1a and P1b despite their apparent failure to find the standard index taxa for those zones. In the absence of *P. eugubina*, this interval could just as easily be assigned to Zone P0 (Table 1). Strong and others (1987) then went on to assign a planktonic foraminiferal assemblage characterized by *G. daubjergensis* from the interval 50–100 cm above the boundary clay to Zone P1c. On the basis of our composite datum sequence, however, the global first appearance for this datum was found to reside within Zone P1a

Figure 12. Relative-abundance data and event-datum distributions supporting recognition of the upper Zone P1a and Zone P0/P1a boundary hiatuses in the Sinai section. Hiatus levels are marked by solid horizontal lines, whereas the K/T boundary is marked by a dashed horizontal line. Data from Keller and Benjamini (1991). Biostratigraphic zonation is that of Keller (1989a).
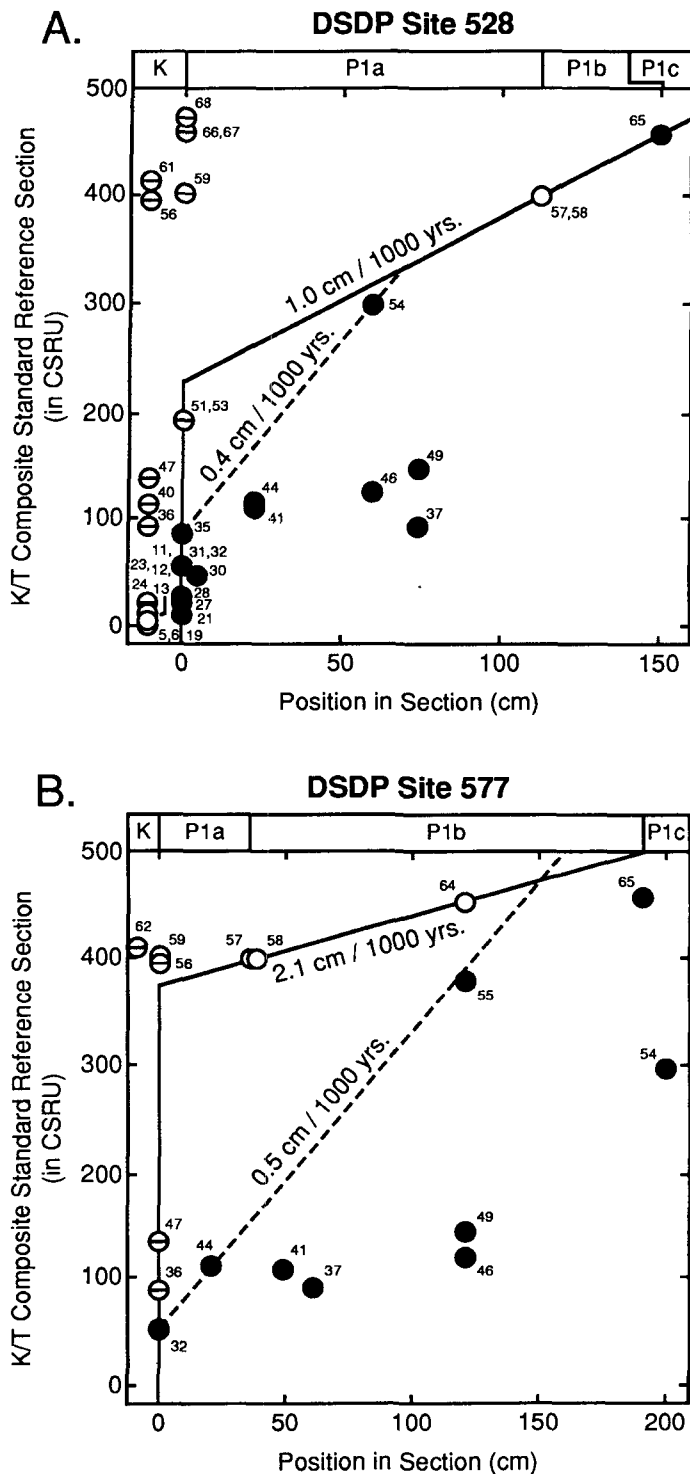
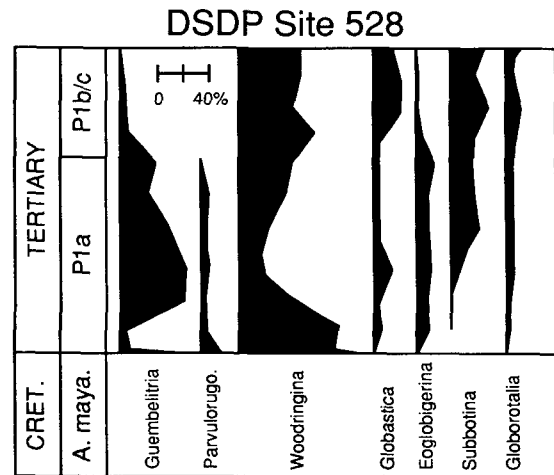## Sinai

A.

DSDP Site 528

DSDP Site 528

Figure 14. Relative-abundance data and event-datum distributions supporting recognition of K/T boundary hiatuses in the Site 528 core. Hiatus level is coincident with the K/T boundary. Data from D'Hondt and Keller (1991). Biostratigraphic zonation is that of Keller (1989a).

B.

DSDP Site 577

Figure 13. Graphic correlations for DSDP Sites 528 (A) and 577 (B) with the K/T–CSRS. Note the difference in the character of the correlations in these deep-sea sections when compared to coeval correlations from middle-neritic to upper-slope sections (Figs. 4, 6, 8, 10, and 11). See Figure 4 caption for explanation of symbols. Sediment accumulation rates based on preliminary geochronologic calibration of the K/T–CSRS (Fig. 3). Data from D'Hondt and Keller (1991). Biostratigraphic zonation is that of Keller (1989a).

(Table 1). A more parsimonious interpretation of these data suggests that the Flaxbourne River section may be temporally complete from the K/T boundary through the lower part of Zone P1a, but that large intervals corresponding to Zones P1a and P1b are probably missing.

DSDP Site 465A. Although the Site 465A core displays strong drilling disturbance, Smit and Romein (1985) noted that the K/T boundary can be identified by a sharp lithological change from white Maastrichtian oozes to a 2-mm-thick, black clay at the base of a dark marl containing Tertiary planktonic Foraminifera. These authors reported a few *P. eugubina* specimens in an assemblage of small Tertiary planktonic Foraminifera from the overlying marl and assigned it to the lower part of Zone P1a (prior to the *G. taurica* FAD). The apparent absence of the characteristic Zone P0 planktonic foraminiferal fauna in this core, however, cannot provide direct evidence for the presence of Zone P0. Consequently, it seems more reasonable to suspect that the whole of this biozone is missing, along with the lower part of Zone P1a. In this respect, the Site 465A core is similar to that of the nearby Site 577 (discussed above).

DSDP Sites 356, 516F, 524, 525A, and 527. Smit and Romein (1985) reported that Site 356 may include a substantial hiatus in the earliest Paleocene because the earliest Tertiary fauna recovered from this core is similar to their "*G. eugubina-V./G. pseudobulloides* Zone" (= portion of Zone P1a after the *S. pseudobulloides* FAD). This implies the existence of a basal Danian hiatus that includes all of Zone P0 and the lowermost part of Zone P1a. Smit and Romein (1985) also reported that the earliest Tertiary sediment present in Walvis Ridge Sites 524, 525A, and 527 includes middle to upper *P. eugubina* Zone (= Zone P1a) planktonic foraminiferal faunas like those observed at Site 528 (see Fig. 12). Likewise, Boersma (1984) described the co-occurrence of *W. hornerstownensis, P. eugubina, G. daubjergensis, G. minutula* (= *G. conusa*), *E. fringa,* and *Ch. midwayensis* FAD's in the basal Danian parts of these cores. All of these data are consistent with our interpretation of a K/T boundary to lower Zone P1a hiatus in these South Atlantic deep-sea cores (Table 1). Site 516F in the southwestern Atlantic contains a well-defined 2-cm-thick clay layer at the K/T boundary. Pujol (1983) described a small (<150 µm) eoglobigerinid fauna as possibly belonging to Zone P1a 0–4
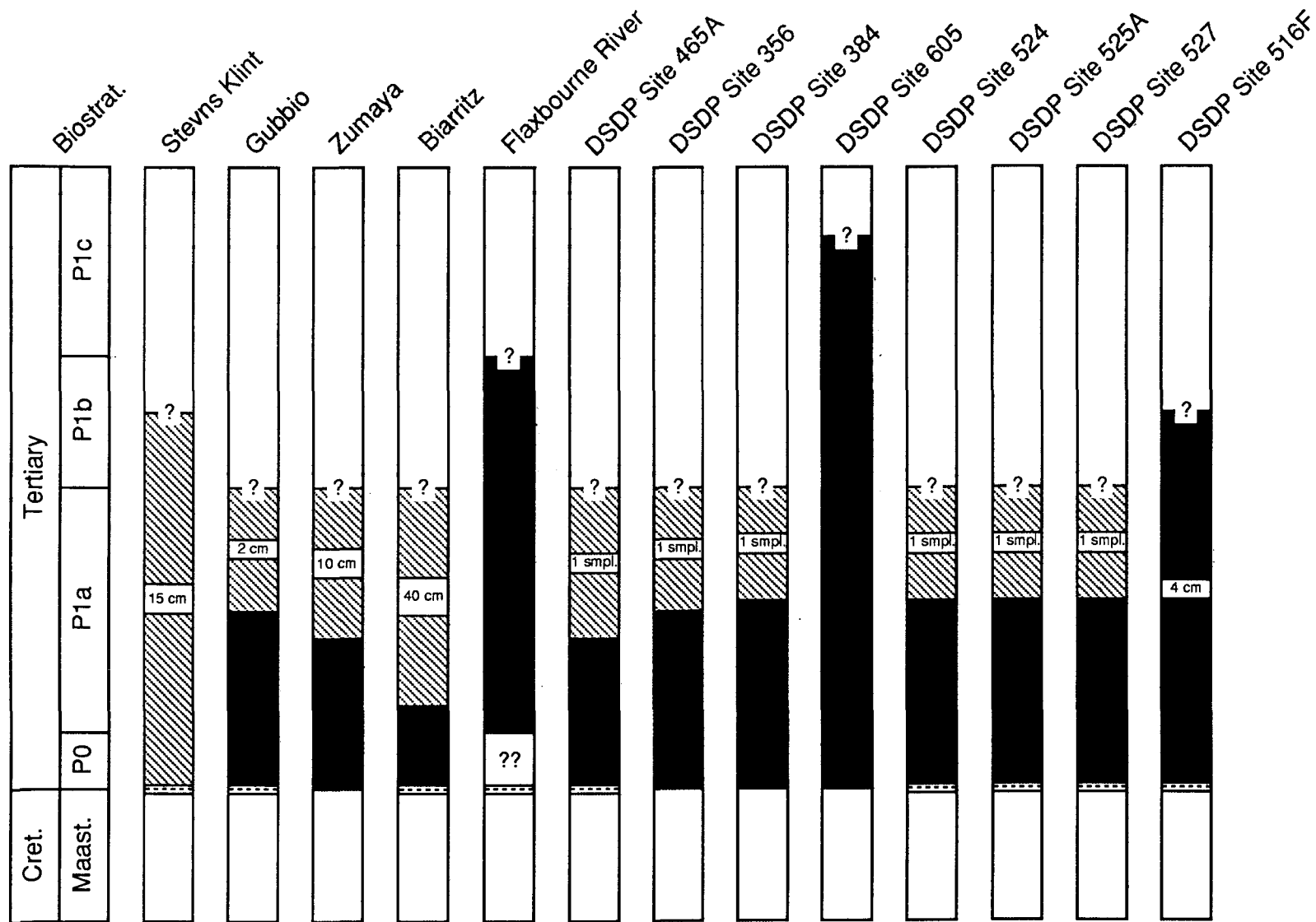
Figure 15. Generalized chronostratigraphic models for 13 secondary K/T boundary sections with minimum estimated durations of hiatus events. All sections and cores, with the exception of Stevns Klint, represent deep-sea depositional environments. See text for discussion. White, interval present in section; black, interval missing from section; diagonal stipple, enclosed layer (representing either a lithostratigraphic thickness or a number of samples) is located within the designated time interval but does not necessarily account for the entire temporal interval; ?, position of upper or lower hiatus boundary uncertain; dashed line, section contains basal Tertiary red clay layer. Biostratigraphic zonation is that of Keller (1988a).

cm above this boundary clay. Immediately above that interval, a well-developed planktonic foraminiferal fauna containing *G. daubjergensis*, *S. triloculonides*, *S. varianta*, and *S. pseudobulloides* was collected. This assemblage of species would be expected to co-occur only within Zone P1c or higher (Table 1). These data suggest that although a narrow lithologic interval may be assignable to Zone P1a, there is no direct evidence to suggest that any of Zone P0 or the lower part of Zone P1a is present within this core. A similar biostratigraphic record is also preserved at southeastern Atlantic Site 356.

DSDP Sites 384 and 605. Planktonic foraminiferal datums at Site 384 exhibit a lithostratigraphic distribution similar to that found at Site 356 (Smit and Romein, 1985), suggesting that this site lacks the same basal Danian interval (see above). Site 605 in the northwestern Atlantic lacks a boundary clay. At the base of the Paleocene in this core, Smit and van

Kempen (1987) reported a well-developed fauna containing abundant *Guembelitria*, *Chiloguembelina*, *Eoglobigerina*, and *S. pseudobulloides*. As shown on the K/T–CSRS (Table 1), this assemblage of taxa could be found anywhere within the interval from Zone P1a through P1c.

DISCUSSION AND CONCLUSIONS

One of the major obstacles to inferring chronostratigraphy from biostratigraphy is the high level of diachrony present in raw biostratigraphic data. Figure 16 illustrates the magnitude of this diachrony for seven commonly used lower Danian biostratigraphic datums, by mapping their observed positions in five different K/T boundary sections onto the K/T–CSRS. Despite the fact that several of these events are practically isochronous, correlations based on others may incorporate substantial age
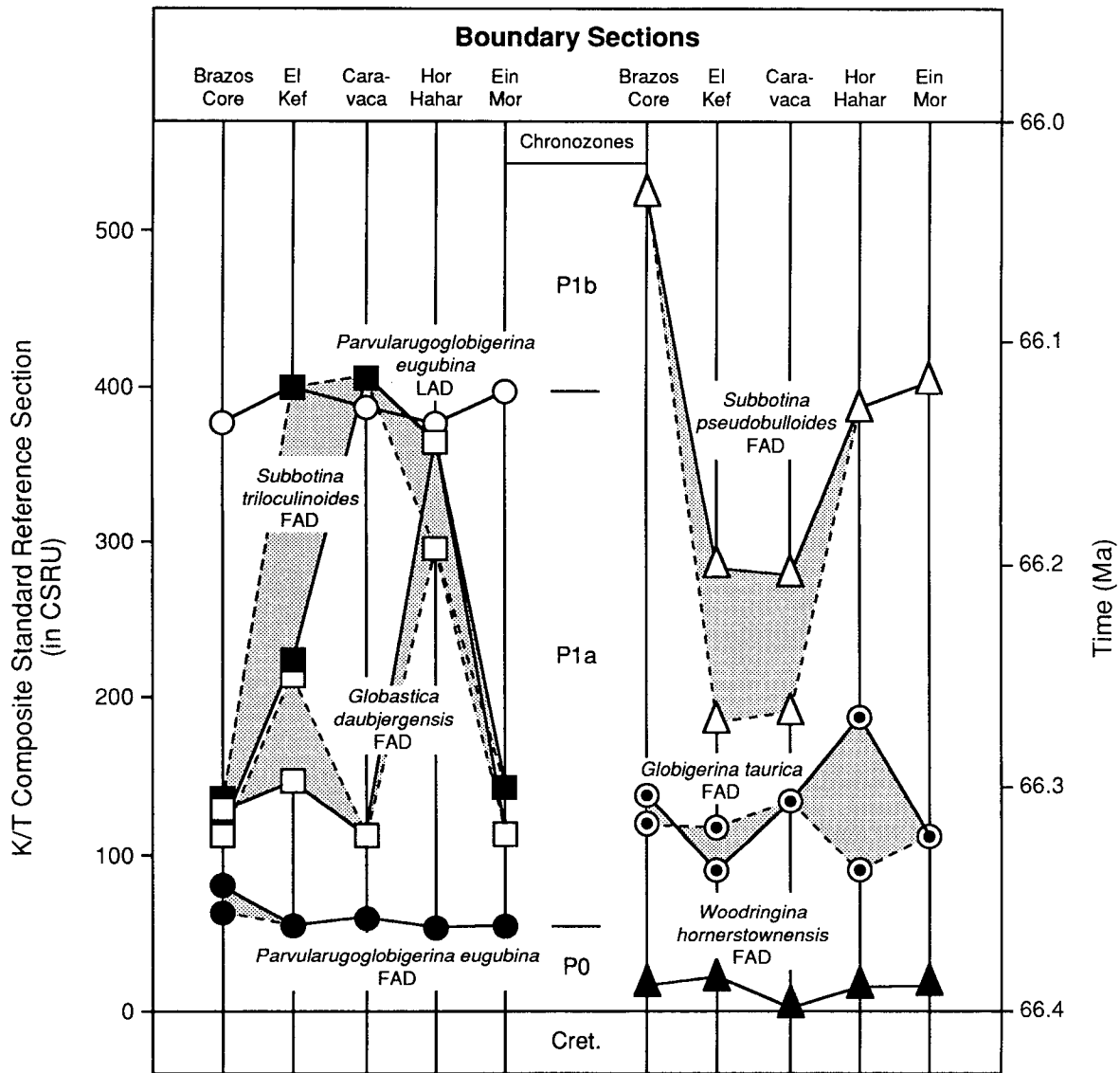

Figure 16. Estimated temporal positions of seven commonly used lower Danian planktonic foraminiferal datums in five K/T boundary sections. Stippled areas represent alternative temporal placements of event datums, based on best-case and worst-case correlation models (see text). Age scale based on preliminary geochronologic calibration of the K/T–CSRS (Fig. 3). Note the widespread diachrony (ranging to as much as 250,000 yr) among several datums, along with the generally inverse relationship between the physical proximity of sections and datum event isochrony. Biostratigraphic zonation (center column) is that of Keller (1988a).

differences (geochronologically estimated to range as high as 250,000 yr). Because there is no way of predicting, *a priori* which datums are diachronous and which are not, the temporal completeness of any K/T boundary section or core cannot be assessed in isolation from coeval sections or cores and must not be based on the recognition of single biostratigraphic or lithostratigraphic datums.

Results of our analyses also reveal an intriguing difference between the distribution of hiatuses in neritic and deep-sea environments. Figure 17 shows that continental-shelf sections (for example, El Kef, Brazos River, Caravaca, Agost) generally exhibit either short condensed intervals or

hiatuses near the Zone P0/P1a boundary and again in the upper part of zone P1a. In contrast, deep-sea cores (for example, Sites 528 and 577; see also Fig. 15) typically lack the earliest Tertiary Zone P0 and the lower part of Zone P1a. This conspicuous, environmentally mediated discrepancy in the temporal distribution of hiatuses appears to be related to early Danian sea-level fluctuations through the attendant disruption of sedimentation patterns.

Currently, the most detailed lower Danian sea-level curve is based on the analysis of dinoflagellate cysts, sporomorphs, and land-derived organic matter within the lower part of the El Kef section (Fig. 17; see
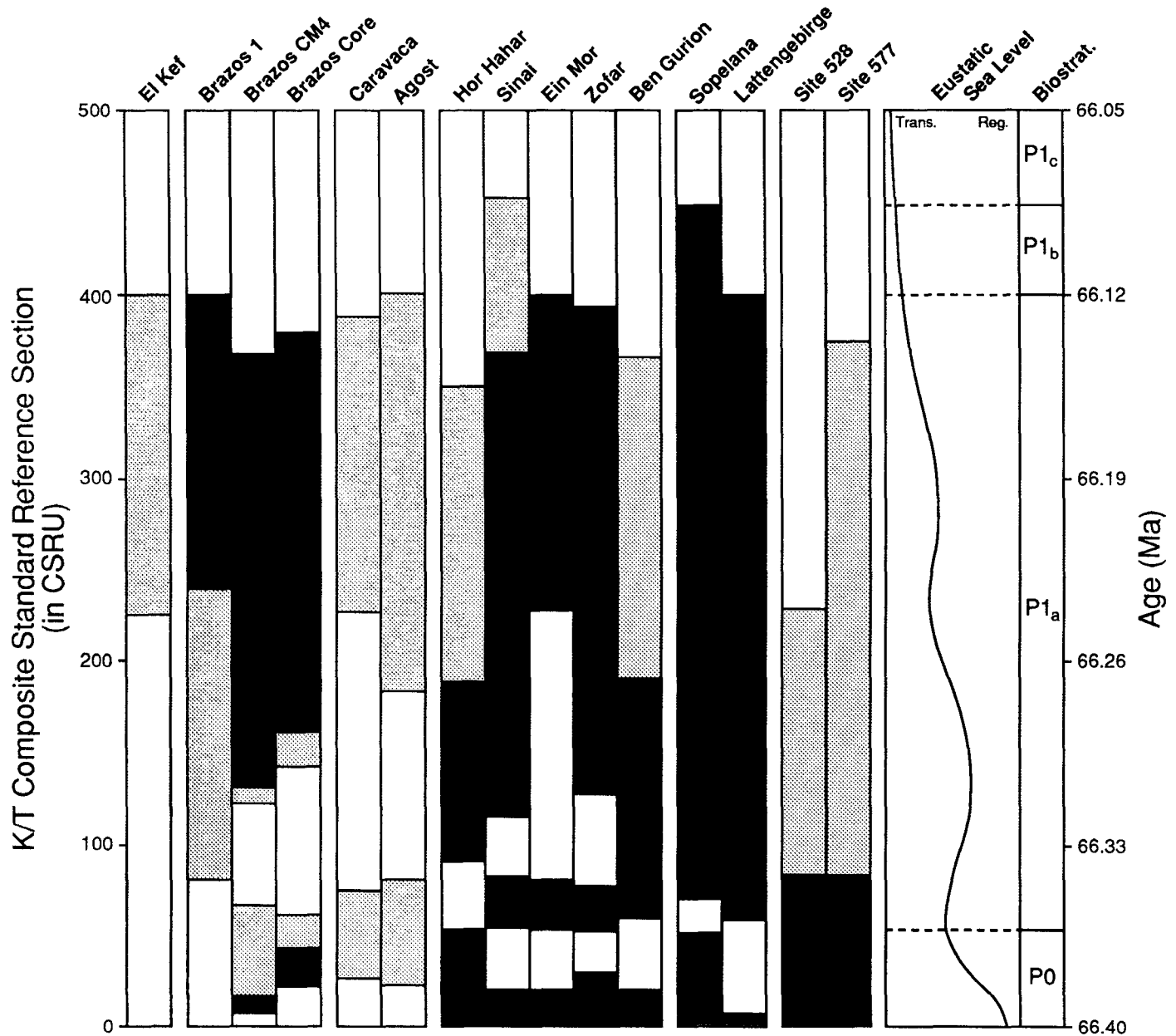

Figure 17. Extent and temporal distribution of lower Danian intrazonal hiatuses in the set of 15 primary K/T boundary sections plotted against the sea-level curve of Brinkhuis and Zachariasse (1988). White, interval present under both best-case and worst-case correlation models; stippled, interval present under best-case correlation model but missing under worst-case correlation model; black, interval missing under both best-case and worst-case correlation models. Age scale based on preliminary geochronologic calibration of the K/T–CSRS (Fig. 3). Biostratigraphic zonation is that of Keller (1988a).

Brinkhuis and Zachariasse, 1988). This investigation, along with a number of other basal Tertiary sea-level studies (Vail and others, 1977; Hancock and Kauffman, 1979; Matsumoto, 1980; Weimer, 1984; Cloetingh and others, 1986; Haq and others, 1987; Donovan and others, 1988; Hallam, 1989), has shown that a global drop in eustatic sea level began in the Late Cretaceous and reached a maximum just below the K/T boundary. This eustatic sea-level fall was followed by a long-term rise in eustatic sea level that lasted throughout the lower Paleocene. Throughout the lowermost Danian, though, this long-term pattern of sea-level rise was repeatedly interrupted by periods of short-term sea-level instability.

The effect of a rapid sea-level rise in lower Zone P0 would have been to trap terrigenous sediment and organic carbon high on the already extensive continental shelves, thus temporarily depriving deep ocean basins of an inorganic sediment source and enhancing carbonate dissolution (Berger, 1970; Berger and Winterer, 1974; Loutit and Kennett, 1981; Haq and others, 1987; Haq, 1990). During these intervals, outer-shelf and deep-sea localities would have experienced reduced sediment accumulation, with the deep sea suffering more extreme declines in sediment supply and more intense dissolution. The succeeding short-term drops in eustatic sea level would have reversed this pattern by disrupting sediment accumulation on the continental platforms and renewing delivery to the deep sea. Our reconstructed lower Danian hiatus distribution patterns in both neritic and deep-sea depositional environments (Fig. 17) are consistent with this general model.

The chronostratigraphic scheme described above represents a preliminary attempt to provide an accurate temporal framework for K/T boundary sections by quantitatively synthesizing relevant biostratigraphic and lithostratigraphic data. Our results show that continental-shelf to upper-slope sections, such as those at El Kef, Brazos River, Caravaca, and Agost, contain the most complete basal Tertiary records of biological and environmental change. Keller (1988a, 1989a, 1989b) and Canudo and others (1991) have shown that these sections contain no evidence for the "mass extinction" of all but one Cretaceous planktonic foraminiferal species, as previously claimed by Smit (1982, 1990). Rather, rates of planktonic foraminiferal fauna turnover rise well before the biostratigraphically defined K/T boundary and continue for a prolonged period thereafter. Additionally, these results suggest that abrupt excursions in the deep sea $^{12}C/^{13}C$ ratio at the K/T boundary, which were originally used to develop the "strangelove ocean" model (Hsü and others, 1982; Zachos and Arthur, 1986), may also be attributable to deep-sea stratigraphic discontinuities. This stratigraphic model would also reconcile the recent discovery of gradually changing K/T boundary oxygen and carbon isotopic ratios at the much shallower and temporally more complete Brazos River sections (Barrera and Keller, 1990), with the deep-sea isotopic record.

In summary, the presence of previously unrecognized lower Danian stratigraphic hiatuses in both deep-sea cores and continental-shelf sections may have seriously biased the paleoenvironmental/paleobiological interpretation of many K/T boundary sections. After these distortions are removed, there are many reasons to suspect that the contiguous disappearance of practically all Cretaceous planktonic foraminiferal species, abrupt shifts in stable-isotopic abundances, and single-peak Ir anomalies used to support scenarios of cataclysmic extinction via bolide impact are artifacts of either a temporally incomplete or greatly condensed deep-sea stratigraphic record.

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