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Age, stratigraphy, and deposition of near-K/T siliciclastic deposits in Mexico: Relation to bolide impact?

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ABSTRACT

Examination of 10 K/T boundary sections in northeastern and east-central Mexico, and new data presented from 7 sections, permit the following conclusions. (1) The globally recognized K/T boundary and mass extinction in planktic foraminifera is stratigraphically above, and separated by a thin marl layer of Maastrichtian age, from the siliciclastic deposit that is commonly interpreted as a short-term (hours to days) K/T-impact–generated tsunami deposit. A similar relationship between the K/T boundary and siliciclastic or breccia deposits is observed at Brazos River in Texas, Beloc in Haiti, and Poty Quarry in Brazil. (2) Stratigraphic control indicates that deposition of the siliciclastic member occurred sometime during the last 150 k.y. of the Maastrichtian, and ended at least several thousand years prior to the K/T boundary. (3) At least four discrete horizons of bioturbation have been observed within the siliciclastic deposit that indicate episodic colonization by invertebrates over an extended time period. (4) The glass- and spherule-rich unit, which has been linked to the Haiti spherule layer and the Chicxulub structure, is at the base of the siliciclastic deposit and thus significantly predates the K/T boundary event.

The stratigraphic separation of the K/T boundary and siliciclastic deposits and the evidence of long-term deposition between them, suggests the presence of two events: (1) a globally recognized K/T boundary (impact) event marked by Ir anomaly and the mass extinction, and (2) a Caribbean event (impact or volcanic and probably linked to the Chicxulub structure) that predates the K/T boundary and is marked by glass and siliciclastic or breccia deposits.

INTRODUCTION

Yucatan

The subsurface Chicxulub structure in northern Yucatan is now widely believed to be the long-sought Cretaceous/Tertiary (K/T) boundary bolide impact crater (Hildebrand et al., 1991; Pope et al., 1991, 1993; Sharpton et al., 1992, 1993, 1996; Pilkington and Hildebrand, 1994; Ward et al., 1995; Kring, 1995; Buffler et al., 1995). Supporting evidence for this interpretation includes the following. (1) Concentric geophysical anomalies suggest a large basin with a still-disputed size of either 180 km (Hildebrand et al., 1991, 1995; Pilkington and Hildebrand, 1994; Kring, 1995) or 300 km (Sharpton et al., 1993, 1996) in diameter. (2) There are anomalously high iridium values in some isolated melt rock or andesitic rock fragments of Yucatan cores Y6 (breccia sample N19) and C1 (sample N10) reported by Sharpton et al. (1992), although these results could not be confirmed by Hildebrand et al. (1993) or Rocchia (1994, written commun.). (3) There is evidence of shock metamorphism in quartz and feldspar grains in some breccia samples (Hildebrand et al., 1991; Sharpton et al., 1992, 1996). (4) There is a similarity in chemical compositions between Chicxulub glass within andesitic rocks and tektite-like glasses in Haiti and northeastern Mexico (Smit et al., 1992; Stinnesbeck et al., 1993; Koeberl et al., 1994). (5) A ^{40}Ar/^{39}Ar age of about 65.2 ± 0.4 Ma (Sharpton et al., 1992) or 64.98 ± 0.05 Ma (Swisher et al., 1992) is based on one sample from core C1-N9; eight other samples analyzed from core Y6 (N14, N17, N19) yielded ages between 58.2 and 65.4 Ma and were considered the result of low-temperature alteration. (6) The stratigraphic position of the breccia is within Maastrichtian sediments at or near the K/T boundary (Ward et al., 1995). These lines of evidence are interpreted to suggest that a bolide impact is the most likely origin for the Chicxulub structure and breccia.

Nevertheless, questions remain as to the precise age and stratigraphic position of the breccia with respect to the K/T boundary–was this a K/T or pre-K/T event? Was breccia deposition a single event or multiple events? The reported presence of Maastrichtian age marls above the breccia observed in wells Y6 and C1 (Lopez Ramos, 1973; Ward et al., 1995) and the apparent presence of limestone and anhydrite layers interbedded within Chicxulub breccias in several wells (Y2, Y4, Y6) suggest that breccia deposition could predate the K/T event and that there could have been several breccia deposition events (Ward et al., 1995). Alternatively, it is possible that the marls were erroneously identified as Maastrichtian age based on reworked Cretaceous faunas, and that the limestone and anhydrite layers within the breccia represent large boulders (Ward et al., 1995). The present Chicxulub cores and incomplete sample set available for study provide no conclusive evidence for either interpretation. At present, however, it is commonly assumed that the breccia is of K/T boundary age and impact induced.

As a result of the interpretation of the Chicxulub structure as an impact crater, near-K/T boundary siliciclastic deposits in northeastern, east-central, and southern Mexico, Texas, and the Gulf of Mexico (Fig. 1), which were previously related to sea-level lowstands, turbidites, or gravity flows, have been reinterpreted by some workers as impact-generated tsunami deposits (e.g., Bourgeois et al., 1988; Hildebrand and Boynton, 1990; Smit et al., 1992, 1994a, 1994b; Alvarez et al., 1992; Montanari et al., 1994). Likewise, limestone breccia deposits from Yucatan cores, southern Mexico, Guatemala, Belize, and northeastern Brazil that were previously related to tec-

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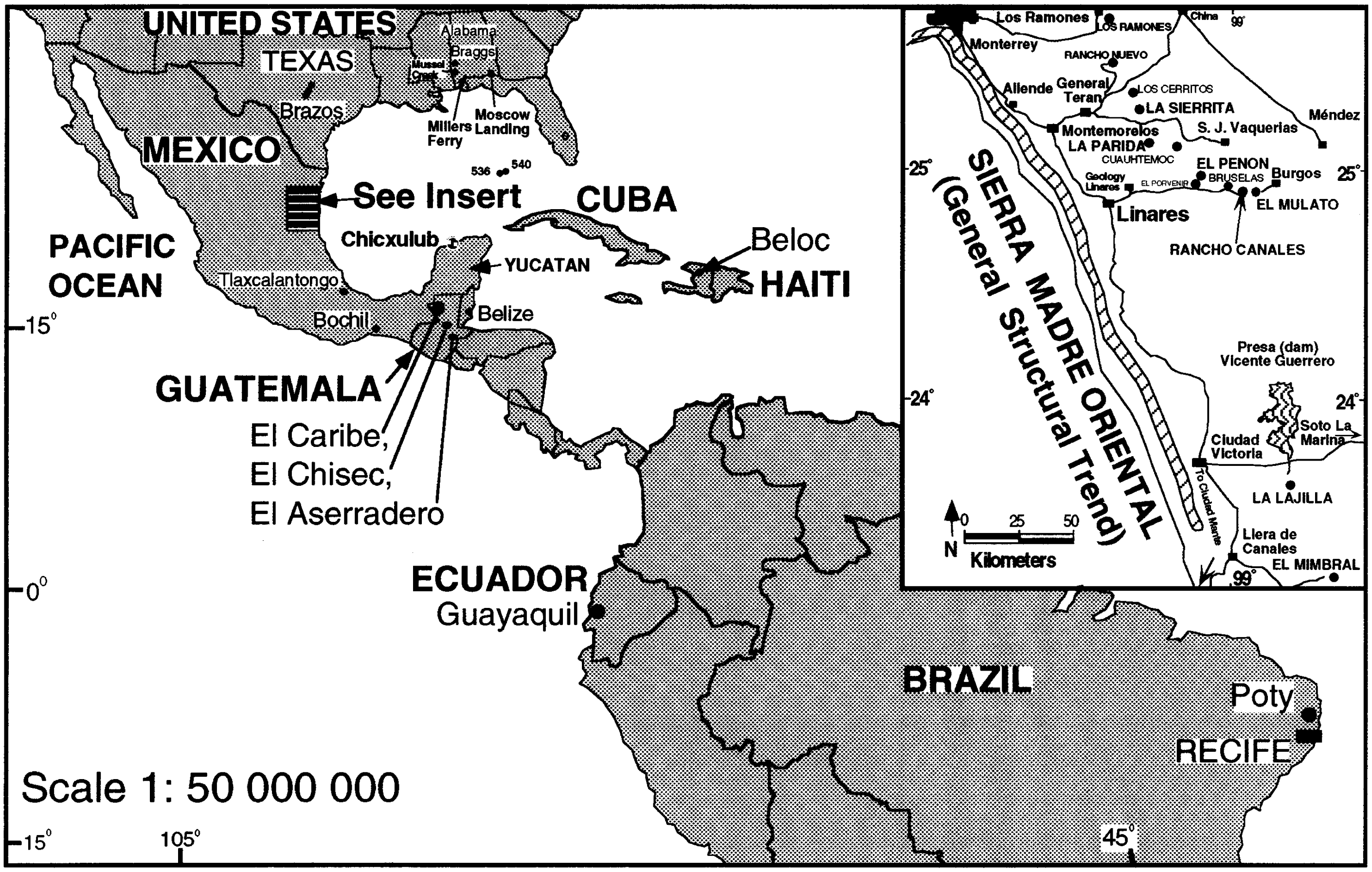


Figure 1. Location map of K/T boundary sections with near-K/T siliciclastic or breccia deposits from Texas to Brazil. Inset shows locations of northeastern Mexico sections. Note that all of these sections are located 40 to 80 km east of the front range of the Sierra Madre Oriental.

tonic activity or collapse, have been reinterpreted as impact-generated breccias and ejecta blankets (Sharpton et al., 1992, 1996; Hildebrand et al., 1993; Ocampo and Pope, 1994; Albertão et al., 1994; Ocampo et al., 1996; Ward et al., 1995). These revised interpretations fundamentally alter previous concepts of these siliciclastic and breccia deposits, although many questions still remain regarding their depositional nature, timing and duration of emplacements, and their stratigraphic correlation to the Chicxulub breccia and the K/T boundary worldwide (Keller and Stinnesbeck, 1996a, 1996b). Until these problems are resolved, interpreting all near-K/T siliciclastic and breccia deposits as K/T impact related may be incorrect.

Northeastern Mexico

The most thoroughly studied Central American K/T sections to date are in northeastern Mexico where more than a dozen outcrops have been examined (Fig. 1) to determine a possible relationship of the siliciclastic deposits to the Chicxulub event (Smit et al., 1992, 1994a, 1994b; Longoria and Grajales Nishimura, 1993; Stinnesbeck et al., 1993, 1994a, 1994b, 1996; Bohor and Betterton, 1993; Keller et al., 1994a, 1994b; Lopez-Oliva, 1996). Despite this effort, the two most critical questions have remained unanswered. (1) Are the siliciclastic deposits precisely of K/T boundary age? (2) Was deposition a single short-term event or long-term, multiple events? Both of these questions are difficult to answer because of the unusual nature of these deposits and their proximity to the stratigraphic K/T boundary.

It is generally agreed that the siliciclastic deposits are coeval, but questions remain about their stratigraphic position relative to the K/T boundary. The possibility that the siliciclastic deposits in northeastern Mexico may predate the K/T boundary event was first mentioned by Keller et al. (1994a) and was later detailed by Lopez-Oliva and Keller (1996). This suggestion was based on the observation that at the La Lajilla section, a 5–10-cm-thick marl layer with Maastrichtian planktic foraminifers lies between the top of the siliciclastic deposit and the Tertiary Velasco shales. Similar stratigraphic relationships were earlier observed at Brazos River, Texas (Jiang and Gartner, 1986; Keller, 1989), at Beloc, Haiti, between the glass spherule layer and Tertiary sediments (Jéhanno et al., 1992; Leroux et al., 1995), and at the Poty Quarry near Recife, Brazil, between the breccia and Tertiary sediments (Stinnesbeck and Keller, 1995, 1996; Fig. 1). Some workers have suggested that this is simply a matter of how the K/T boundary is defined; i.e., the siliciclastic or breccia deposits define the K/T boundary, and the marl layer with Maastrichtian faunas simply represents reworking from the water column after the impact-generated tsunami event (Smit et al., 1994a). However, this interpretation ignores standard stratigraphic methods used to recognize reworking and to identify the K/T boundary worldwide. In this study we present further evidence that a similar stratigraphic relationship is present in all relatively complete K/T boundary sequences in northeastern Mexico, southern Mexico, Texas, Haiti, and Brazil. On the basis of these data we argue that a pre-K/T age for the siliciclastic and breccia deposits, rather than reworking, should be considered a real possibility.

Answers to the question whether the siliciclastic sediments represent a single short-term event or long-term multiple events have also been elusive and controversial. Smit et al. (1992, 1994a, 1994b) argued for short-term deposition by a megatsunami generated by the presumed Yucatan (Chicxulub) impact. In this scenario, the siliciclastic member was deposited within hours to days after the impact. In contrast, Stinnesbeck et al. (1993, 1994a, 1994b) argued for long-term deposition by normal sedimentary processes such as gravity flows associated with a sea-level lowstand. Regardless of the merits of either scenario, the critical question concerns the nature of deposition. Arguments in favor of long-term deposition, generally based on biostratigraphy and sedimentology (Keller et al., 1994b), or clay mineral and whole rock analyses (Adatte et al., 1996), have been inconclusive: proof or disproof, the "smoking gun" of an impact-tsunami origin, is still missing. During a 1994 field trip to northeastern Mexico (Keller et al., 1994a), an international team of 55 geologists agreed that the presence of burrows within the siliciclastic deposit would constitute the smoking gun that proves long-term deposition and disproves the short-term tsunami interpretation. That proof remained elusive during the 1994 field trip. However, subsequent field work by Ekdale and Stinnesbeck (1994, 1997, this study) discovered several discrete burrowed layers within the siliciclastic deposits. We document these burrowed layers and argue that they provide strong evidence that deposition occurred over a longer time period and therefore could not be related to a K/T-impact–generated tsunami event.

In addition to the two critical questions on age and depositional nature of the siliciclastic deposits, we do the following: (1) document the biostratigraphic position of these deposits with respect to the K/T boundary based on the global stratotype criteria for identifying this boundary; (2) provide minimum and maximum biostratigraphic age constraints for deposition of these siliciclastic sediments; (3) evaluate the stratigraphic position of the iridium anomaly and spherule layer and the likelihood that they represent the same event; and (4) reevaluate the relationship of the Chicxulub structure to the northeastern Mexico siliciclastic deposits.

MATERIALS AND METHODS

Ten northeastern and east-central Mexican localities containing excellent exposures of the siliciclastic deposits at the K/T boundary transition were examined during numerous field excursions over the past three years (Fig. 1, inset). The locations and preliminary stratigraphies of many of these sections were recently published in a field guide (Keller et al., 1994a). We analyzed four sections that span the K/T boundary in northeastern Mexico (El Mimbral, La Lajilla, El Mulato, and La Parida) and one, Tlaxcalantongo, in east-central Mexico (also called Ceiba by Smit et al., 1994b) to determine the position and nature of the K/T boundary. Here we present the biostratigraphy and foraminiferal ranges of two new sections (El Mulato and La Parida), and a new analysis of the El Mimbral section. The preliminary stratigraphy of the El Mimbral section was originally published by Smit et al. (1992) and Stinnesbeck et al. (1993), and a detailed biostratigraphic analysis of the Danian interval appeared in Keller et al. (1994b). We reproduce here the biostratigraphic analysis of El Mimbral because (1) further studies have improved the age resolution; (2) this section is critical in comparison with other nearby sections which differ significantly from El Mimbral in the K/T boundary interval; and (3) the tsunami interpretation was originally based on the siliciclastic deposit at El Mimbral. The La Lajilla and Tlaxcalantongo sections were reported in Lopez-Oliva and Keller (1996) and Lopez-Oliva (1996), respectively. In addition to these trans-K/T sections, we present analyses of four new sections where the siliciclastic deposits top the sequences and Tertiary sediments are eroded (Los Ramones, Rancho Nuevo, La Sierrita, and El Peñon; Fig. 1). Within the seven sections analyzed for this report, the thickness of siliciclastic deposits ranges from several meters at El Peñon to only 2 cm at La Parida. Species ranges and relative abundances for all sections were presented in Lopez-Oliva (1996).

For comparison, we also examined several new K/T boundary sections in southern Mexico, Guatemala, and Brazil (Fig. 1; Stinnesbeck and Keller, 1994, 1995; Keller and Stinnesbeck, 1996). Each of the studied sections was measured and sampled at closely spaced intervals of 5 to 20 cm from several meters below to several meters above the siliciclastic deposits, sample spacing was generally 1 to 2 cm across the K/T boundary. Sample splits were processed for foraminiferal analysis using standard laboratory techniques and analyzed quantitatively (based on random sample splits of 300 specimens) for biostratigraphy and faunal turnover changes. Planktic foraminifera are abundant, though frequently recrystallized and poorly preserved, in all samples except for various intervals within the siliciclastic deposits of northeastern Mexico. Diagenetic alteration of foraminiferal tests does not appear to have significantly affected either species ranges or their relative abundances, as suggested by the similarity in patterns among different sections (Keller et al., 1994b; Lopez-Oliva and Keller, 1996).

Sample splits were also processed for whole-rock, clay mineral, and grain-size analyses at the geochemical laboratory of the University of Neuchâtel, Switzerland. Whole-rock and clay mineral samples were analyzed with a SCINTAG XRD 2000 diffractometer using analytical methods described in Kübler (1987). Small-scale sedimentary structures and petrology of the siliciclastic deposits and the spherule-rich sediments were examined in thin sections. Grain-size spectra of the insoluble residues were obtained by a laser particle counter Galai CIS 1 system using the method described by Jantschick et al. (1992).

BIOSTRATIGRAPHY

Biozonation

Keller's (1988, 1993) planktic foraminiferal biozonation of the K/T transition is used in this study (Fig. 2; zonal index taxa are marked in bold type). The revised zonation by Berggren et al. (1995) is shown for comparison. First and last appearances of Danian species are shown in their approximate sequential order based on a composite database that integrates more than 30 of the most complete K/T boundary sections worldwide (MacLeod and Keller, 1991a). The presence of several of these datum events at the same stratigraphic horizon generally represents a hiatus. A new latest Maastrichtian *Plummerita hantkeninoides* zone was recently added (Pardo et al., 1996). This biozone is similar in range to the *P. reicheli* zone of Masters (1984, 1993), and provides a significant refinement in stratigraphic resolution of the uppermost Maastrichtian. *P. hantkeninoides* is a short-lived species present in the top 6 m of the Maastrichtian at the El Kef section in Tunisia and in the top 3.5 m at the Agost section in Spain. In both sections the first appearance of this species correlates to within the lower part of the nannofossil *Micula prinsii* zone (Pardo et al., 1996). Paleomagnetic stratigraphy at Agost (Groot et al., 1989) shows that the first appearance of *P. hantkeninoides* occurs near the base of C29R, or 170–200 k.y. below the K/T boundary. The presence of this biozone therefore indicates that part or all of the last 170–200 k.y. of the Maastrichtian sediments are present. Moreover, the presence of *P. hantkeninoides* in sections that contain siliciclastic sediments or breccias provides important time constraints for deposition.

Although biostratigraphers using either the Keller or Berggren et al. zonal schemes should obtain the same results, this is not always the case. Whether the biostratigraphic zonation of one worker can be reproduced by another depends on many factors, including (1) sampling of the same stratigraphic locality and sequence at the equivalent sample resolution; (2) cleaning of the outcrop to avoid contamination; (3) similar laboratory processing techniques particularly in sieve size and analysis; (4) use of the same taxonomic

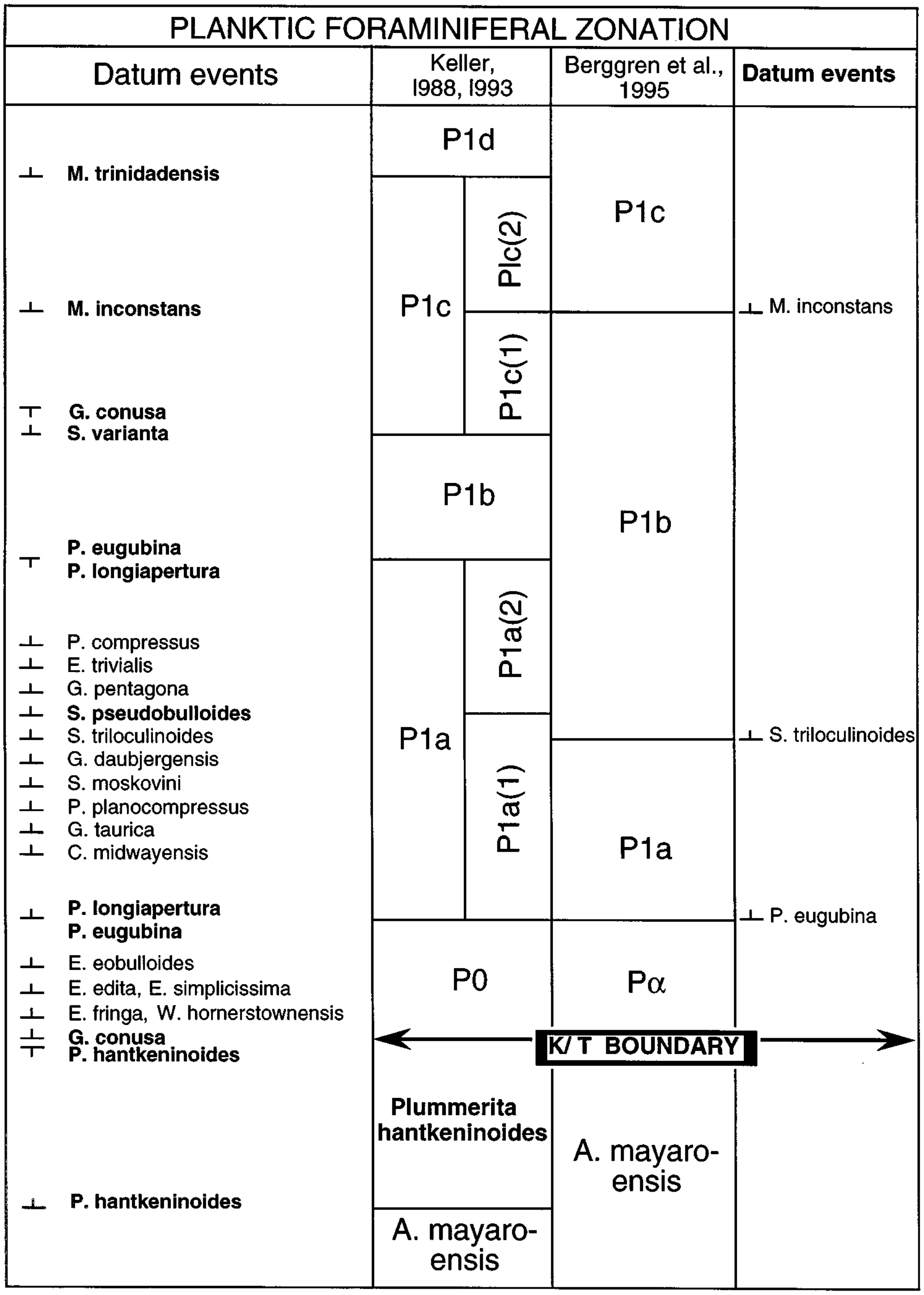


Figure 2. Correlation of commonly used planktic foraminiferal schemes for the K–T transition. Zonal index species for the Keller (1988, 1993) biozonation are marked in bold type. Index species for the Berggren et al. (1995) biozonation, which differ from Keller's, are the first appearances of *S. triloculinoides* for Pla/Plb and *M. inconstans* or *P. compressus* for Plb/Plc. The *Plummerita hantkeninoides* zone spans the last 170–200 k.y. of the Maastrichtian. Zones P0 and Pla span the first 40–50 k.y. and 180 k.y. of the Paleocene, respectively (MacLeod and Keller, 1991a, 1991b).

concepts; and (5) the amount of time expended in searching for first and last appearances of particular species which mark the zonal boundaries. It is therefore not surprising that there have been some disagreements among foraminiferal workers as to where specific zonal boundaries should be placed in a section, or whether certain zones are absent and indicate a hiatus. In general, however, there has been a surprising degree of agreement. This is largely because the K/T boundary is easily recognized and many zonal index taxa are easily identified. Disagreements mainly concern interpretations. For example, are Maastrichtian species survivors or reworked when present in Danian sediments? (See MacLeod and Keller [1994] for a discussion of this problem.)

K/T Boundary Definition—El Kef Stratotype Section

Controversy regarding placement of the K/T boundary in the northeastern Mexico sections, whether at the base or above the siliciclastic deposits, has frequently surfaced. The disagreement is partly ideological. Although both sides agree that evidence of a bolide impact (e.g., Ir anomaly, shocked quartz, Ni-rich spinels) in part marks the K/T boundary, proponents for placing the boundary at the base of the siliciclastic deposits argue that the deposit itself is the impact layer. Thus, they argue that the impact layer in the Gulf of Mexico area is represented by a complex sequence of impact ejecta (spherules, shocked quartz), followed by coarse detrital beds repre-

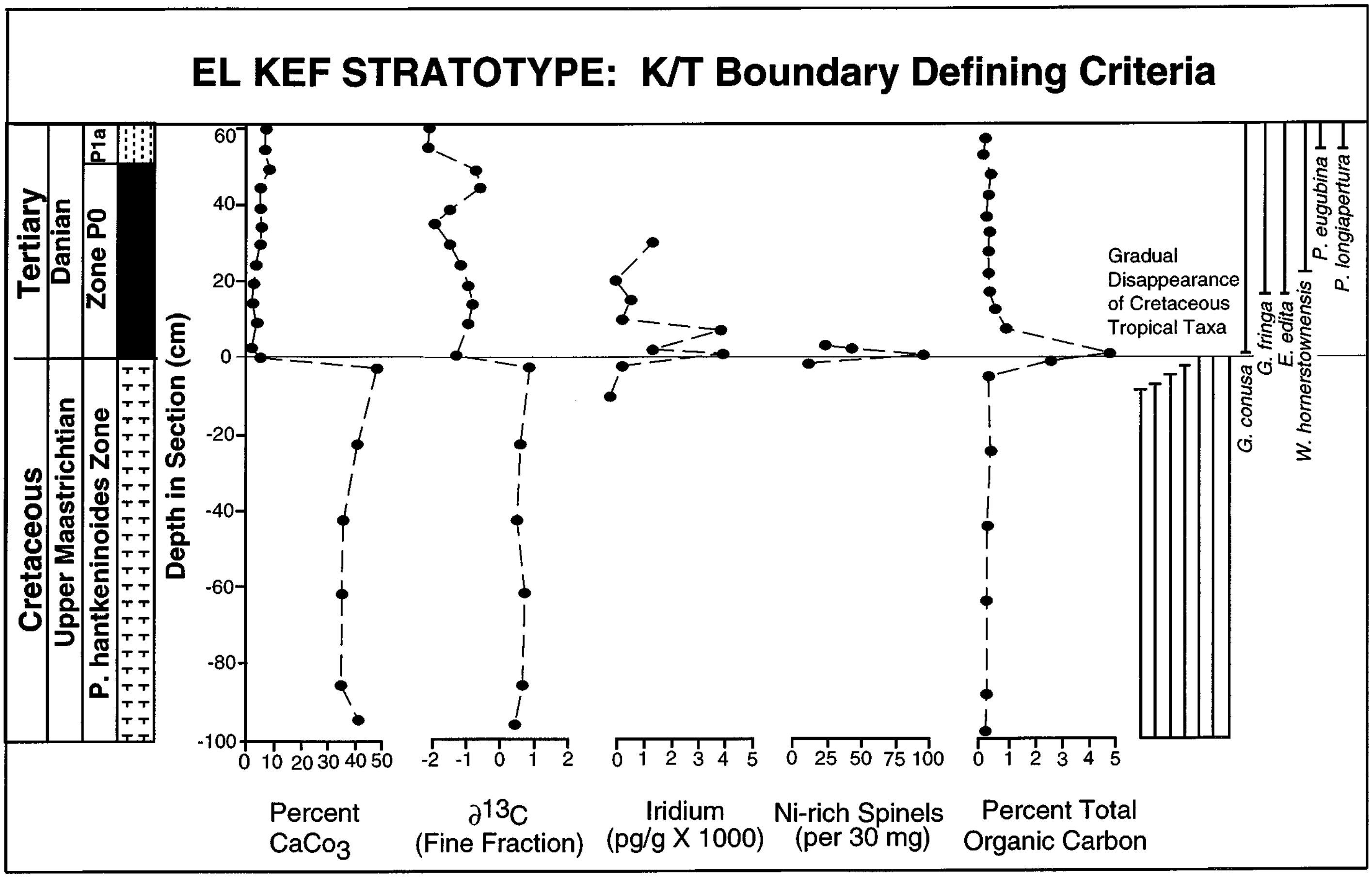


Figure 3. K/T boundary defining criteria at the El Kef stratotype section. CaCO$_3$, total organic carbon, and ^{13}C data from Keller and Lindinger (1989), iridium and Ni-rich spinel data from Robin et al. (1991), planktic foraminiferal data from Keller et al. (1996) and Ben Abdelkader (1992). The boundary clay layer is marked in black.

senting tsunami deposits and megawave seiching, and finally fine-grained detrital beds containing the finer products of the impact clouds, including iridium, and the last sediment suspension from the turbulent waters (Smit et al., 1992, 1994a; Alvarez et al., 1992). Proponents of this view have thus made interpretation of the several-meters-thick siliciclastic deposits in northeastern Mexico an ad hoc definition of the K/T boundary event for that particular region. In addition to being a highly irregular stratigraphic practice and circular reasoning, this redefinition of the K/T boundary excludes the biostratigraphic tools that would allow correlation with K/T boundary sites worldwide. Moreover, because the hypothesis has been made into “fact” by definition, testing its veracity becomes moot. Even if the tsunami interpretation of these siliciclastic units was undisputed, this would at best be unsound stratigraphic practice. However, because this interpretation is also questionable (see discussion below), the use of this deposit as a K/T boundary marker bed is unacceptable. If the stratigraphic position and global correlation of the K/T boundary event and the siliciclastic deposits in the Gulf of Mexico region are to be determined, then global stratotype criteria for the K/T boundary must be employed.

The defining criteria for the K/T boundary are well established on the basis of the stratotype section at El Kef, Tunisia, which represents the most complete K/T transition known to date. Stratotype sections are chosen to provide workers with uniform criteria in stratigraphic interpretations and correlations–they cannot, therefore, be changed to suit a particular region. The defining criteria for the El Kef stratotype are shown in Figure 3 and include the following. (1) There is a lithologic break from marl to clay deposition. At El Kef this boundary clay layer is 55 cm thick and represents zone P0, but in most sections worldwide this clay layer is only one to a few centimeters thick. Estimates for the duration of zone P0 vary from 40–50 k.y. on the basis of Milankovitch cycles in laminated clays and extrapolation from the paleomagnetic time scale (Herbert and D’Hondt, 1990; MacLeod and Keller, 1991a, 1991b) to 30–70 k.y. (Berggren et al., 1995). (2) A 2–3 mm oxidized red layer occurs at the base of the boundary clay. (3) Maximum Ir concentrations are found in the red layer and boundary clay, although they may tail tens of centimeters above because of bioturbation or postdepositional remobilization. (4) Ni-rich spinels are present in the red layer or base of the boundary clay. (5) A negative excursion of 2‰–3‰ occurs in ^{13}C values of surface waters, but this excursion is restricted to low latitudes (Keller, 1996). (6) The first appearance of the Tertiary planktic foraminifera *Globoconusa conusa* occurs at the base of the boundary clay, and *Eoglobigerina fringa*, *E. edita*, and *Woodringina hornerstownensis* appear within a few centimeters of the base of the boundary clay, red layer, Ir anomaly, and Ni-rich spinels (Fig. 3; Ben Abdelkader, 1992; Keller et al., 1996). (7) The extinction of tropical and subtropical taxa occurs at or below the K/T boundary clay. The coincidence of these lithological, geochemical, and paleontological criteria is unique in the geologic record and virtually ensures that the stratigraphic placement of the K/T boundary is uniform and coeval in marine sequences across latitudes. We have applied these K/T boundary criteria to the sections containing near-K/T siliciclastic deposits. Thus, in this report the "K/T boundary event" refers to the globally recognized K/T boundary and is stratigraphically distinct from the event that caused the Chicxulub structure and the siliciclastic deposits.

Except for the siliciclastic deposits, the K/T boundary sequences of northeastern Mexico are similar to those found at Agost and Caravaca in Spain (Smit et al., 1982; Canudo et al., 1991; Pardo et al., 1996), Stevns Klint and Nye Klov in Denmark (Schmitz et al., 1992; Keller et al., 1993b), and Brazos River, Texas (Jiang and Gartner, 1986; Keller, 1989). Similar to these localities, the northeastern Mexico sections exhibit short discontinuities in sedimentation due either to condensed intervals (dissolution and/or reduced productivity) or to short hiatuses, and the boundary clay (zone P0) is generally absent.

K/T Boundary at El Mimbral

We have analyzed two K/T transects at El Mimbral. Mimbral I is at the center of the channelized siliciclastic deposit and is the same location as the transect shown by Smit et al. (1992) and Stinnesbeck et al. (1993). Mimbral II is 122 m to the southwest near the edge of the channel where the siliciclastic sediments thin out, and only the topmost 20-cm-thick rippled sandy limestone layer is present. Mimbral II is more complete across the K/T boundary than Mimbral I, as demonstrated by Keller et al. (1994b), whereas Mimbral I has a more complete Maastrichtian interval exposed at the outcrop. In Figure 4 the species ranges of Mimbral I and II are shown as a composite, the Maastrichtian being represented by Mimbral I and the Tertiary by Mimbral II. Only the Mimbral section has been widely studied to date, and the bolide impact-generated tsunami interpretation is based on this section (Smit et al., 1992, 1994a; Stinnesbeck et al., 1993, 1994b). This may have led to erroneous interpretations. Although all northeastern Mexico sections are similar in overall aspects (e.g., the presence of siliciclastic sediments), they differ fundamentally in detail. For example, only the Mimbral section has Danian sediments directly overlying the siliciclastic member. In the three other localities examined (El Mulato, La Lajilla, and La Parida), a thin marl layer of Maastrichtian age overlies the top of the siliciclastic deposits, as discussed below.

Figure 4 shows that the Maastrichtian Méndez marls contain a diverse subtropical assemblage followed by relatively few foraminifers within the siliciclastic deposit, including the rippled sandy limestone layer in the topmost 20 cm. Above this layer at Mimbral II (but not Mimbral I) is a 3–4-cm-thick clay layer with a 2–3-mm-thick red oxidized layer at its base. This led Keller et al. (1994b) to suggest that this clay layer may represent zone P0, although no Tertiary species or Ni-rich spinels are present (Stinnesbeck et al., 1993). However, Rocchia and Robin (1994, personal commun.) suggested that this is probably not the K/T boundary clay because of the absence of spinels and high iridium.

Ir values analyzed for Mimbral I by Smit et al. (1992) and for Mimbral II by Rocchia (1993, written commun.; see also Rocchia et al., 1996), Stinnes-

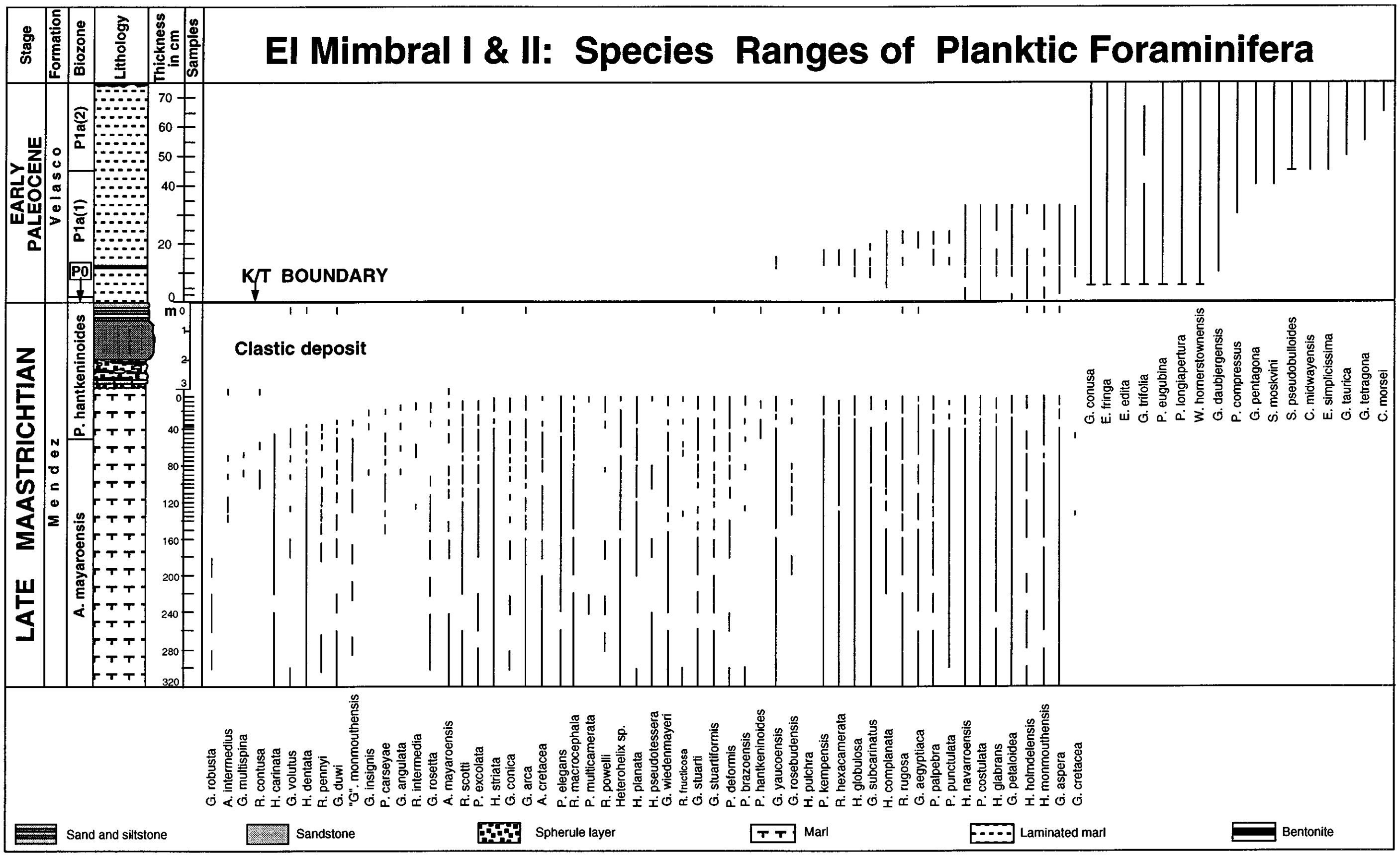


Figure 4. Stratigraphic ranges of planktic foraminifera across the K/T boundary at El Mimbral: Méndez marl and siliciclastic deposit from Mimbral II, K/T boundary and Tertiary part from Mimbral I, which is more complete than Mimbral II. Note that only at El Mimbral is the top of the siliciclastic deposit directly underlying Danian sediments. In all other K/T transitions examined, a Maastrichtian age marl layer overlies this member.

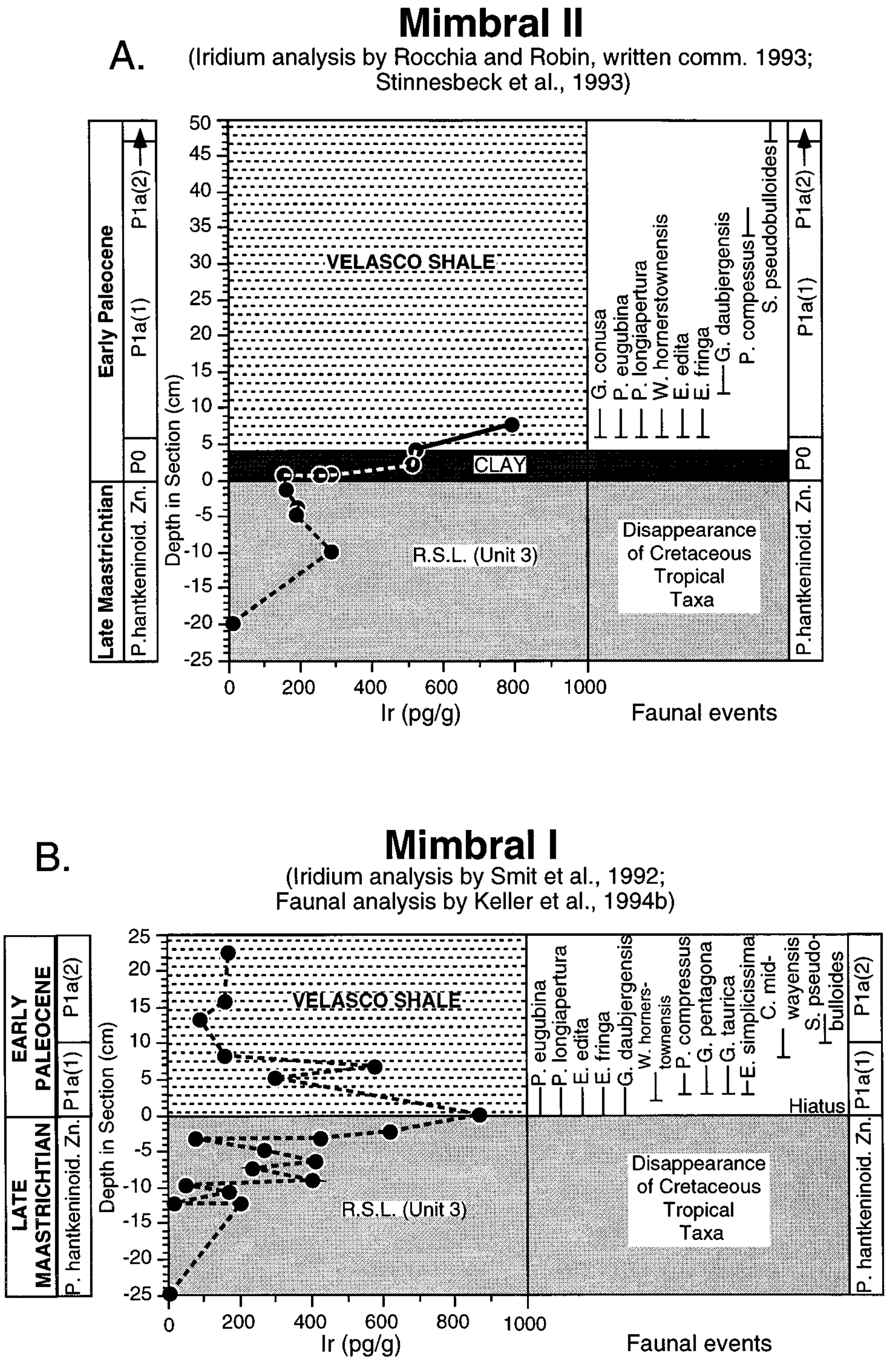


Figure 5. Iridium distribution, lithology, and first appearances of planktic foraminifera across the K/T interval at Mimbral II (A) and Mimbral I (B). Note that Ir distribution reaches maximum values in the shales 7.5 cm above the clay layer and top of the siliciclastic deposit at Mimbral II, but immediately above the siliciclastic member at Mimbral I. Together with faunal events, this indicates that Mimbral I is less complete. However, both sections have a K/T hiatus as seen by the simultaneous appearance of many Danian species which in K/T-complete sections evolve sequentially over the first 50–100 k.y. of the Danian. RSL—rippled sandy limestone at top of siliciclastic member.

beck et al. (1993), and Keller et al. (1994a) are shown in Figure 5 (A and B) along with the first appearances of Danian planktic foraminifera. Mimbral II was sampled for geochemical and foraminiferal analyses at the same time, whereas Mimbral I was first collected by Smit and others for geochemical and faunal analyses. Smit and others clearly marked their sampled interval with red numbers on the rock outcrops and Keller subsequently recollected this interval for faunal analysis. Because of the sharp lithologic changes at Mimbral I and the closely measured intervals given by Smit et al. (1992), the faunal record can be closely matched with the iridium record.

Only background iridium values were measured in the Méndez marl, the basal spherule bed (unit 1), the middle sandstone (unit 2), and the upper sand-silt beds (unit 3) of the siliciclastic deposit (Smit et al., 1992; Stinnesbeck et al., 1993). Within the top 10 cm of the siliciclastic deposit (rippled sandy limestone layer of Fig. 5, A and B), iridium values are generally less than 0.2 pg/g and are 0.6 pg/g within the overlying clay layer at Mimbral II. Maximum values of 0.8 pg/g are reached within the shales at 7.5 cm above the base of the clay and red layer in the more complete Mimbral II section (Fig. 5A). At Mimbral I, iridium values are similar to Mimbral II except that in the absence of the clay layer peak Ir concentrations are found in the shales immediately above the top of the rippled sandy limestone layer (Fig. 5B). In addition, slightly higher (0.4–0.6 pg/g) Ir concentrations are present in the top 2–3 cm of the rippled sandy limestone layer. This led Smit et al. (1992, 1994a) to interpret the top of the siliciclastic deposit as the final impact air fallout and settling from the water column. We suggest that postdepositional remobilization of iridium and concentration due to carbonate dissolution and nondeposition between the top of the siliciclastic sediments and overlying Velasco shales is a more likely interpretation for the following two reasons.

First, Mimbral I may be incomplete with zone P0 and much of the lower part of zone Pla(1) missing. This is apparent in the stratigraphy of the two transects as shown in Figure 5 (A and B). At Mimbral I, index species of zone Pla (1) (*P. eugubina* and *P. longiapertura*) are present in the basal 1 cm of the Velasco shale along with three other new Danian species followed by another five new Danian species 3 cm above (Fig. 5B). This simultaneous appearance of 10 new Danian species, which in K/T-complete sections evolve sequentially over the first 100–150 k.y. of the Danian, represents a hiatus. Moreover, index species of zone Pla(2) (*P. eugubina*, *P. longiapertura*, and *Subbotina pseudobulloides*), which appear at only 10 cm above the top of the siliciclastic deposit, also suggest a hiatus (Fig. 5B). In contrast, Mimbral II has a more expanded section, with zone Pla(1) appearing immediately above the clay layer and zone Pla(2) appearing at 47 cm (Fig. 5A). Nevertheless, this section also has a short hiatus, as indicated by the simultaneous first appearance of six species that evolved sequentially in the early Danian.

Second, Ir concentrations, which are supposed to represent settling from the air, should have settled within weeks or at most a year. Paleontological evidence, however, suggests a much longer time period. This is evident in the presence of several new Tertiary species (e.g., *Parvularugoglobigerina eugubina*, *P. longiapertura*, and *Globoconusa daubjergensis*) in the first few centimeters of the Tertiary Velasco Formation within peak Ir concentrations. Because these species evolved after the K/T boundary, settling from the water column after the K/T-impact–generated tsunami wave is unlikely. Although there is a possibility that Danian foraminifers were mixed downward by bioturbation, this could not account for the observed Ir profile. Perhaps the most likely explanation for the presence of higher Ir concentrations in Danian shales is postdepositional alteration of the original Ir maximum at the K/T boundary by erosion, remobilization, and bioturbation.

On the basis of currently available data and application of the stratotype criteria, we conclude that the K/T boundary at Mimbral is between the top of the siliciclastic deposit and the overlying Velasco shale, as discussed by Keller et al. (1994a, 1994b) and Stinnesbeck et al. (1993, 1994b). However, we agree that should the siliciclastic deposit at Mimbral and other sections be clearly shown to represent an impact-generated tsunami event deposited over a few hours or days, then the K/T boundary could arguably be placed at the base of this deposit, as Smit et al. (1992, 1994a) suggested. However, because trace fossil evidence and lithological and mineralogical data indicate that deposition occurred over an extended time period, placing the K/T boundary at the base of the siliciclastic deposit is not warranted. Ekdale and Stinnesbeck (1994, in press) observed several discrete burrowed horizons, often truncated by erosion in units 2 and 3 of the siliciclastic deposits. Because each of these bioturbated horizons indicates colonization by invertebrates of the ocean floor, and their truncation suggests interruption by an erosive event followed by sedimentation and subsequent recolonization, deposition by a tsunami over a few hours to days is definitely not the causal mechanism for the entire package of the siliciclastic deposits of northeastern Mexico.

K/T Boundary at El Mulato and La Parida

In the other three K/T sections examined (El Mulato, La Parida, and La Lajilla), a distinctive clay layer is not present, though planktic foraminifers clearly mark the K/T boundary (Figs. 6 and 7; see Lopez-Oliva and Keller,

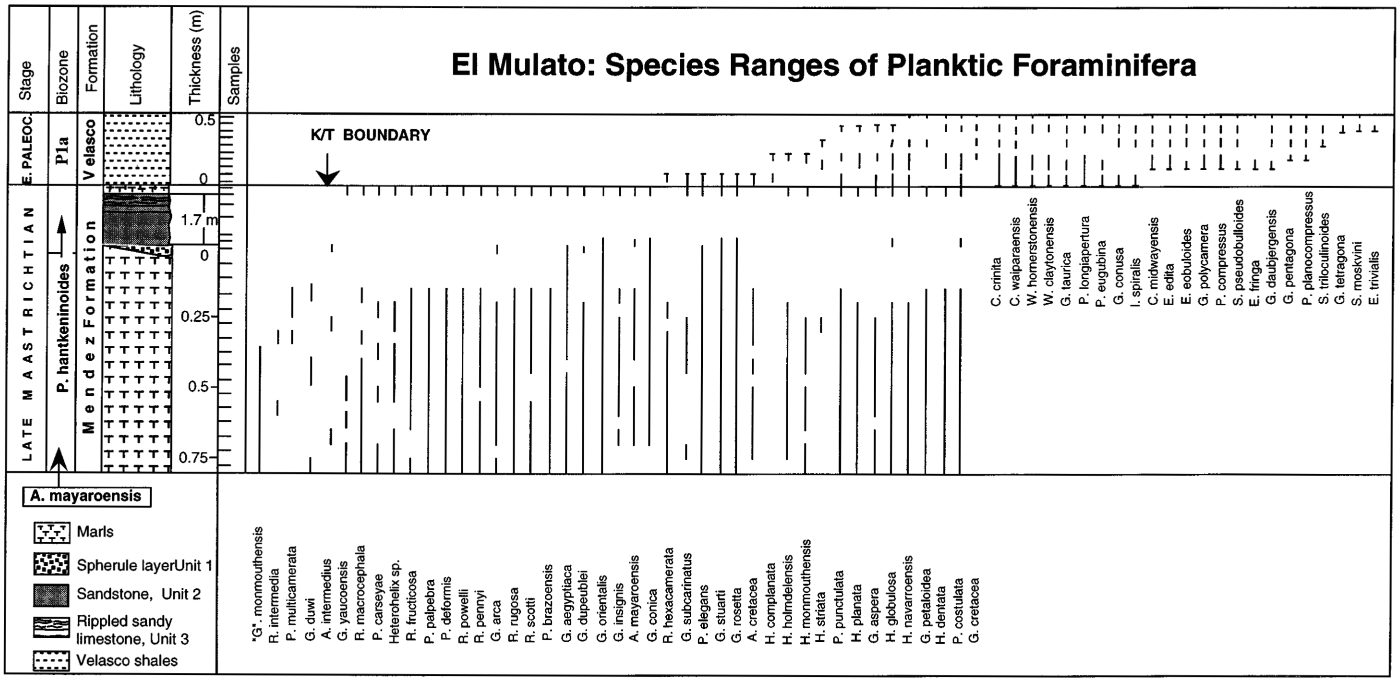


Figure 6. Stratigraphic ranges of planktic foraminifera across the K/T boundary at El Mulato. Note the presence of a rich Maastrichtian assemblage in the marl layer below the K/T boundary suggests the return of normal hemipelagic sedimentation after siliciclastic deposition and before the K/T boundary event. Note also that the simultaneous first appearance of nine Danian species marks a short hiatus at the K/T boundary. In the absence of *P. hantkeninoides*, this zone is tentatively identified based on correlation with other nearby sections.

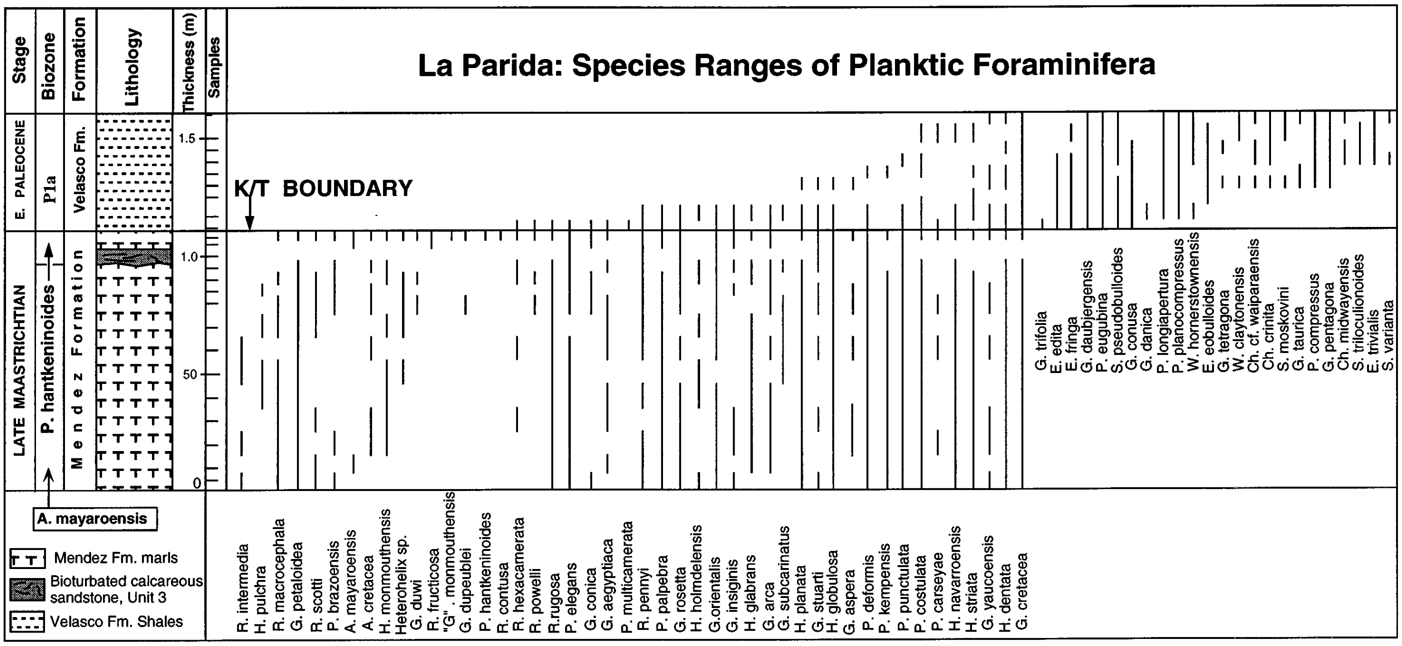


Figure 7. Stratigraphic ranges and relative abundances of planktic foraminifera across the K/T boundary at La Parida. Note that the presence of a rich Maastrichtian assemblage in the 5–10-cm-thick marl layer above the siliciclastic deposit and below the K/T boundary suggests the return of normal hemipelagic prior to the K/T boundary event. The siliciclastic deposit at this location is very thin and laterally disappears.

1996, for La Lajilla). In each of these sections, a 5–10-cm-thick marl layer with upper Maastrichtian planktic foraminifers directly overlies the top of the siliciclastic deposit and is in turn overlain by shales of the Tertiary Velasco Formation. The age and origin of this marl layer are critical in determining the stratigraphic position of the K/T boundary and the underlying siliciclastic deposit. However, interpretations differ. Smit et al. (1994a, personal commun.) maintained that this marl layer represents settling from the water column after the tsunami event and that therefore all planktic foraminifers present must be reworked. Thus, prior to locating the stratigraphic position of the K/T boundary, the reworking hypothesis must be examined.

Test of Reworking Hypothesis

The reworking hypothesis can be tested on the basis of several identifying criteria. (1) For example, if the fauna is reworked, then only a select subset of the fauna from which it is reworked should be present. This subset should consist of generally smaller taxa that are easily transported and resistant to breakage. However, the marl layer contains a diverse upper Maastrichtian foraminiferal assemblage, including nearly all and sometimes more species than are present in the Méndez marl below the siliciclastic deposit from which it is supposed to be reworked. Comparison of species richness in the marl layer with that within the Méndez marl below the siliciclastic deposit shows that at El Mulato there are 33 of 40 species present (Fig. 6). At La Parida, 40 species are present in the Méndez marl, but 41 species are within the thin marl layer above the siliciclastic deposit and 3 of these species are not present in the marls below (Fig. 7). Although high species richness and nonselectivity in the faunal assemblage is an inconclusive test of the reworking hypothesis, it provides strong evidence in favor of normal hemipelagic sedimentation.

(2) If faunas are reworked, then the relative abundance of species present should be random and/or biased toward species resistant to breakage; they should not reflect the proportions present within the original sediments from which they were derived. In fact, the marl layer in question has relative abundances of species that reflect normal upper Maastrichtian assemblages. Moreover, many species, both resistant and less resistant to breakage and small and large in size, have similar or higher relative abundances than in those assemblages from which reworked material is supposed to have derived. This is evident for both El Mulato and La Parida sections, as shown in Figures 8 and 9. However, normal high species abundances do not rule out the possibility of abundant reworking, but together with high species richness and no evidence of faunal selectivity, they significantly reduce the probability.

(3) If assemblages are reworked, there should be many benthic foraminifers present that are transported from shallower shelf regions into deeper waters, as observed within some intervals of the siliciclastic deposit (Keller et al., 1994b). This is not the case within the thin marl layer overlying the siliciclastic sediments; we observed a benthic foraminiferal assemblage that is similar to the late Maastrichtian Méndez Formation with no obvious transport from shallower regions. We conclude that the standard foraminiferal criteria used to identify reworking provide no obvious support for this hypothesis.

(4) We also attempted to test the reworking hypothesis based on whole rock analysis of seven different rock types within the three units of the siliciclastic sediments, the Méndez Formation marls below and the Velasco Formation shales above (Table 1). The thin marl layer appears most similar to the Méndez Formation marl and differs substantially from the various rock types within the siliciclastic deposit. This suggests a hemipelagic origin similar to the Méndez marl.

(5) Clay minerals have been analyzed as an additional test of the reworking hypothesis. Table 2 shows the average clay mineral compositions for the Maastrichtian thin marl layer in comparison with different rock types within the siliciclastic deposit, the Méndez Formation marl below and the Velasco Formation shale above. Clay mineral compositions differ considerably both within the three marl layers analyzed (Méndez marl, marl layers of unit 1 and Maastrichtian thin marl) and between shale, silt, and sandstone layers. The

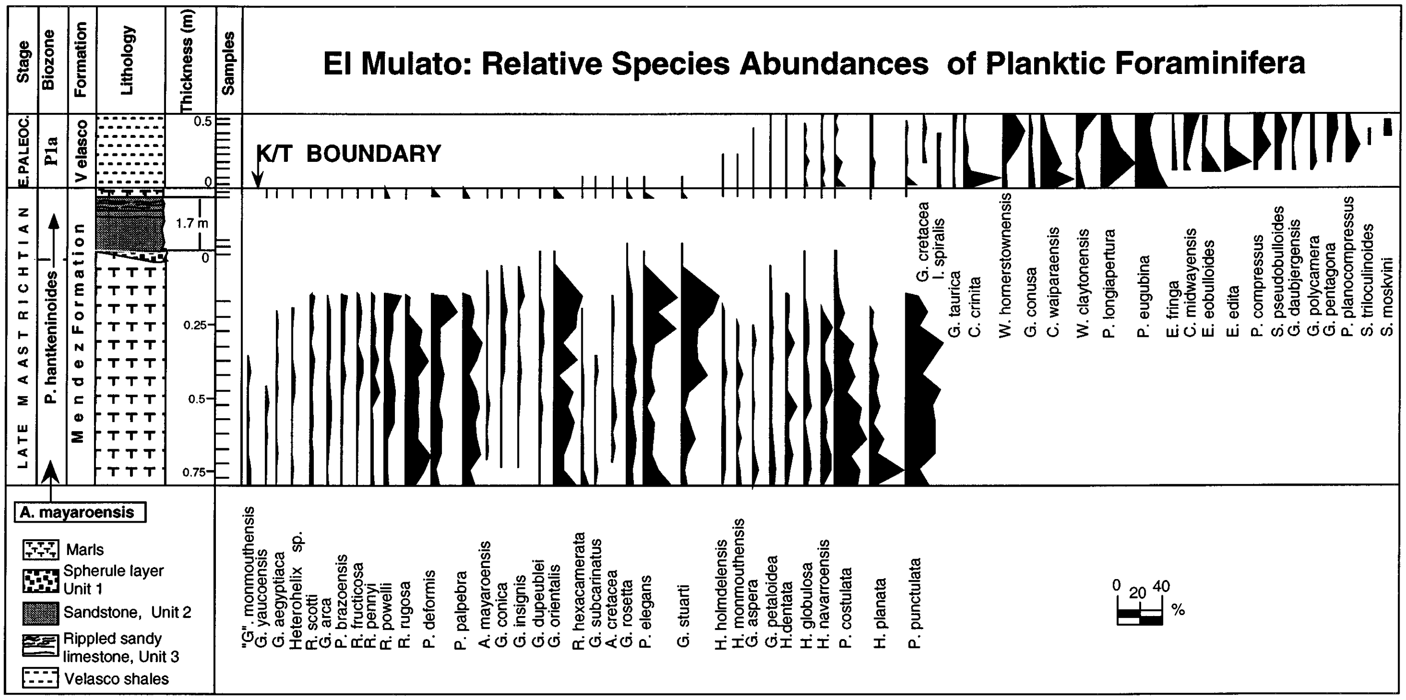


Figure 8. Relative abundances of planktic foraminifera across the Cretaceous–Tertiary transition at El Mulato. Note that the relative species abundances within the thin marl layer between the K/T boundary and siliciclastic deposit are similar or greater than species abundances in the Méndez marl below and indicate normal hemipelagic sedimentation prior to the K/T event. These species distributions are unlike the sporadic occurrences of mainly reworked species in most parts of the siliciclastic deposit that indicate shallow water transport.

thin marl layer is enriched in zeolites (2%), similar to two subunits in the upper unit 3 of the siliciclastic deposit; it is generally rich in chlorite and mica, similar to the Méndez marl, but also similar to most subunits of the siliciclastic deposit. Although we do not believe that diagenesis severely altered the clay minerals because the 1200 m of sediments which overlie the K/T boundary in this region are insufficient to cause significant transformation of clay minerals (e.g., from smectite to illite-smectite mixed layers and to illite), the presence of zeolites suggests some diagenesis through water-rock interaction.

(6) The reworking and settling from the water column hypothesis can be further tested on the basis of grain-size analysis of insoluble residues. If the marl layer is reworked, then the grain size should be coarser than the Méndez marl below. However, if the marl layer represents settling of fines from the water column, then the grain size should be fining upward from the top of the siliciclastic deposit. Table 3 shows granulometric data for various lithologic layers. These data show that the mean grain-size distribution of the Maastrichtian thin marl layer (4.95 mm) is similar to (though slightly lower than) the mean grain size of the Velasco shale (6.56 mm) above and the Méndez marl (6.63 mm) below, as well as the mean grain size of the sandy limestone layer within unit 1 (5.9 mm, Table 3). In contrast, the underlying rippled sandy limestone layer and sand layers of unit 3 and the sands of unit 2 have grain sizes that range from 8.92 to 10.85 mm. These granulometric data suggest a similar normal hemipelagic environment for deposition of the thin marl layer above the siliciclastic deposit, as for the Velasco shale and the Méndez marl. A comparison of the grain-size spectrum as a test for the reworking hypothesis also has its limitations; e.g., if significant diagenesis is present, as may be the case in the zeolite-enriched layers. However, these limitations seem to have been overlooked by Smit et al. (1994c), who used grain-size analysis of the Brazos River section to claim a reworking origin for the marl layer below the K/T boundary.

We conclude that of the six criteria tested for a reworking origin of the thin marl layer above the siliciclastic deposit, none show conclusive support for or against the reworking hypothesis.

K/T Boundary

Figures 6 and 7 show stratigraphic ranges of planktic foraminifera in the Mulato and Parida sections, which are similar to the trans-K/T stratigraphy of the Lajilla section (Lopez-Oliva and Keller, 1996). In each of these sections 50% to 66% of the Maastrichtian species disappear simultaneously at the top of the thin Méndez marl layer. In addition, six to nine Tertiary species simultaneously appear at the base of the overlying Velasco shale. This major faunal change between Cretaceous and Tertiary assemblages marks the globally recognized K/T boundary, although a hiatus is present. For example, at El Mulato, the K/T boundary is marked by the simultaneous appearance of 9 Danian species (*Chiloguembelina crinita*, *C. waiparaensis*, *Woodringina hornerstownensis*, *W. claytonensis*, *Globanomalina taurica*, *Parvularugoglobigerina eugubina*, *P. longiapertura*, *Globoconusa conusa*, and *Igorina spiralis*; Fig. 6), whereas at Parida (Fig. 7), 6 Tertiary species simultaneously first appear (*G. conusa*, *E. edita*, *E. fringa*, *P. eugubina*, *Subbotina pseudobulloides*, and *Globoconusa daubjergensis*), and at Lajilla, 11 Tertiary species simultaneously appear (Lopez-Oliva and Keller, 1996). This sudden change and the simultaneous appearance of many Tertiary species, which are known to evolve sequentially over the first l00 to 150 k.y. of the Tertiary, indicate a hiatus. A hiatus is also suggested by the high relative abundance of Danian species at their initial occurrence in all four sections examined and here shown for El Mulato and La Parida in Figures 8 and 9 (see Keller et al., 1994b, for El Mimbral relative abundances). Newly evolving species are generally rare at their initial appearances and only later

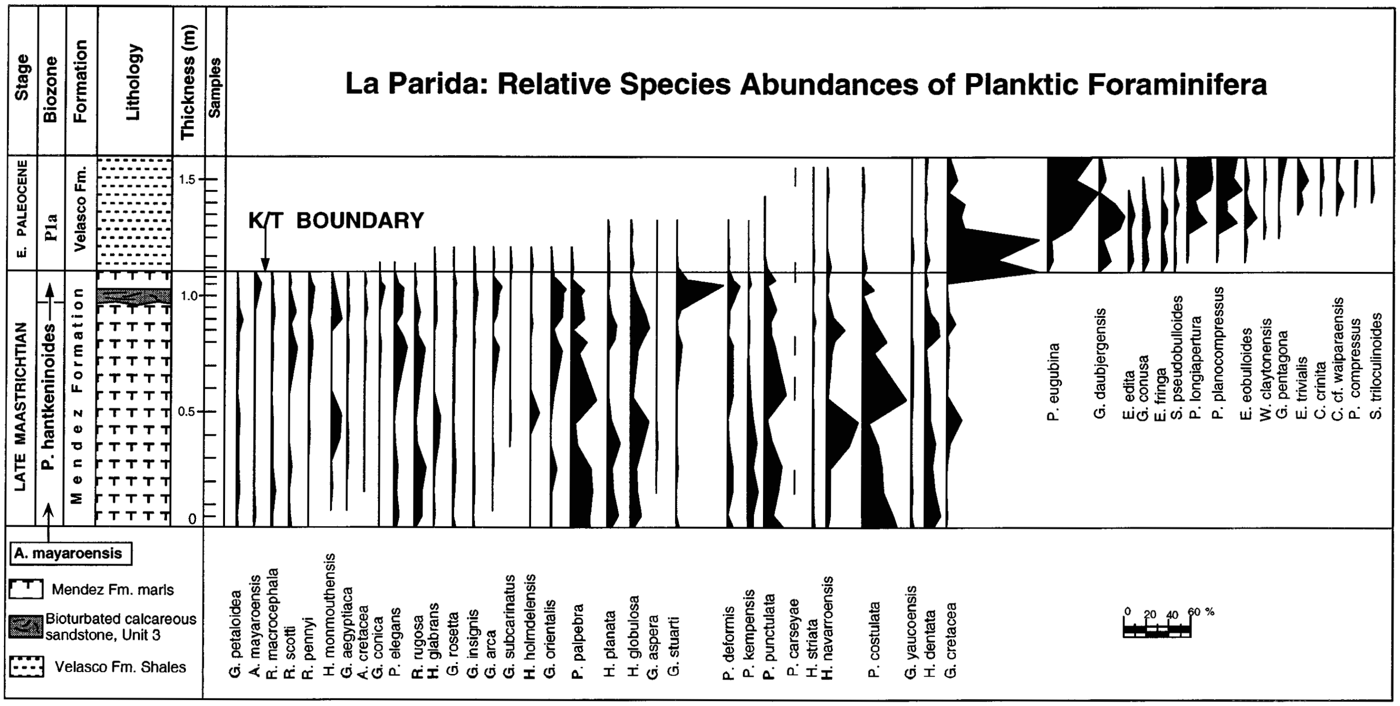


Figure 9. Relative abundances of planktic foraminifera across the Cretaceous–Tertiary transition at La Parida. Note that the relative species abundances within the thin marl layer between the K/T boundary and siliciclastic deposit are similar or greater than species abundances in the Méndez marl below and suggest normal hemipelagic sedimentation prior to the K/T event.

develop populations with numerous individuals; for this reason, high relative abundances of species at their initial appearance are generally interpreted as strong support for a hiatus or condensed interval.

The time interval missing at this hiatus can be estimated from key foraminiferal index species. In each of the sections examined, zone P1a index taxa, *P. eugubina* and *P. longiapertura*, and several species that first appear within zone P1a are present in the basal Tertiary Velasco shale. This indicates a short hiatus with zone P0 and varying parts of the lower part of zone P1a (Pla 1) missing in all three sections, as also observed at El Mimbral (Figs. 4 and 5A). It is possible that uppermost Maastrichtian sediments were also eroded at this hiatus, although this cannot be determined with the present stratigraphic resolution. A K/T boundary hiatus, or condensed interval, has been observed in K/T sections worldwide (MacLeod and Keller, 1991a, 1991b).

TABLE 2. CLAY-MINERAL ANALYSIS

Unit	Zeolite (%)	Chlorite (%)	Mica (%)	Illite-smectite (%)	Chlorite-smectite (%)
Velasco Formation	0.5	47	35	11	7
Maastrichtian thin marl layer	2	32	46	15	5
Unit 3 rippled sandy limestone	3	39	35	16	7
Unit 3 silt-shale layers	0	30	18	41	11
Unit 3 sandstone layers	2	41	42	12	3
Unit 2 massive sandstone	0	37	43	17	0
Unit 1 spherule-rich layers	0	40	19	22	18
Unit 1 S.S.L.	0	39	37	15	9
Unit 1 marl layers	0	19	18	54	9
Méndez Formation	0	40	35	25	1

Note: Average clay-mineral compositions for El Peñon, El Mulato, and La Lajilla sections (in percent of the size fraction <2 mm) for the marls of the Méndez Formation, three units and subunits of the siliciclastic deposit, the thin late Maastrichtian marl layer overlying the siliciclastic deposit, and the early Paleocene Velasco Formation. Number of samples analyzed for each layer is indicated in Table 3.

TABLE 1. WHOLE-ROCK ANALYSIS

Unit	Calcite (%)	Quartz (%)	Phyllosilicate (%)	Plagioclase (%)
Velasco Formation	35	21	36	8
Maastrichtian thin marl layer	53	9	34	6
Unit 3 rippled sandy limestone	36	28	22	15
Unit 3 silt-shale layers	31	22	36	11
Unit 3 sandstone layers	39	28	16	17
Unit 2 massive sandstone	34	31	19	16
Unit 1 spherule-rich layers	64	10	20	6
Unit 1 S.S.L.	43	24	23	10
Unit 1 marl layers	38	13	41	8
Méndez Formation	48	15	30	8

Note: Average whole-rock compositions for marls of the Méndez Formation, three units and subunits of the siliciclastic deposit, the thin late Maastrichtian marl layer above the siliciclastic deposit, and the early Paleocene shales of the Velasco Formation. Number of samples anlayzed for each layer is indicated in Table 3.

TABLE 3. GRAIN-SIZE ANALYSIS

Unit	Samples (no.)	Grain size	
		Median	Mean
Velasco Formation	12	5.6	6.56
Maastrichtian thin marl layer	5	3.98	4.95
Unit 3 rippled sandy limestone	6	8.14	9.2
Unit 3 silt-shale layers	17	5.56	7.08
Unit 3 sandstone layers	19	9.01	10.85
Unit 2 laminated sandstone	13	7.09	8.92
Unit 1 spherule-rich layers	10	12.6	14.12
Unit 1 S.S.L.	3	4.5	5.9
Unit 1 marl layers	11	7.92	7.92
Méndez Formation	18	6.63	6.63

Note: Average grain-size spectra, and samples analyzed, for El Peñon, El Mulato, La Lajilla, and El Mimbral for marls of the Méndez Formation, three units and subunits of the siliciclastic deposits, the thin late Maastrichtian marl layer overlying the siliciclastic deposit, and the early Paleocene Velasco Formation.

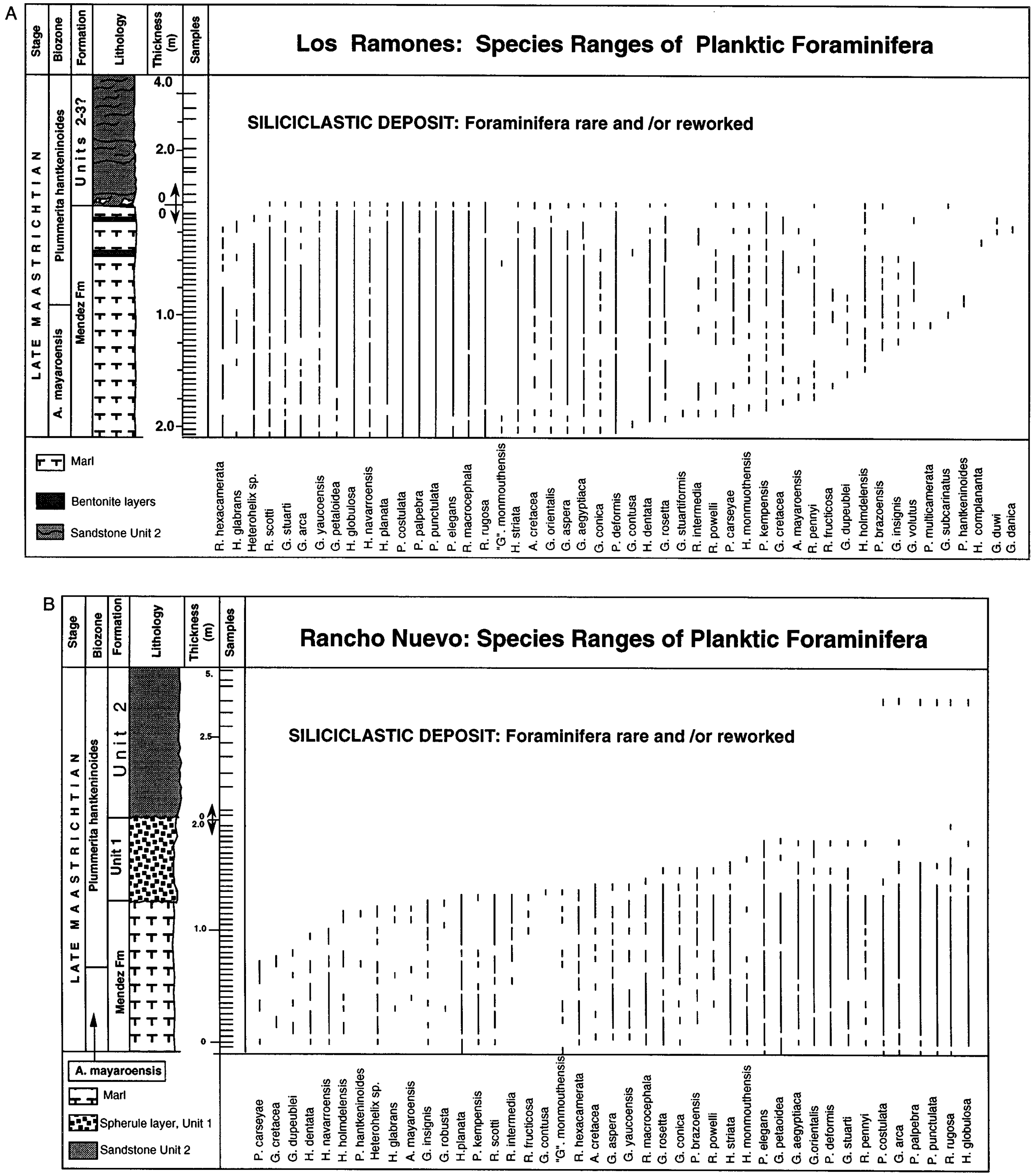


Figure 10. Stratigraphic ranges of planktic foraminifera at Los Ramones (A) and Rancho Nuevo (B). Note the presence of *P. hantkeninoides* below the clastic deposit indicates that deposition occurred during the last 170–200 k.y. of the Maastrichtian.

Age of Siliciclastic Deposits

What is the relationship of the siliciclastic deposits to the K/T boundary event? The presence of Maastrichtian and absence of Danian planktic foraminifera leaves no doubt that the siliciclastic sediments are of Maastrichtian age deposited at or before K/T boundary time (Stinnesbeck et al., 1993, 1994a; Keller et al., 1993a, 1993b, 1994a, 1994b). Until now, however, it has been impossible to bracket the time interval during which deposition took place. This is now possible with the new *Plummerita hantkeninoides* zone, which spans the last 170–200 k.y. of the Maastrichtian (chron 29R be-

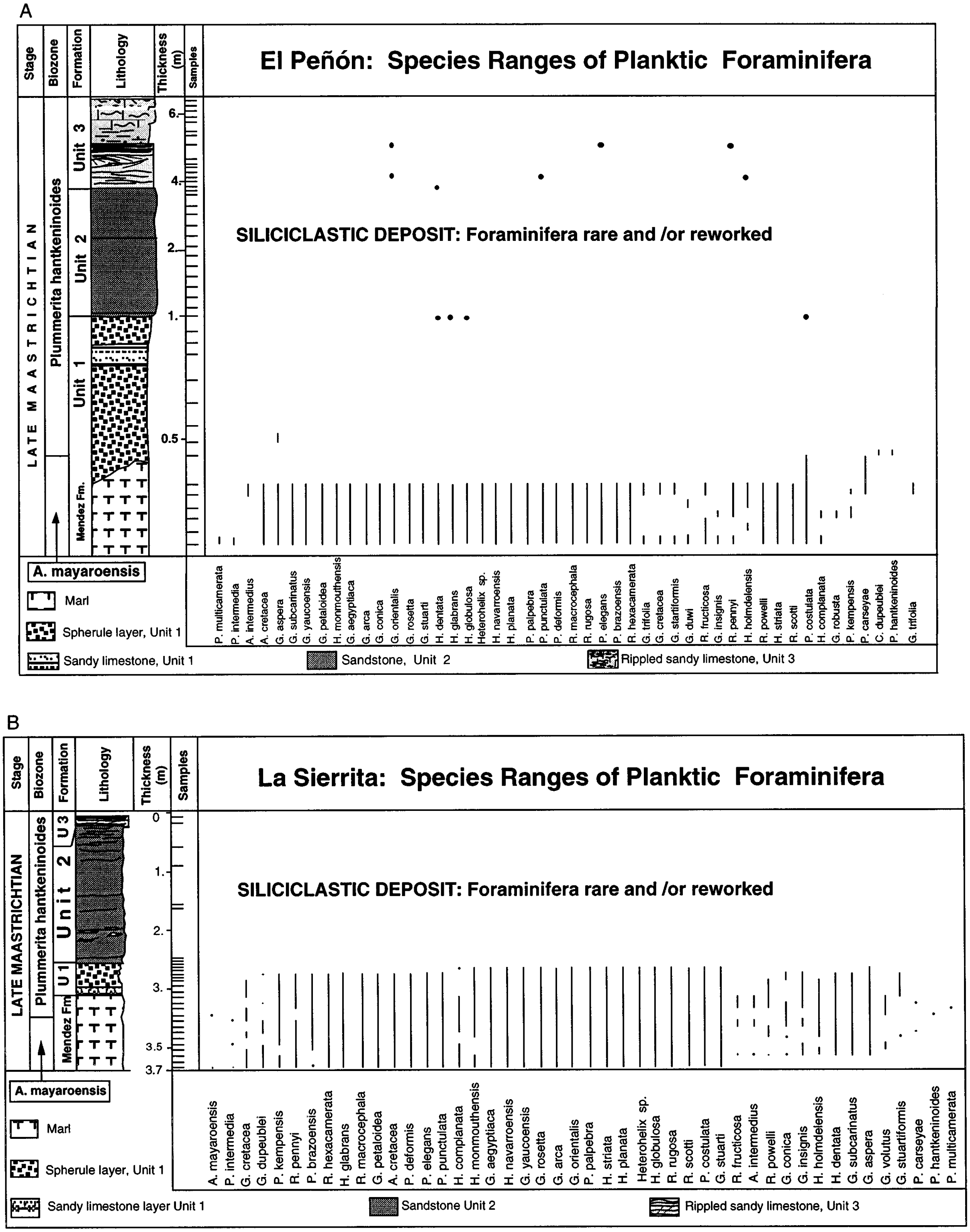


Figure 11. Stratigraphic ranges of planktic foraminifera at El Peñon (A) and La Sierrita (B). Note the presence of *P. hantkeninoides* just below the clastic deposit indicates that deposition occurred during the last 170–200 k.y. of the Maastrichtian.

low the K/T boundary at Agost; Pardo et al., 1996). In all but one (Mulato) of ten Mexican K/T sequences examined to date, *P. hantkeninoides* is present below, within, or often above the siliciclastic deposits, but always below the K/T boundary (Figs. 4 and 7). Moreover, in each of the sections examined where the siliciclastic deposit surfaces with no overlying Tertiary sediments (e.g., Ramones, Rancho Nuevo, Peñon, Sierrita; Figs. 10 [A and B] and 11

[A and B]), *P. hantkeninoides* is present in the 0.2 m to 1.0 m of Méndez marls below the siliciclastic deposits. This indicates that deposition of this member occurred sometime within the last 170–200 k.y. of the Maastrichtian. Because the siliciclastic deposit rests on an undulating erosional surface of Méndez marl, one would expect variable erosion and hence a variable thickness of this zone. However, the well-constrained presence of *P. hantkeninoides* below the siliciclastic deposits in all sections suggests that erosion was minor and that the onset of siliciclastic deposition could have occurred as early as 150 k.y. before the K/T boundary (lower part of *P. hantkeninoides* zone). Figure 12 shows the stratigraphic correlation of the four most complete K/T sections in northeastern Mexico. Although siliciclastic deposits vary in thickness from a few centimeters to several meters, all were deposited within the *P. hantkeninoides* zone and are thus correlative.

Siliciclastic deposition appears to have terminated some time before the K/T boundary event as indicated by the presence of the thin (5–10 cm) marl layer above the siliciclastic deposit at the Lajilla, Mulato, and Parida sections. In the absence of any evidence of reworking, we suggest that this marl layer represents normal hemipelagic sedimentation which resumed at least some thousands of years before the K/T boundary event.

LONG-TERM DEPOSITION—THE SMOKING GUN

Case of the Burrows

Abundant burrows present at the top of the siliciclastic deposit were originally interpreted by Smit et al. (1992, 1994a, 1994b) as originating from overlying Tertiary organisms that burrowed downward, and by Stinnesbeck et al. (1993, 1994) and Keller et al. (1994b) as resident Maastrichtian burrowers. However, neither argument was conclusive. With new evidence of burrowing within the siliciclastic deposits, the depositional nature can now be clarified.

The siliciclastic deposits of northeastern Mexico have been described in detail in several publications, including Smit et al. (1992), Stinnesbeck et al. (1993, 1996), Longoria and Grajales Nishimura (1993), and Keller et al. (1994a). Three lithologic units are generally recognized as shown for the El Peñon I section along with burrowed intervals and disconformities (Fig. 13A). The basal unit 1 consists of a spherule-rich 65–75-cm-thick friable interval of alternating laminae of clay and calcite spherules that is apparently unbioturbated. Within this unit is a 20-cm-thick well-cemented

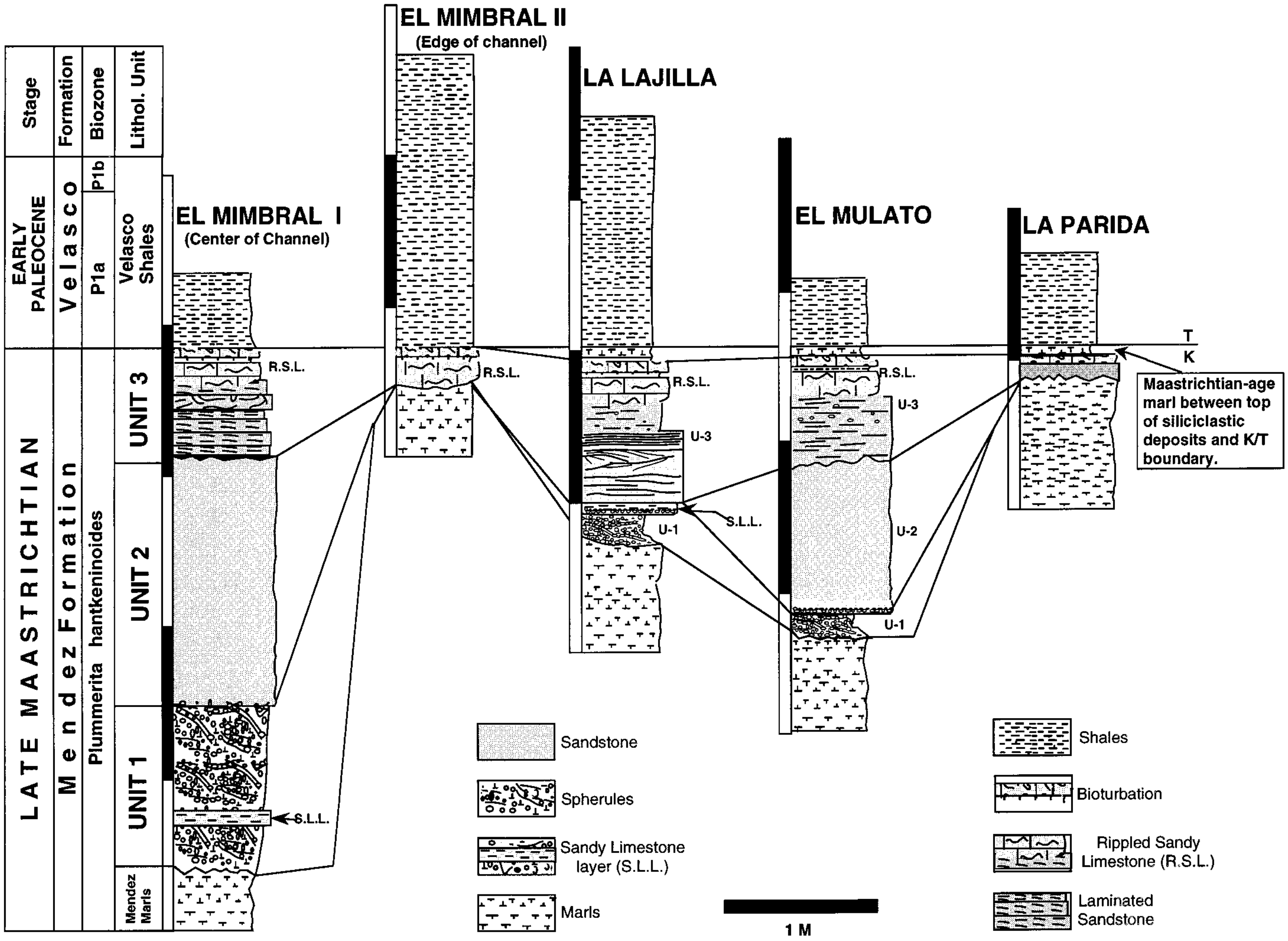


Figure 12. Lithologic and biostratigraphic correlation of the four most continuous K/T boundary sections in northeastern Mexico. Note that the three units (U-1, U-2, U-3) of the siliciclastic deposits can be correlated over 250–300 km. In three out of the four sections a Maastrichtian marl layer overlies the siliciclastic deposits, suggesting that normal hemipelagic sedimentation resumed prior to the K/T boundary. R.S.L.—rippled sandy layer, S.L.L.—sandy limestone layer.

sandy limestone layer (Fig. 12) that in many sections is bounded by disconformities and that contains few graded spherules at the base and top. Unit 1 is the most exotic of the three units with its abundant spherules and rare glass. The chemical composition of the glass is similar to that of glass spherules from Beloc, Haiti, and suggests the same origin, whether volcanic or impact (see Koeberl, 1994; Lyons et al., 1992; Robin et al., 1994).

Unit 2 is a sandstone that disconformably rests upon unit 1 and consists of texturally and compositionally homogenous sediments with little evidence of primary sedimentary structures. In some sections, the basal part has alternating fine and coarse-grained laminae. Spherule-filled burrows of crabs or other crustaceans are present in the laminated lower part of unit 2 as shown for El Peñon in Figure 13B, and these burrows are truncated by the overlying sand layers. Ekdale and Stinnesbeck (1997) interpreted these burrows as having been excavated as open burrows following deposition of the first sand layers and then filled with spherules, scoured and overlain by more unit 2 sand. The presence of these burrows indicates a hiatus in sedimentation long enough to allow burrowers to colonize the substrate, followed by deposition of the massive sandstone of unit 2. Thus, deposition of unit 2 was from multiple events and could not have occurred over a period of hours to days.

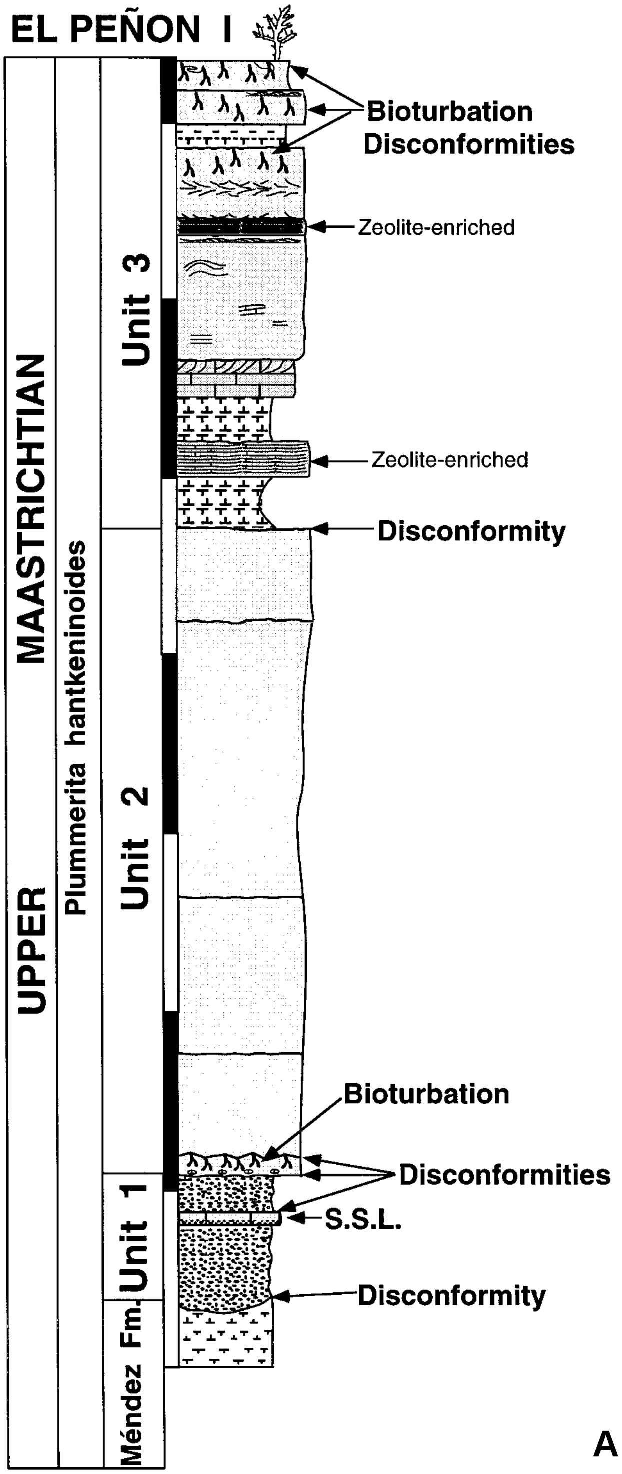
Unit 3 disconformably overlies unit 2 and consists of alternating sand, silt, and shale beds topped by one to several rippled sandy limestone layers (Figs. 12 and 13A). Fine-grained layers contain typical Maastrichtian planktic foraminiferal assemblages, which suggest periods of normal hemipelagic sedimentation (Keller et al., 1994a, 1994b). Two distinct layers are enriched in zeolites and suggest a glass precursor (Keller et al., 1994a; Adatte et al., 1994, 1996). Unit 3 is heavily burrowed by a group of deposit feeders (e.g., *Ophiomorpha*, *Chondrites*, *Zoophycos*, *Planolites*, and *Thalassinoides*) that represent permanent or semipermanent colonization of the substrate. A detailed discussion of these burrows and burrowing organisms is provided by Ekdale and Stinnesbeck (in press). At least three discrete intervals of bioturbation were observed in two rippled sand beds of the upper part of unit 3 and at the top of unit 3 (Fig. 13, C–E). In some bioturbated layers, *Chondrites* and (separately) *Ophiomorpha* are truncated by overlying sand beds. Sediment infilling of borrows in the topmost bioturbated layer of unit 3 contain exclusively late Maastrichtian foraminifera. This suggests that they were infilled prior to deposition of the overlying Tertiary shales of the Velasco Formation. Burrowing evidence thus indicates that the sands of unit 3 were deposited episodically and interrupted at least three times by successive episodes of colonization by invertebrates.

Bioturbation is thus the “smoking gun” that disproves the short-term impact-generated tsunami scenario for the siliciclastic deposits of northeastern Mexico. However, the discovery of multiple horizons of bioturbation also throws doubt on current alternative depositional scenarios such as a turbidite triggered by an impact-generated tsunami or earthquake (Bohor and Betterton, 1993), or the sea-level regression-transgression scenario (Stinnesbeck et al., 1993; Keller et al., 1994a). No satisfactory scenario exists to explain the unusual siliciclastic deposits. It is possible that they represent several tsunamis or unusual storm beds over a period of time, as suggested for the Brazos River clastic deposit by Yancey (1995).

TIMING OF IMPACT—OR IMPACTS?

It is often assumed, largely on the basis of the presence of glass, that the siliciclastic deposits of northeastern Mexico represent the globally recognized K/T boundary (impact) event. We caution that this may not be the case. It is generally agreed that glass from Mimbral, Haiti, and Chicxulub is of similar chemical composition (e.g., Smit et al., 1992; Swisher et al., 1992; Koeberl and Sigurdsson, 1992; Stinnesbeck et al., 1993; Koeberl et al., 1994) and hence probably the same origin. A consensus seems to be

Figure 13. (A) Lithostratigraphy of the Peñon I section with bioturbated intervals and disconformities marked. Scale is in meters. (B) Close-up of spherule-filled burrow truncated by scour and overlying sand, near the base of unit 2 at El Peñon. Burrows of this nature are 0.5 to 1.5 cm in diameter and 6 to 10 cm long. (C) Chondrites burrows exposed on bedding planes within unit 3 at El Peñon. (D) Vertical shafts of Chondrites burrows some of which are truncated by scour and overlying sand, within unit 3 at El Peñon. (E) *Ophiomorpha* burrows exposed on bedding planes within sandstone near top of unit 3 at Los Ramones.



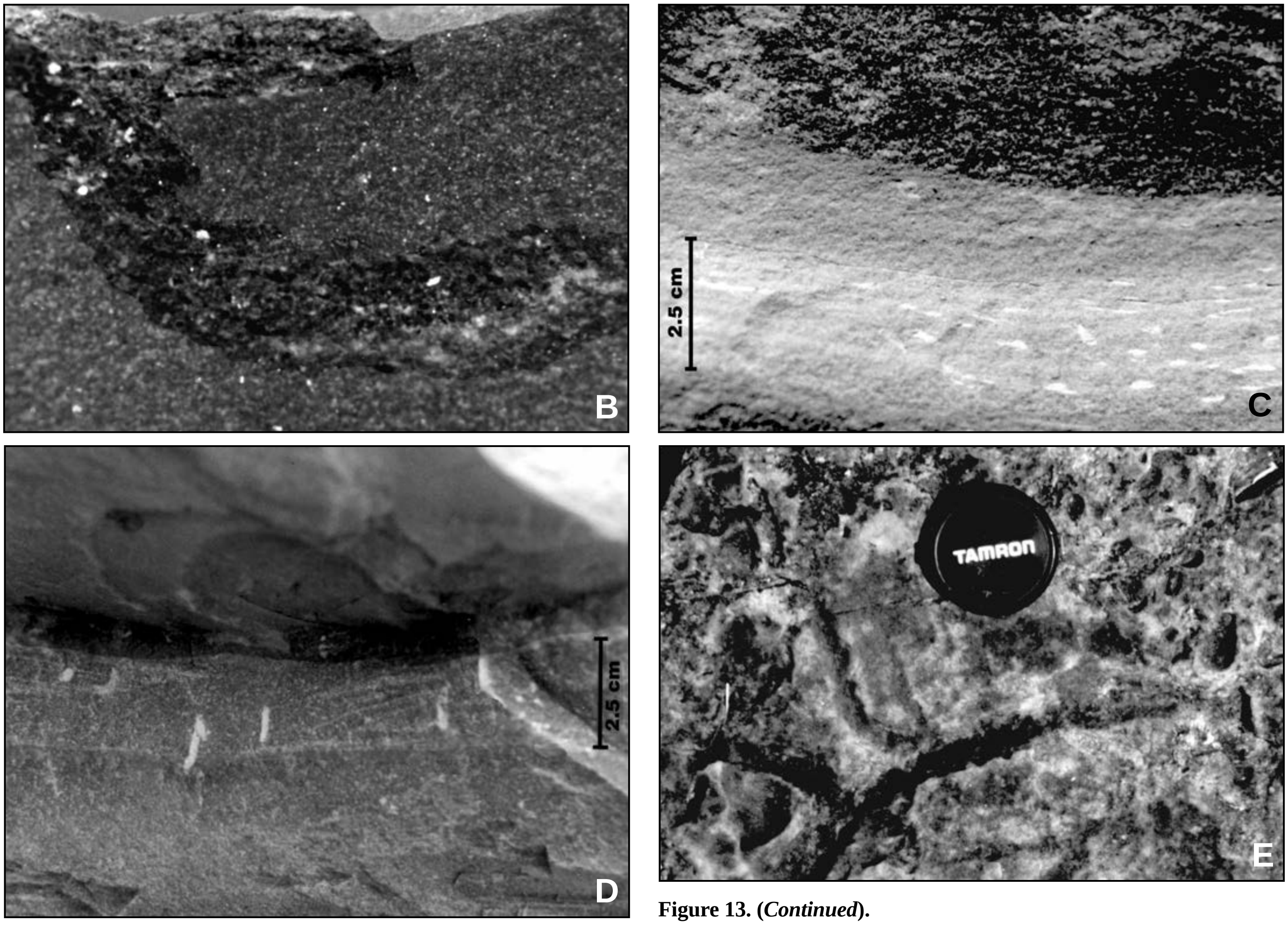


Figure 13. (*Continued*).

emerging that the origin of the glass is a bolide impact near Chicxulub, Yucatan; however, there are still some concerns that a volcanic origin cannot be excluded, as some authors have argued (for a discussion of the pros and cons of this argument, see Koeberl, 1994; Lyons et al., 1992; Robin et al., 1994; Leroux et al., 1995). Whether impact or volcanic origin, it appears safe to assume that the same event produced the glass at all three locations.

The next obvious question is the timing of this event. Was the glass produced by the K/T boundary impact, as generally assumed? Jéhanno et al. (1992) and Leroux et al. (1995) suggested that the glass in the Beloc (Haiti) section may have originated from a second event that preceded the K/T boundary. They based their argument on the 25–30-cm-thick carbonate-rich layer that stratigraphically separates the spherule layer from the overlying Ir anomaly, and peak abundance of Ni-rich spinels, which are associated with the globally recognized K/T boundary. Shocked quartz has two distinct peak distributions in the Beloc section, one at the K/T boundary and one below, at the top of the spherule-rich layer. Thus, Jéhanno et al. (1992) and Leroux et al. (1995) suggested the possibility of two events, one impact and the other impact or volcanic. Evidence from the northeastern Mexico sections seems to support their observations and may provide some time constraints for the depositional age of the pre-K/T event. In these sections, the stratigraphic position of the glass-bearing spherule layer is at the base of the siliciclastic deposit and separated from the K/T boundary by multiple event, episodic, and long-term deposition (e.g., bioturbation). Stratigraphic control suggests that this deposition occurred sometime during the last 100–150 k.y. of the Maastrichtian, but ended at least several thousand years before the K/T boundary. A stratigraphic age estimate of glass deposition within the last 150 k.y. of the Maastrichtian is well within the age uncertainties of the ^{40}Ar/^{39}Ar ages measured from two glasses from Mimbral, which yielded 65.05 ± 0.30 Ma and 65.09 ± 0.45 Ma (Swisher et al., 1992).

Chicxulub—A Pre-K/T Event?

^{40}Ar/^{39}Ar ages of between 65.2 ± 0.4 Ma and 64.98 ± 0.05 Ma for melt rock of andesitic composition beneath breccias from Chicxulub cores and a mean age of 65.01 ± 0.08 Ma for glass from Mimbral and Haiti are frequently quoted as evidence for a K/T boundary age of the Chicxulub structure (Sharpton et al., 1992; Swisher et al., 1992). Although these ages suggest that the measured glass in all three locations is probably coeval, as supported by geochemical compositions, they provide no age resolution for distinguishing two events that may have occurred within less than 100 k.y. of each other.

Our investigation suggests that there may have been two closely spaced events at K/T boundary time: a global (impact) event at the K/T boundary that is marked by mass extinctions, an iridium anomaly, and spinels, and a second Caribbean event preceding the boundary event by a minimum of several tens of thousands of years and a maximum of 150 k.y. The earlier

Caribbean event produced abundant glass and shocked quartz (Beloc), but no iridium anomaly or spinels (Smit et al., 1992; Stinnesbeck et al., 1993; Leroux et al., 1995). Which of these events is represented at Chicxulub? Geochemical studies of Mimbral, Beloc, and Chicxulub glasses have yielded very similar compositions, leading to the conclusion that they have the same origin (Izett, 1990; Jéhanno et al., 1992; Smit et al., 1992; Lyons and Officer, 1992; Koeberl, 1993; Koeberl et al., 1994). On the basis of these studies, the Chicxulub structure should have been produced by the earlier, pre-K/T event.

There is some stratigraphic evidence for a possible pre-K/T age of the Chicxulub structure (Ward et al., 1995). For example, in well C1, Lopez Ramos (1973, 1983) reported 180 m of interbedded shales, marls, and limestones containing a well-developed Maastrichtian age foraminiferal fauna overlying the breccia unit. Ward et al. (1995) suggested, on the basis of electric-log correlations, that only about 18 m of these Maastrichtian sediments may be true marls and limestones. Nevertheless, their presence suggests that breccia emplacement may have preceded the K/T boundary event, although this must still be confirmed by micropaleontological analysis.

DISCUSSION AND CONCLUSIONS

The critical questions to be answered in deciphering the sequence of events across the K/T boundary in Mexico are: Where, stratigraphically, is the K/T boundary and mass extinction? What is its stratigraphic relationship to the breccia and siliciclastic deposits? What is the nature and tempo of siliciclastic deposition; is it single event or multiple events? What is the stratigraphic relationship of these deposits to the Chicxulub event? In the previous sections we presented evidence in answer to each of these questions. In some cases, the new evidence fundamentally alters previous concepts and interpretations of siliciclastic deposition in Mexico (e.g., short-term tsunami deposition over hours or days is disproved), and in others, reevaluation of current K/T-impact scenarios on Yucatan are called for (e.g., Chicxulub structure may represent a second pre-K/T event). Major findings of this study are discussed and summarized below.

Siliciclastic deposits predate the K/T boundary. The globally recognized K/T boundary, Ir anomaly, and associated mass extinction of planktic foraminifera are stratigraphically above and separated by a thin marl layer from the siliciclastic deposits in three of four sections examined in northeastern Mexico (Lajilla, Mulato, Parida; Figs. 6, 7, 12). We find no evidence of reworking in this marl layer and suggest that it represents the resumption of normal hemipelagic sedimentation prior to the K/T boundary. A similar stratigraphic sequence of siliciclastic deposits or breccias followed by marls preceding the K/T boundary has been observed in sections from Texas to Brazil (Fig. 14, Keller and Stinnesbeck, 1996a). For example, the K/T boundary and Ir anomaly in the Brazos River sections are 15–20 cm above the clastic deposit (Jiang and Gartner, 1986; Keller, 1989); in Beloc, Haiti, they are 25–30 cm above the spherule layer (Jéhanno et al., 1992; Leroux et al., 1995); at Bochil, southern Mexico, they are 1 m above the breccia (Mon-

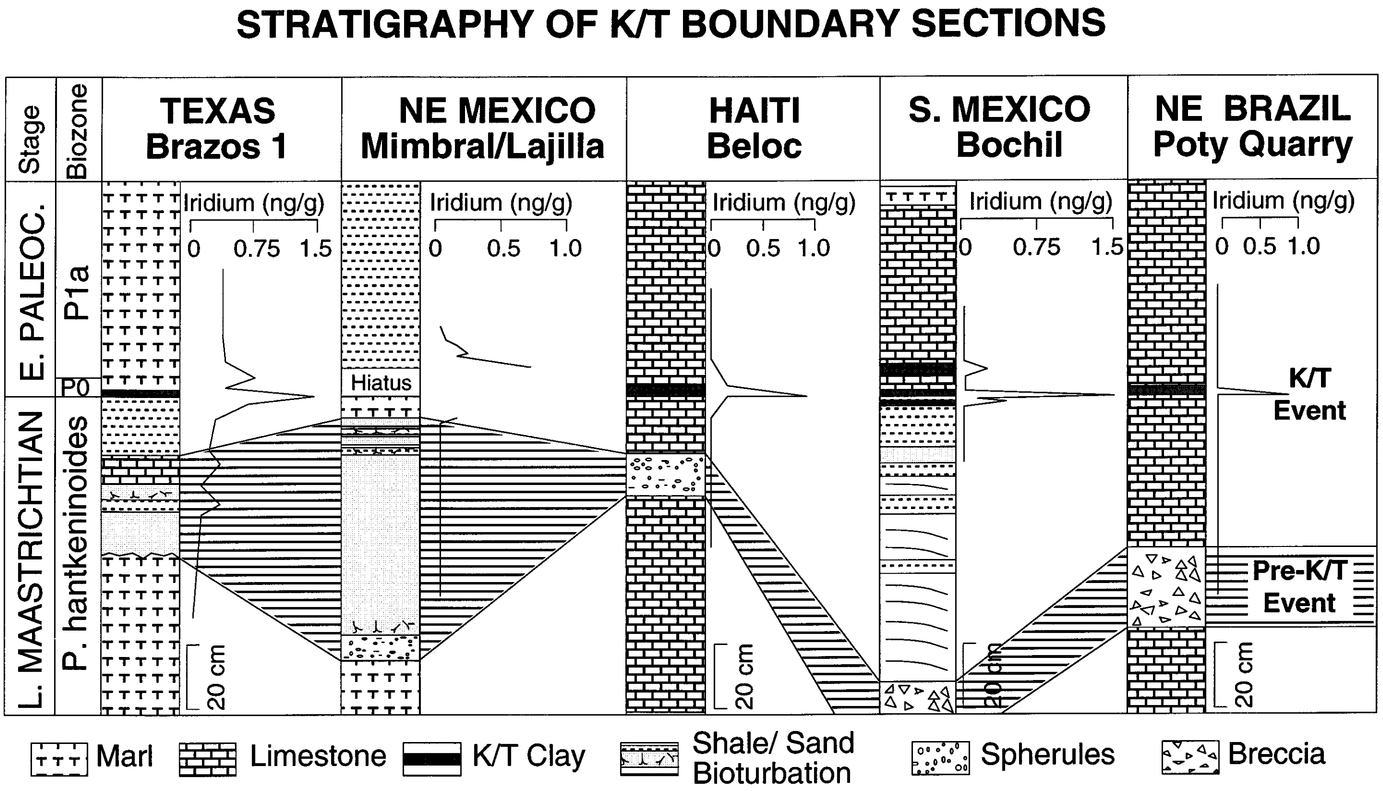


Figure 14. Stratigraphy and lithology of K/T boundary sections from Brazos in Texas, Mimbral and Mulato in northeastern Mexico, Beloc in Haiti, Bochil in Chiapas, and Poty in Brazil. Note that in each of these sections the K/T boundary is well defined by a clay layer (except northeastern Mexico sections), which contains anomalously high iridium concentrations, and the first Tertiary planktic foraminifera appear immediately above it. In each section, the siliciclastic or breccia deposits are well below the K/T boundary and separated from it by claystone, marl, or limestone layers that indicate that normal hemipelagic sedimentation resumed before the K/T boundary event. These data indicate the presence of two events: a K/T boundary impact event associated with high iridium concentrations, and a pre-K/T event associated with glass.

tanari et al., 1994); and in Brazil, they are 70 cm above the breccia (Stinnesbeck and Keller, 1994; 1995). In the Yucatan Chicxulub well C1, at least 18 m of Maastrichtian limestones may overlie the breccia (Ward et al., 1995). Thus, siliciclastic deposition prior to the K/T boundary in northeastern Mexico is consistent with a regional pattern of siliciclastic and breccia deposits.

There was episodic deposition of siliciclastic sediments. Siliciclastic deposits in northeastern Mexico contain indisputable evidence of bioturbation indicating repeated colonization by invertebrates (Ekdale and Stinnesbeck, 1994, in press; this study). In addition, discrete and correlatable intervals enriched in zeolites, and marl and shale layers indicate normal hemipelagic sedimentation. All of these point to episodic, multiple-event deposition over an extended time period. Moreover, Yucatan breccias may also represent multiple event deposition, if a boulder origin can be excluded for the limestone and dolostone layers within breccias of Yucatan wells Y2, Y4, and Y6 (Ward et al., 1995).

Were there two impact events? K/T sections in Texas, Mexico, Haiti, and Brazil have clearly marked K/T boundaries, on the basis of biostratigraphic and geochemical criteria that identify this boundary in the El Kef stratotype and worldwide (Fig. 14). In each of these sections, only the K/T boundary is marked by an iridium anomaly and mass extinctions. No elevated Ir concentrations have been found in the siliciclastic or breccia deposits. However, these deposits are characterized by glass that is stratigraphically below the K/T boundary (northeastern Mexico sections, Haiti [Beloc], Chicxulub wells). The stratigraphic separation of the K/T boundary and siliciclastic and breccia deposits and the evidence of long-term deposition of the siliciclastic deposits suggest the presence of two events: one at the K/T boundary and the second (Chicxulub event?) within the last 100–150 k.y. of the Maastrichtian.

Mass extinction is associated with K/T boundary event. The mass extinction in planktic foraminifera that eliminated all tropical and subtropical Cretaceous species coincided with the globally recognized K/T boundary event, as also observed in the presence of this mass extinction above the siliciclastic deposits in northeastern Mexico (Figs. 6–9). Few species disappeared at or below the base of the siliciclastic deposit that marks the pre-K/T event. However, as much as 12% of pre-K/T species extinctions and a major decline in relative abundance of tropical and subtropical taxa during the last 300 k.y. of the Maastrichtian have been observed (Keller, 1988, 1996; Pardo et al., 1996). These faunal changes are generally attributed to the latest Maastrichtian maximum cooling (Barrera and Keller, 1994; Barrera, 1994) and sea-level lowstand about 300 k.y. before the K/T boundary, followed by rapid warming and sea-level transgression during the last 50–100 k.y. of the Maastrichtian (Schmitz et al., 1992; Keller et al., 1993b; Keller and Stinnesbeck, 1996b; Pardo et al., 1996). It is possible that these faunal changes may, in part, be related to the second pre-K/T boundary event.

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