Near-K/T age of clastic deposits from Texas to Brazil: impact, volcanism and/or sea-level lowstand?

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ABSTRACT

Near-K/T boundary clastic deposits from Texas, Mexico, Haiti, Guatemala and Brazil, often described as impact-generated tsunami deposits, are stratigraphically below well-defined K/T boundary horizons and appear not to be causally related to the K/T boundary event. Stratigraphic evidence indicates that their deposition began during the last 170–200 kyr of the Maastrichtian, coincident with a major eustatic sea-level lowstand that lowered sea level by as much as 70–100 m. Clastic deposition ended a few tens of thousands of years before the K/T boundary during a rapidly rising sea level. The presence of glass in clastic deposits in Haiti, northeastern Mexico and Yucatan suggests that the sea-level lowstand coincided with a time of major volcanism or pre-K/T boundary bolide impact.

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INTRODUCTION

A widely publicized scenario holds that a bolide struck northern Yucatan at Cretaceous/Tertiary (K/T) boundary time and caused global mass extinctions. This scenario has led some workers to reinterpret near-K/T boundary clastic deposits from Texas to Brazil, which were previously related to sea-level lowstands, collapsed margins, or gravity flows, as impact-generated tsunami deposits (Hildebrand and Boynton, 1990; Smit *et al.*, 1992; Alvarez *et al.*, 1992; Montanari *et al.*, 1994; Albertão *et al.*, 1994). This interpretation is based primarily on (i) the proximity of the clastic deposits to the K/T boundary. (ii) The presence of rare glass fragments at the base of some clastic deposits in northeastern Mexico and glass spherules in Haiti which are presumed to be impact melt droplets (Izett, 1991). And (iii) the similarity of these glasses with melt rock from Yucatan cores which link them to a common source (Sigurdsson *et al.*, 1991; Smit *et al.*, 1992; Stinnesbeck *et al.*, 1993; Koeberl, 1993; Koeberl *et al.*, 1994).

Alternative interpretations of these clastic deposits favour deposition over an extended time period related to the latest Maastrichtian sea-level lowstand and possibly a time of active volcanism and/or pre-K/T boundary impact (Donovan *et al.*, 1988; Keller, 1989; Stinnesbeck *et al.*, 1993; Keller *et al.*, 1994a). Supporting evidence for this viewpoint includes: (i) multiple disconformities and erosion within the clastic deposits. (ii) Multiple horizons of bioturbation with burrows truncated by erosion indicating repeated recolonization by burrowing organisms during deposition of the clastic sediments (Ekdale and Stinnesbeck, 1994; in prep.). (iii) The presence of distinct and correlatable zeolite-enriched layers within the clastic deposits as well as multiple bentonite/ash layers above and below which are indicative of repeated volcanic influx (Keller *et al.*, 1994a; Adatte *et al.*, 1994; Adatte *et al.*, in press). (iv) The presence of marl or limestone layers with Maastrichtian fauna, between the top of the clastic deposit and K/T boundary, that indicates normal hemipelagic sedimentation resumed prior to the K/T boundary event (Keller, 1989; Keller *et al.*, 1994a; Stinnesbeck and Keller, 1994, 1996; Ward *et al.* 1995; Adatte *et al.* in press; Lopez-Oliva and Keller, in press). Based on this evidence, the glass present in the basal unit of the clastic deposit could be either of volcanic origin (Jéhanno *et al.*, 1992; Lyons and Officer, 1992; Leroux *et al.*, 1995), or an impact that preceded the K/T event [pros and cons of impact vs. volcanic origins were discussed by Koeberl (1994) and Robin *et al.* (1994)].

This report summarizes and presents further evidence that clastic deposits present in sections from Texas to Brazil (Fig. 1) are stratigraphically below the K/T boundary, that they were deposited sometime during the last 200 kyr of the Maastrichtian, and that their deposition coincided with a low eustatic sea level.

CLASTIC DEPOSITS

Near-K/T boundary siliciclastic or breccia deposits have been described from Brazos River, Texas (Hansen *et al.*, 1987; Bourgeois *et al.*, 1988; Keller, 1989; Montgomery *et al.*, 1992), northeastern Mexico (Smit *et al.*, 1992; Stinnesbeck *et al.*, 1993; Keller *et al.*, 1994a), southern Mexico (Montanari *et al.*, 1994; Stinnesbeck *et al.*, 1994), Yucatan (Lopez Ramos, 1973, 1975, 1983; Weidie, 1985; Meyerhoff *et al.*, 1994; Ward *et al.*, 1995), Guatemala (Hildebrand *et al.*, 1994; Stinnesbeck *et al.*, 1995), Haiti (Jéhanno *et al.*, 1992; Leroux *et al.*, 1995), and Brazil (Stinnesbeck, 1989; Stinnesbeck and Keller, 1994, 1995, 1996; Albertão *et al.*, 1994; Koutsoukos, 1995). Sections in Alabama (Braggs, Mussel Creek, Millers Ferry, Moscow Landing) contain clastic deposits above the K/T boundary and are not considered here (Mancini *et al.*, 1989; Savrda, 1993; Liu and Olsson, 1993).

Near-K/T clastic or breccia deposits can be roughly divided into two groups; those which predominantly consist of carbonate (limestone) breccias, and those which predominantly consist of

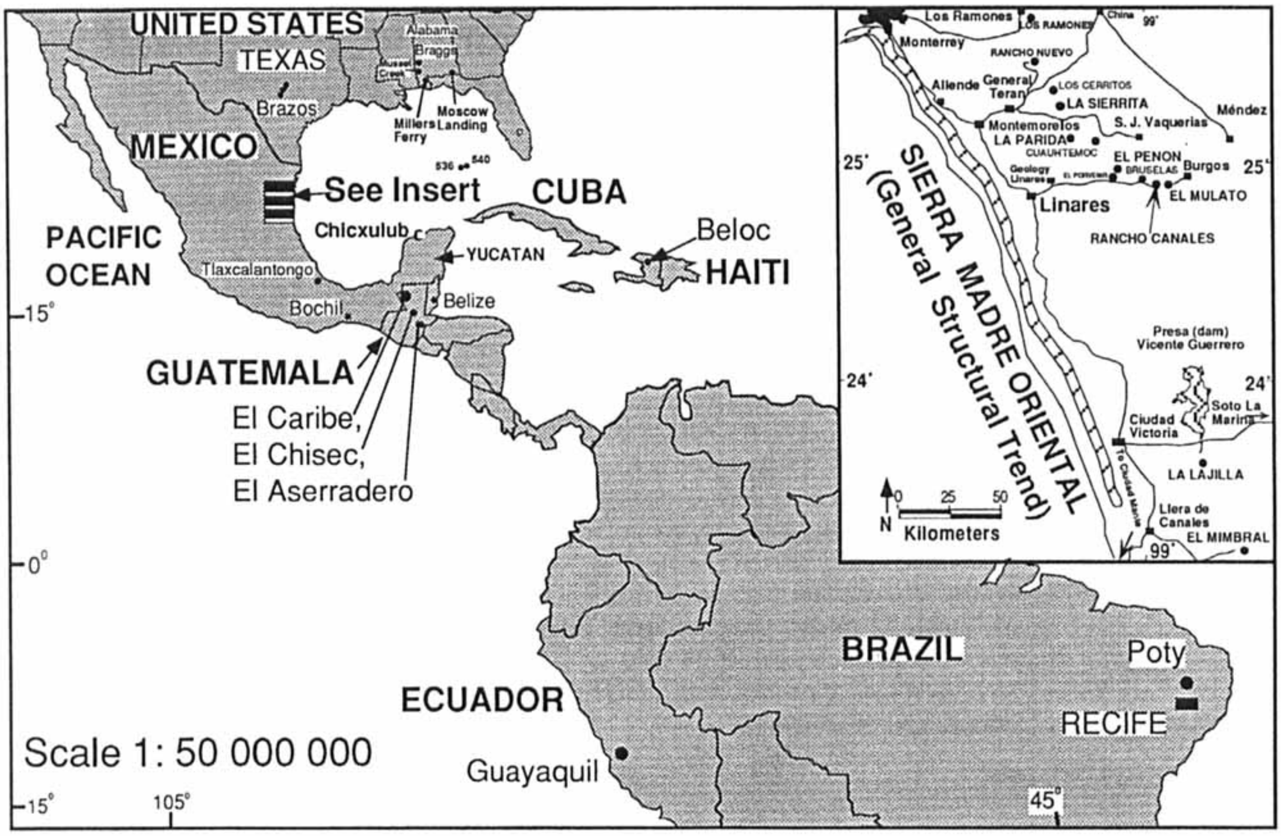

Fig. 1 *Geographical location of Cretaceous–Tertiary sections with near-K/T boundary clastic deposits from Texas to Brazil. Locations of all northeastern Mexico sections are shown in the insert. Note that these sections are east of and parallel to the Sierra Madre Oriental, the major source of terrigenous clastic sediments during the late Maastrichtian to Palaeocene.*

terrigenous debris. Carbonate breccias are found in southern Mexico (Bochil, Chiapas), Yucatan wells, Guatemala (e.g. El Caribe, El Chisec, El Acerradero), and Brazil (Poty Quarry, Recife). These limestone breccias were generally deposited on shallow carbonate platforms (at < 50–150 m depth), or on platform margins as indicated by their abundant invertebrate faunas, shallow neritic benthic foraminifers and near-absence of open marine planktic foraminifera. Glauconite, pyrite concretions, calcispheres and phosphatic spherules and lumps are common. No glass spherules or glass particles have been found in the Brazil (Poty Quarry), southern Mexico (Bochil) or Guatemala sections. Melt rock is present in some of the Yucatan wells (Sharpton *et al.*, 1992; Koeberl *et al.*, 1994; Ward *et al.*, 1995).

Siliciclastic deposits in east-central and northeastern Mexico and Texas (Fig. 1) predominantly consist of sand, silt, shale and sandy limestone layers. They are generally located within range of terrigenous influx. For example, the dozen or more siliciclastic-bearing K/T sequences in northeastern and east-central Mexico all parallel the Sierra Madre Oriental (see insert in Fig. 1). These sections frequently contain a basal layer with abundant calcareous spherules, algal resting cysts, pyrite, glauconite, phosphate, shallow benthic foraminifera and rare glass particles (Stinnesbeck *et al.*, 1993, 1995; Keller *et al.*, 1994a). The Beloc section is unique in that it contains calcareous and glassy spherules (Izett, 1990; Sigurdsson *et al.*, 1991; Jéhanno *et al.*, 1992).

Palaeodepth of deposition was middle to inner neritic at the Brazos River, El Caribe, El Chisec, El Aserradero, Poty Quarry and Los Ramones (northeastern Mexico) sections (Keller, 1992; Keller and Stinnesbeck, 1995), and outer neritic to upper bathyal/slope at localities south from Los Ramones (e.g. Parida, Rancho Nuevo, Mulato, Mimbral, Lajilla, Peñon, Sierrita, Tlaxcalantongo and Bochil; Fig. 1). The Beloc section in Haiti was deposited in a deeper bathyal/slope environment (Jéhanno *et al.*, 1992; Leroux *et al.* 1995). Thus, both carbonate breccias and terrigenous clastics were deposited predominantly in shallow continental shelf (< 50–150 m) environments and at shelf/slope margins (150–400 m) in areas most affected by sea-level fluctuations.

STRATIGRAPHY AND AGE

Texas

Outcrops along the Brazos River contain relatively thin siliciclastic units (< 20–100 cm) which rest unconformably upon a scoured surface and are topped by a thin limestone/chalk layer of diagenetic origin (Yancey, 1995). A 15–20 cm-thick

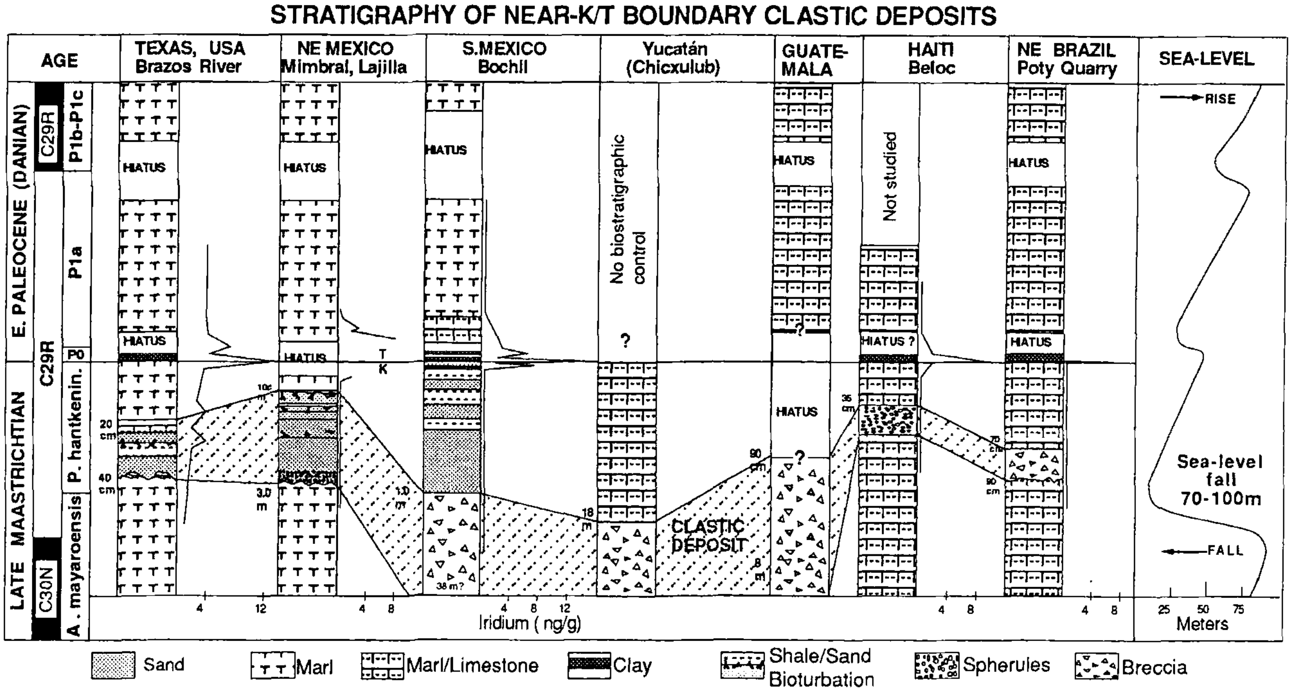

Fig. 2 *Stratigraphy of near-K/T boundary clastic deposits in sections from Texas to Brazil and sea-level fluctuations. Note that the K/T boundary clay layer with maximum iridium concentrations is well above the clastic deposits. The sediments present between the K/T boundary and clastic or breccia deposits are interpreted as indicating the return to normal hemipelagic sedimentation during the latest Maastrichtian to early Palaeocene sea-level transgression. Palaeomagnetic control based on Brazos and Agost sections (Keller, 1989; Groot* et al., *1989; Pardo* et al. *(1996); iridium measurements from Jéhanno* et al. *(1992), Keller* et al. *(1994a), Albertão* et al. *(1994), Montanari* et al. *(1994) and Rocchia and Robin (written communication, 1993). Note that the metre scale varies between sections.*

calcareous claystone overlies the limestone layer, followed by a 0.5 cm-thick brown clay layer that marks the K/T boundary. This brown clay layer contains maximum iridium abundance (Robin and Rocchia, written communication, 1993), the first Tertiary planktic foraminifera (Keller, 1989), nannofossils (Jiang and Gartner, 1986) and palynomorphs (Beeson, 1992; fig. 2). Short hiatuses mark the P0/P1a and P1a/P1b boundaries (fig. 2, Keller, 1989). There is no stratigraphic or geochemical evidence to place the K/T boundary at the base of the clastic deposit as suggested by Bourgeois *et al.* (1988) and Smit *et al.* (1994). In a recent sedimentological restudy of the Brazos River outcrops Yancey (1995, p. A326) concluded that 'the fossil defined K/T boundary event occurs in an interval of normal marine deposition characterized by frequent storm activity and normal marine biota. It is well separated from the extraordinary event deposits of the (underlying) coarse-grained boundary complex and the two are not genetically related in the Brazos section.' Siliciclastic deposition occurred sometime during *P. hantkeninoides* zone which spans the last 170–200 kyr of the Maastrichtian (Pardo *et al.*, 1996) as indicated by the first appearance of this species just below this deposit, and ended at least some thousands of years before the K/T boundary as suggested by deposition of the 15–20 cm claystone layer.

Northeastern Mexico

Over a dozen K/T boundary sections containing siliciclastic deposits, varying from 20 cm to 8 m thick and overlying a scoured surface of late Maastrichtian marls, are known from northeastern and east-central Mexico (fig. 1, Keller *et al.*, 1994a; Stinnesbeck *et al.* 1996). The thick siliciclastic deposits generally contain three lithologically and mineralogically distinct units which can be correlated over 500 km. The basal unit consists of a spherule-rich carbonate layer containing glauconite, rare glass fragments and a 20 cm-thick microlaminated sandy limestone layer with rare spherules except at the contacts above and below (e.g. Mimbral, Lajilla, Peñon, Sierrita, Mulato). The middle unit consists of a laminated sand at the base which is bioturbated and overlain by one to several metres thick structureless sandstone without bioturbation. The upper unit consists of interbedded sand, silt, and shale layers with two zeolite-enriched horizons, topped by one to several rippled sandy limestone layers. At least three discrete and strongly bioturbated horizons separated by erosion are present in the upper part of unit 3 (Keller *et al.*, 1994a; Ekdale and Stinnesbeck, 1994; in press). This siliciclastic sedimentation pattern indicates that deposition occurred over an extended time period during which repeated colonization by invertebrate organisms occurred.

Of five K/T boundary sequences which contain overlying Tertiary (Danian) sediments (e.g. Mimbral, Lajilla, Mulato, Parida, Tlaxcalantonga; Fig. 1), one has a hiatus with the lower Danian Zones P0 to P1c missing (Tlaxcalantongo, Lopez-Oliva, 1996). In three of the remaining four sections (all except Mimbral), a 5–10 cm-thick marl layer of Maastrichtian age overlies the top of the siliciclastic deposits (Lopez-Oliva and Keller, in press; Fig. 2 shows composite of Lajilla and Mimbral sections). There is no grain size sorting within this marl layer. Moreover, whole rock and clay mineral compositions, as well as a latest Maastrichtian planktic foraminiferal assemblage present within this marl layer, are most similar to those in the Mendez marls below the siliciclastic deposit (Adatte *et al.*, 1994, in press). This suggests that normal hemipelagic deposition, similar to the underlying Mendez marls, resumed after siliciclastic deposition and prior to the K/T boundary. A short hiatus marks the K/T boundary between the top of this marl layer and the overlying shale where the lowermost Danian (lower part of Zones P1a and Zone P0) and probably the topmost Maastrichtian sediments are missing (Keller *et al.*, 1994a; Lopez-Oliva and Keller, in press). Iridium analysis at Mimbral shows maximum values in basal Danian (Zone P1a) sediments above the short K/T boundary hiatus as shown in Fig. 2 (Smit *et al.*, 1992; Stinnesbeck *et al.*, 1993; Keller *et al.*, 1994a). The presence of the short-ranging *P. hantkeninoides* marker species just below the siliciclastic deposits indicates that its deposition occurred within the last 170–200 kyr of the Maastrichtian, but ended at least some thousands of years before the K/T event, as suggested by the presence of the Maastrichtian age marl layer below the K/T boundary.

Southern Mexico, Chiapas

The Bochil section in Chiapas contains a limestone breccia 1 m below the K/T boundary. This breccia is discontinuously exposed and 38 m thick. It contains limestone clasts up to several metres in diameter which fine upwards in a calcareous matrix that contains shallow water upper Cretaceous miliolids (Montanari *et al.*, 1994). Below and above this breccia are hundreds of metres of flysch deposits (bedded shales, silt and sandstones) of Campanian, Maastrichtian and Palaeogene age, respectively, which alternate with similar breccia units. Stinnesbeck *et al.* (1994) and Michaud and Fourcade (1989) interpreted these breccias as debris flows caused by the uplift, tilting and collapse of the nearby carbonate platform. The near-K-T breccia is overlain by a 1 m upward succession of sandstone, siltstone and red clay layers. One of the thin clay layers contains an iridium anomaly that marks the K/T boundary (Montanari *et al.*, 1994; Fig. 2). Above the Ir-rich clay layer is a micritic limestone and chalk with an early Danian Zone P1a foraminiferal assemblage which indicates a short hiatus with Zone P0 and the lower part of Zone P1a missing. Montanari *et al.* (1994) interpret the breccia and 1 m-thick sequence of late Maastrichtian sediments overlying it as part of a K/T Yucatan impact-induced megatsunami event. In contrast, the present authors interpret this breccia as a tectonically generated debris flow and the overlying Maastrichtian sediments as representing normal hemipelagic sedimentation prior to the K/T boundary event. The presence of *P. hantkeninoides* in the latter sediments indicates deposition during the last 170–200 kyr of the Maastrichtian.

Yucatan, Mexico

The K-T stratigraphy of the Yucatan Peninsula is primarily inferred from a transect of discontinuously drilled petroleum exploration wells (PEMEX) and the stratigraphic summaries published by Murray and Weidie (1962), Lopez Ramos (1973, 1975, 1983), Weidie (1982) and Meyerhoff *et al.* (1994). Recently, Ward *et al.* (1995) reexamined the stratigraphy based on core samples and electric resistivity logs (e-logs) for five Yucatan wells (Y1, Y2, Y4, Y5 A, Y6) and e-logs of three wells (Ticul 1 (T1), Sacapauc 1 (S1) and Chicxulub 1 (C1)). The thickness of the breccia units is between 200 m and 500 m in these wells. The breccia is composed of angular to subrounded clasts of dolostone, anhydrite and limestone set in a dolomitized carbonate mud matrix. Schuraytz *et al.* (1994) reported minor constituents of altered glass or melt rock and shocked quartz in some breccia layers. Breccia units of wells Y4, Y2, C1 and Y6 show intercalations of dolomite, anhydrite or limestone layers. In Y4 (cores 4 and 5), a dolomite layer separates an upper breccia with rare or no planktic foraminifera from a lower breccia with abundant planktic foraminifera of Maastrichtian age. In well Y2 (core 7), a finely crystalline anhydrite layer within the breccia also possibly represents an undisturbed sedimentary layer. In well C1, Lopez-Ramos (1973) reported marl and limestone intercalations within the thick breccia. This suggests that there may have been more than one episode of breccia deposition (Ward *et al.* 1995). The timing of breccia-tion is poorly constrained by biostratigraphic data because of discontinuous coring. However, there is some evidence that the breccia unit is overlain by upper Maastrichtian marls, suggesting that the brecciation event preceded the K/T boundary. For instance, 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. Based on electric resistivity log correlations, Ward *et al.* (1995) suggested that only about 18 m of these Maastrichtian age sediments are true marls and limestones (Fig. 2). However, their presence suggests that the breccia unit was emplaced sometime prior to the K/T boundary event similar to clastic deposits elsewhere in the region.

Guatemala

Several KT transitions have been examined in the Peten region of Guatemala (e.g. El Caribe, El Chisec, El Aserradero). All of these sections contain limestone breccia deposits that range from several metres to over 50 m-thick and disconformably overly dolomitized rudist-bearing limestones. The breccias contain rounded to angular limestone clasts up to several tens of centimetres in diameter and are generally upward fining within a carbonate matrix. Shallow neritic benthic foraminifera (miliolids) are abundant in the carbonate matrix, whereas small benthic and planktic foraminifera are rare indicating deposition probably occurred in less than 20 m depth. Deposition of this breccia probably occurred sometime during the late Maastrichtian, though the precise age has yet to be determined.

A disconformity, marked by an undulating surface and rip-up clasts is present between the top of the breccia and overlying marly limestone or marl in all sections examined. At El Caribe and El Aserradero the overlying marls contain a well-developed early Danian Zone P1a fauna including *Parvularugoglobigerina eugubina, Eoglobigerina fringa and Globoconusa daubjergensis*. In these two sections, the Zone P1a assemblage spans 1–1.5 m, whereas at El Chisec Zone P1a is only 10 cm thick. These sediments also contain a rich benthic foraminiferal assemblage characteristic of a middle neritic environment which indicates that deposition occurred at 100–150 m depth. This suggests that either deepening of at least 100 m occurred between the time of breccia deposition and the Danian sediments overlying the disconformity, or that the breccia consists of transported shallow water limestone. The present authors believe the latter is more likely, although a sea-level transgression occurred in the latest Maastrichtian beginning about 100 kyr before the K/T boundary and may account for some of the deepening (Keller and Stinnesbeck, 1996; Pardo *et al.* 1996).

Haiti

Over eight K/T boundary outcrops are known from the Beloc area of Haiti and most of these show incomplete and bioturbated K–T transitions (Jéhanno *et al.*, 1992). The two most complete sequences are characterized by a 25 cm-thick size-graded spherule layer that overlies a marly limestone of Maastrichtian age. Overlying the spherule layer is a 25–35 cm thick layer of carbonate-rich sediments with upper Maastrichtian planktic foraminifera followed by a 1 cm-thick gray-green clay layer that contains maximum Ir and spinel concentrations (Jéhanno *et al.*, 1992; Leroux *et al.*, 1995; Fig. 2). The first Tertiary planktic foraminifera are present in the calcareous sediments above this clay layer and Ir anomaly. Based on iridium, spinel, shocked quartz and glass distributions and geochemistry, Jéhanno *et al.* (1992) and Leroux *et al.* (1995) concluded that the spherule layer and 1 cm clay layer may represent two distinct events.

Northeastern Brazil

The Poty Quarry near Recife in northeastern Brazil contains a 20 cm-thick limestone breccia 70 cm below the K/T boundary (Fig. 2). This breccia disconformably overlies marly limestone of upper Maastrichtian age (Stinnesbeck and Keller, 1994, 1996). This limestone breccia contains calcispheres, phosphatic spherules and lumps, glauconite, pyrite concretions, abundant shallow neritic foraminifers, planktic foraminifers and serpulid worm tubes which suggest deposition occurred in an inner neritic environment. The breccia is overlain by a 50 cm-thick detrital limestone followed by a 10–20 cm-thick marly limestone. The latter is similar to the marly limestone below the breccia. A 1–3 cm-thick claystone layer, barren of planktic foraminifera, but containing maximum Ir concentrations, overlies the marly limestone and marks the K/T boundary. The first Tertiary planktic foraminifera (upper Zone P1a) are present in the marly sediments directly overlying the clay layer and suggest the presence of a short hiatus (Fig. 2, Stinnesbeck and Keller, 1994, 1996). The Poty Quarry section thus also indicates that clastic deposition preceded the K/T boundary event and was unrelated to it. Similar to siliciclastic deposits in Texas and Mexico, the presence of *P. hantkeninoides* beginning 50 cm below the breccia indicates that its deposition occurred during the last 170–200 kyr of the Maastrichtian (Stinnesbeck and Keller, 1996).

Albertão *et al.* (1994) recently interpreted the breccia layer at the Poty Quarry as the Yucatan impact-generated tsunami event, and the Ir anomaly as a second impact event of Danian age. Their interpretation is based on the presence of spherules, which they presume to be of impact origin, and the putative presence of Tertiary planktic foraminifers in the breccia (Koutsoukos, 1995). The present authors were unable to confirm the presence of Tertiary species below the clay layer and iridium anomaly. Instead only phosphatic spherules (dissolve in acid) were found, many containing aperture-like protrusions that suggest they are infilled algal resting cysts. They are common throughout the K–T transition from below the breccia to well above the K/T boundary (Stinnesbeck and Keller, 1995). No evidence of Tertiary age sediments below the Ir anomaly was found.

AGE OF CLASTIC DEPOSITS

Figure 2 summarizes the litho- and biostratigraphy of K–T transitions from Texas to Brazil. The K/T boundary is generally well marked by a clay layer which contains maximum concentrations of iridium and the first Tertiary planktic foraminifera at or a few centimeters above the Ir anomaly. In northeastern Mexico sections, this clay layer is generally absent and a short hiatus is present (Keller *et al.*, 1994a,b; Lopez-Oliva and Keller, in press). Immediately above the clay layer, Zone P1a (*P. eugubina*) faunas are present in all relatively continuous K/T boundary sections. Two short hiatuses, or condensed intervals, are often present at the P0/P1a and P1a/P1b boundaries globally (MacLeod and Keller, 1991a,b), as well as in the K/T sequences examined here (Fig. 3).

Clastic deposits are stratigraphically below the K/T boundary. Biostratigraphy indicates that deposition of clastic deposits from Brazos River, Texas, northern, central and southern Mexico, as well as Poty Quarry, Brazil, were coeval and began no earlier than during the last 170–200 kyr of the Maastrichtian. This age estimate is based on the presence of the planktic foraminifer *Plummerita hantkeninoides* which lived during the last 170–200 kyr (lower part of Chron 29R) of the Maastrichtian and became extinct at the K/T boundary as estimated from palaeomagnetic stratigraphy of the Agost and Brazos sections (Keller, 1989; Pardo *et al.*, 1996). *Plummerita hantkeninoides* is present in most clastic-bearing K–T sequences we examined from Texas, Mexico and Brazil in sediments just below, within or above the clastic deposits. This species was not observed in Yucatan wells or in Guatemala sections, and was not reported from Haiti. Erosion at the base of the clastic deposit is generally minor and restricted to within the lower part of the *P. hantkeninoides* Zone as suggested by the presence of this species below the unconformity in many sections (e.g. Poty Quarry, Mimbral, Lajilla, Peñon, Sierrita, Lopez-Oliva and Keller, in

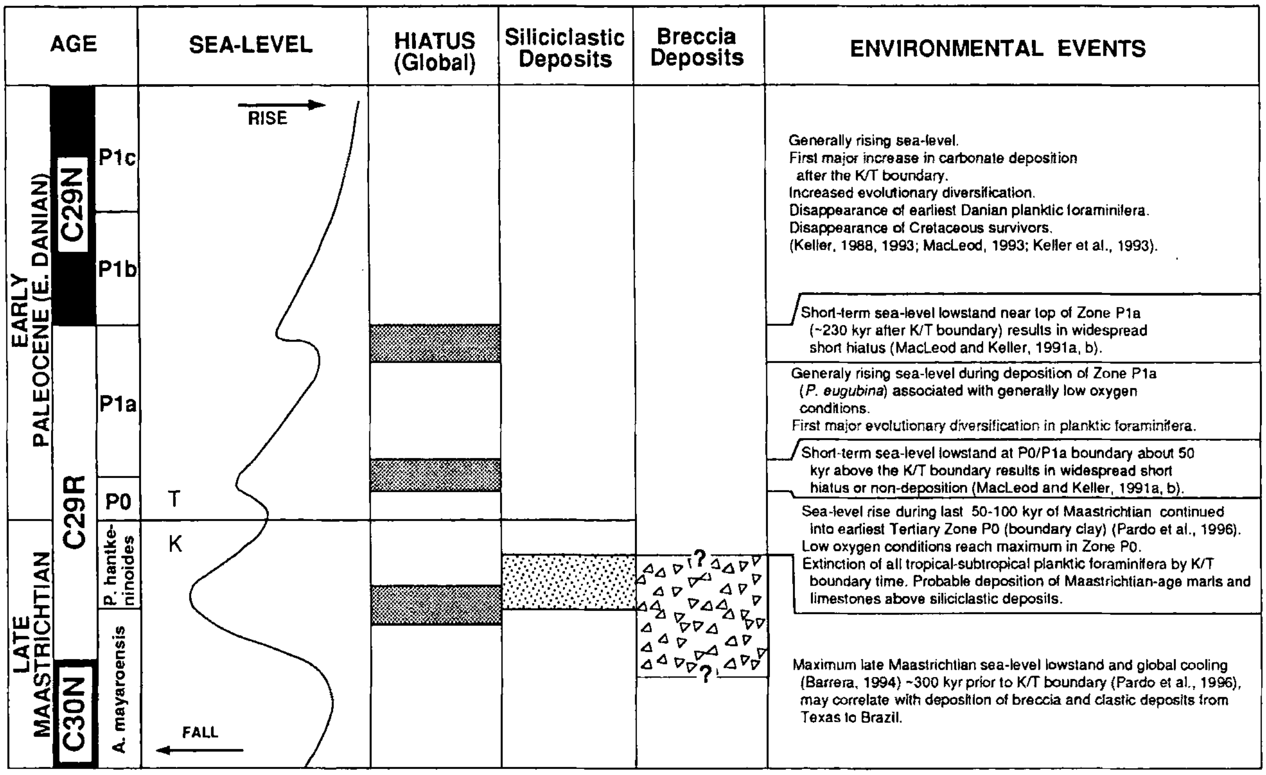

Fig. 3 *Sea-level changes, hiatus distribution, stratigraphic position of clastic deposits and environmental conditions across the K–T transition based on examination of K/T boundary sections globally. Palaeomagnetic stratigraphy and sea-level chronology based on Agost, Spain. Palaeodepth interpretations are based on benthic and planktic foraminifera, spores and pollen, dinoflagellates and macrofossils. Hiatus distribution based on graphic correlation by MacLeod and Keller (1991a;b). Note that K–T transitions frequently contain short hiatuses or condensed intervals associated with sea-level lowstands. Current evidence indicates that the siliciclastic and breccia deposits from Texas to Brazil were probably deposited during the latest Maastrichtian sea-level lowstand (and onset of subsequent rise) which occurred about 200–300 kyr before the K/T boundary (near base of Chron 29R) and which lowered sea-level by 70–100 m. Maastrichtian age marls and limestone layers frequently present above clastic deposits were probably deposited during the sea-level rise preceding the K/T boundary.*

press; Lopez-Oliva, 1996). Clastic deposition ended at least some thousands of years before the K/T boundary. This is suggested by the presence of Maastrichtian age marls or shales above the clastic deposits in most sections in Texas, Mexico, Haiti and Brazil which indicate that normal hemipelagic sedimentation resumed prior to the K/T boundary.

In Guatemala sections the onset of deposition of platform limestone breccias is unknown to date. However, erosion at the basal disconformities was either more extensive than in Texas, Mexico or Brazil, or breccia deposition began much earlier as suggested by the underlying rudist-bearing limestones of early middle Maastrichtian or Campanian age. It is also difficult to precisely determine when clastic deposition ended in these sections because of the absence of planktic foraminifera in these shallow water breccias and the presence of a hiatus between the breccia and overlying early Danian Zone P1a marls. However, our recent discovery of glass spherules in the top 20 cm of the breccia suggests that at least the top of the breccia deposits is coeval with breccia deposits in southern Mexico and Yucatan, and the spherule-rich layers in north-eastern Mexico and Haiti.

SEA-LEVEL FLUCTUATIONS

Relative changes in sea level frequently determine the nature and characteristics of sedimentation in continental shelf and upper slope regions where clastic sediment-bearing K–T sequences from Texas to Brazil were deposited. Figure 3 shows trans-K/T eustatic sea-level changes inferred from microfossils and macrofossils in numerous sections worldwide (for a summary see MacLeod and Keller, 1991a,b; Keller and Stinnesbeck, 1996). This database suggests that sea-level lowered by 70–100 m near the base of Chron 29R about 300 kyr before the K/T boundary and coincident with global cooling (Barrera, 1994; Pardo *et al.*, 1996). Biostratigraphic evidence suggests that the clastic deposits in Mexico and Brazil were deposited during this sea-level lowstand. It is possible that the shallow water breccias in Guatemala may also have been deposited at this time. Benthic foraminiferal data from Nye Klov, Stevns Klint, Agost and El Kef indicate that this latest Maastrichtian sea-level lowstand and cooling was followed by climate warming, low oxygen conditions and a rising sea-level beginning 50–100 kyr before the K/T boundary (Schmitz *et al.*, 1992; Keller, 1992; Keller *et al.*, 1993; Pardo *et al.*, 1996). It is likely that the Maastrichtian age marls or limestone deposits above the clastic deposits were deposited during this sea-level rise.

This rising sea-level trend continued into the early Danian Zone P0 when minimum low oxygen conditions were reached and the first Tertiary species evolved. A short-term sea-level lowstand identified at the P0/P1a boundary about 50 kyr after the K/T boundary in most KT sections worldwide is associated with a short hiatus or non-deposition (Fig. 3, MacLeod and Keller, 1991a,b). Relatively low oxygen conditions prevailed during the subsequent rising sea level in Zone P1a and at a time marked by the first major evolutionary diversification of Tertiary planktic foraminifera and the gradual disappearance of many Cretaceous K/T survivors! This sea-level rise was interrupted by another short-term sea-level lowstand near the P1a/P1b Zone boundary about 230 kyr after the K/T boundary (near the top of Chron 29R) and is marked by another globally widespread short hiatus which is also recognized in sections from Mexico, Guatemala and Brazil (MacLeod and Keller, 1991a,b; Keller *et al.*, 1994; Stinnesbeck and Keller, 1994, 1996; Fig. 3). Thereafter, sea level is generally rising in Zones P1b and P1c (Chron 29N), carbonate sedimentation returns to near pre-K/T levels, planktic foraminifera undergo a major evolutionary radiation and earliest Danian species disappear along with nearly all Cretaceous survivor species (Keller, 1988, 1993, 1995; Keller *et al.*, 1993; MacLeod, 1993; MacLeod and Keller, 1994).

CONCLUSIONS

The K/T boundary is defined globally, as well as in sections from Texas to Brazil, by the first appearance of Tertiary planktic foraminifera and the extinction of tropical–subtropical Cretaceous species which coincides with an iridium anomaly and, less frequently, Ni-rich spinels. Near-K/T clastic and breccia deposits from Texas, Mexico, Haiti, and Brazil are all stratigraphically below well-defined K/T boundary horizons and are therefore not causally related to the K/T boundary impact event. There is biostratigraphic evidence that limestone breccia deposits from Yucatan wells predate the K/T boundary and may represent multi-event episodic deposition, including a possible second pre-K/T boundary bolide impact. The latter is suggested by the presence of coeval and geochemically similar glass spherules in Haiti and Guatemala, melt rock in some breccia layers reported from Yucatan wells, and rare glass near the base of siliciclastic deposits in some north-eastern Mexico sections. In sections with strong biostratigraphic control (e.g. Brazos River, Texas, north-east, central and southern Mexico, Brazil), clastic deposition began sometime during the last 170–200 kyr of the Maastrichtian, coincident with a sea-level lowstand, and may have ended some thousands of years before the K/T boundary at a time of a rising sea-level. Whether deposition of the siliciclastic and breccia units was causally related to the sea-level lowstand, a major increase in tectonic activity during the Maastrichtian, or an independent coinciding event such as a second pre-K/T boundary bolide impact or major volcanic eruptions, cannot be determined. However, current evidence strongly suggests a multi-event scenario of long-term environmental changes, including regional tectonic activity, volcanism, global climate change and sea-level fluctuations, which are possibly overprinted by a pre-K/T boundary bolide impact that is unrelated to the K/T boundary bolide impact and iridium anomaly.

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