# Coarse-grained, clastic sandstone complex at the K/T boundary around the Gulf of Mexico: Deposition by tsunami waves induced by the Chicxulub impact?

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#### ABSTRACT

The K/T boundary in marine deposits in and around the Gulf of Mexico at a distance of <800 km from the Chicxulub impact structure is marked by a series of unusual sandstone beds in almost any outcrop. These sandstone beds have a complex architecture, varying with depth of deposition. At neritic to upper-bathyal depths (100 to 500 m) the sandstone beds can consistently be subdivided into three (sometimes four) successive lithological units. From bottom to top, the units decrease in grain size and change in composition and texture. The first unit (I) is characterized by millimeter-sized particles: spherules and other splash-form particles with internal filled vesicles and limestone clasts; both are interpreted as altered impact ejecta. Those ejecta, mixed with clay/marl rip-up clasts from underlying formations, washed-out foraminifers, and various material scavenged from the seafloor, fill shallow channellike depressions. The second unit (II) consists of a sequence of several lenticular sandstone layers made up of a mixture of foraminifers, bioclasts, plant remains, and terrigenous material. The sandstones may be massive, graded, or parallel- or currentripple laminated. Some rare spherules and limestone clasts infrequently occur at the base of each layer. The Unit II sands are deposited in very shallow, stacked channels or erosional depression infillings and display a variety of sedimentary features containing evidence for repeated up-section changes in current direction and current strength. The third unit (III) consists of strings of fine sand ripples alternating with thin silt layers. Only Unit III and the overlying unit (IV) contain anomalous iridium and Ni-rich spinels, concentrated in the silt layers. Unit IV is a graded silt-mudstone, representing a quiet depositional phase of fine material, settling—over at least a few days—together with the fine iridium-rich dust.

The coarser basal units in particular show internal unconformable stratigraphic relationships, but all the units and beds are amalgamated on top of each other, with-

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out interruption by layers of normal, background sediment. There is no unequivocal evidence (such as intercalated burrowed layers) that the deposition of the entire sandstone complex took more than a few days.

(Re)deposition by a series of large, waning tsunami waves is the most likely explanation for the texture of the K/T sandstone beds, although locally gravity flows may have assisted in the transport of sands from nearshore areas. In shallow shelf-seas (Alabama, Texas) earliest Danian sea-level fluctuations have modified or (partially) removed the K/T sandstone complex. In the shallowest marine K/T site studied, the Parras Basin in northeastern Mexico, no sign of the K/T sandstone complex has been found.

#### INTRODUCTION

The K/T boundary in the Gulf of Mexico region is often marked by a graded unit of sandstone beds ranging in thickness from 5 cm to 9 m (Fig. 1) (Ross and Scotese, 1988; Smit et al., 1992b; Alvarez et al., 1992b). The sandstone complex is intercalated in a more or less continuous relatively shallow-water fine-grained clay or chalk sequence in Alabama and Texas and in a pelagic marl sequence in eastern Mexico, Haiti, and DSDP holes 536/540 (Alvarez et al., 1992a). We refer in this chapter to these sandstone beds as the K/T sandstone complex.

Elsewhere in the world—preserved only in the most continuous sections (El Kef, Tunisia; Agost, Caravaca, and Zumaya, Spain; Stevns Klint, Denmark; Woodside Creek, New Zealand)—the K/T boundary is marked by a few millimeters-thick layer of (red-stained) clay (Smit, 1990). This clay layer is characterized by anomalous enrichment of siderophile elements (iridium) (Alvarez

et al., 1980), shocked minerals (Bohor, 1990), spherules that resemble microkrystites (Smit et al., 1992a), and spherules with Ni-rich spinels (Kyte and Smit, 1986; Montanari et al., 1983). The thin clay layer is therefore interpreted by many as an altered distal impact ejecta—or fallout—layer. The Ir-rich clay is immediately overlain by a few centimeters-thick detrital marl or clay layer, impoverished in microfossils in comparison with marls from just below the ejecta layer. The detrital clay probably reflects effects of low-productivity, "strangelove" ocean conditions (Hsü and McKenzie, 1990) following the mass mortality and extinction at the K/T boundary.

The discovery of the 180- to 300-km-diameter Chicxulub crater in Mexico—the best candidate for the K/T impact site (Hildebrand et al., 1991)—close to all the outcrops with sandstone units prompts the question of the origin of the sandstone complex: Is it really related to the K/T boundary and does it show signs of (Chicxulub) impact-related processes?

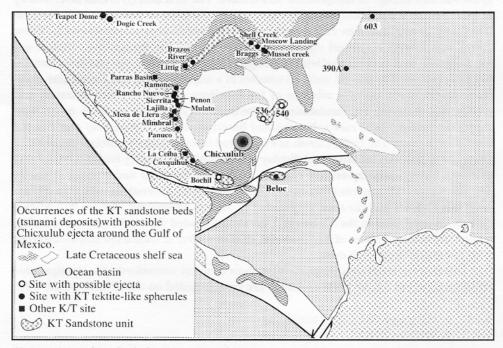


Figure 1. Map of the Gulf of Mexico, about 65 m.y. ago (Ross and Scotese, 1988), showing the Chicxulub impact and the location of outcrops with K/T sandstone complex deposits and sites where spherules (altered ejecta) have been found. 603, 390A, 536, and 540 are Deep Sea Drilling project sites.

The timing of the deposition of the sandstone complex is controversial: Does the sandstone complex occur precisely at the K/T boundary as proposed by Bourgeois et al. (1988), Smit et al. (1992b), and Smit and Romein (1985)? Or does the unit predate the K/T boundary (Jiang and Gartner, 1986; Keller et al., 1993, 1994b; Stinnesbeck et al., 1993, 1994b)? The question has also been posed of whether the beds of the sandstone complex were deposited in one, pulsating event or during several events spread over several thousands of years (Keller et al., 1994b; Stinnesbeck et al., 1993).

The K/T sandstone complex is sedimentologically complex, differing in architecture and composition from place to place. Therefore, many different interpretations have been offered for its origin. The beds have been interpreted as nonmarine sandstones (Kellum, 1937; Muir, 1936), shallow-water deposits (Morgan, 1931), low-stand channel infills (Mancini and Tew, 1993; Savrda, 1991), storm deposits (Hansen et al., 1987), gravity flows (turbidite and debris flows) (Bohor and Betterton, 1993; Stinnesbeck et al., 1993), and tsunami deposits (Bourgeois et al., 1988; Smit et al., 1992b; Smit and Romein, 1985).

The oldest reports on the sandstone deposits at or near the K/T boundary in Mexico between the Upper Cretaceous Mendez and Paleocene Velasco formations date back to the 1930s (Kellum, 1937; Muir, 1936). They interpreted the sandsone unit as shallow-water or nonmarine deposits marking a hiatus and an unconformity. Muir (1936) described a "ripple marked" sandstone and/or a bentonite bed between the Mendez and Velasco (Tamesi) Formations. He reported the contact between the Mendez and the Velasco (Tamesi) Formations in the Arroyo de Mimbral (Membral) outcrop as follows: "The base of the Velasco fm consists of mixed material, including inclusions from the Mendez, filling irregularities at the unconformity between the two formations. Next comes a sandstone, variable in thickness and local in extent." The worm track and plant remains in the sandstones were seen as evidence for a nonmarine origin. Morgan (1931) noted an abrupt change in (planktic) faunal composition between the Mendez and Velasco shales and suspected an unconformity because a "bentonitic conglomerate" occurs at the base of the Velasco Formation in the Tampico area. Hay (1960) described an angular unconformity between the Mendez and Velasco Formations at Mimbral and in addition inferred a major regression at the K/T boundary.

In Texas, the conglomeratic Littig member of the Paleocene Kincaid Formation often unconformably overlies the Cretaceous Corsicana Formation where it marks a considerable hiatus (Jiang and Gartner, 1986; Hansen et al., 1987). However, in the Brazos River outcrops, 1 to 4.5 m of the Kincaid Formation is preserved below the Littig member, containing a graded sandstone unit at its base (here called the K/T sandstone complex). Ganapathy (1980) mentioned that the sandstone unit occurred just below the K/T iridium anomaly (and consequently assigned it a Late Cretaceous age) at Brazos River but did not further interpret it. Smit and Romein (1985) interpreted the Brazos River sandstone unit as a K/T boundary turbidite or tsunami-generated deposit, indi-

cating a nearby impact. Hansen et al. (1987) lithologically subdivided the K/T sandstone unit in detail and mentioned a possible tsunami origin but favored a tempestite interpretation, later supported by Montgomery et al. (1992).

Bourgeois et al. (1988) elaborated on the tsunami interpretation and calculated high current velocities at an estimated water depth of 50 to 100 m, where even hurricane storm waves cannot transport coarse material. Hansen et al. (1987) and Bourgeois et al. (1988) suspected that the 25-cm-thick micritic or silty limestone and mudstone layers overlying the highest sandstone layers could represent silt and clay sediment that settled from the water column following the initiating-storm or tsunami-event. To test this idea, we performed a detailed analysis of the grain-size distribution in this interval (see below). Considerable confusion exists as to where the K/T boundary should be positioned in the Brazos River sections. For example, Hansen et al. (1987), Montgomery et al. (1992), and Smit and Romein (1985) favor a K/T boundary at the base of the sandstone complex, whereas Jiang and Gartner (1986) and Keller (1989a) favor a K/T boundary position at the top, or above the sandstone unit. The positioning of the K/T boundary is further discussed below.

In Alabama, the sandstone complex occurs as discontinuous irregular bedded sandstone bodies, known as the basal Clayton sands (see, e.g., Habib et al., 1992; Mancini and Tew, 1993; Mancini et al., 1989). Those sandstone bodies were interpreted—applying sequence stratigraphic methods—as transgressive infilling of low-stand channels (Mancini and Tew, 1993) or low-stand incised valley fills (Savrda, 1991). An origin by tsunami waves was shortly discussed but rejected (Savrda, 1991, 1993) Another approach was taken by Pitakpaivan et al. (1994) and Smit et al. (1994b), who reported pseudomorphs of impact spherules from the very base of the Clayton sands at Shell Creek and Moscow Landing, Alabama, suggesting a close temporal relation with the Chicxulub impact.

Recently, the K/T clastic complex has been studied in the classical Borrega Canyon–Arroyo de Mimbral section (Bohor, 1994; Keller et al., 1994b; Smit et al., 1992b; Stinnesbeck et al., 1994a) and in many other K/T outcrops in eastern Mexico (Alvarez et al., 1992b), Chiapas (Montanari et al., 1994), Guatemala (Hildebrand et al., 1994), and DSDP sites 540 and 536 (Alvarez et al., 1992a). Below we will report our observations on some of these sites.

# **METHODS**

In this chapter, we present sedimentologic and stratigraphic data of surface outcrops in Alabama, Texas, Mexico, and Haiti. Foraminiferal faunas were studied in thin sections and washed residues, obtained using standard laboratory techniques. Thin sections were petrographically analyzed to evaluate variations in composition and texture of the different sublayers of the K/T sandstone unit, with the aim of establishing the (bio)stratigraphic and sedimentologic relationships of the pre-, syn-, and post-K/T units.

The grain-size distribution of the insoluble residue of

55 samples across the K/T sandstone complex in the Brazos River section was determined with a Fritsch A-22 laser particle-sizer. The samples were dissolved in HCl and oxidized with  $H_2O_2$  to remove carbonate, organic material and some authigenic phases, such as pyrite. The remaining residue was treated in  $Na_4(P_2O_7)$  to prevent coagulation of the clay particles. The laser diffraction patterns were translated to a grain-size distribution according to the Fraunhofer model (Hess and Gatzemeier, 1991). From a few key profiles the iridium content was determined by coincidence neutron activation methods (F. Asaro, personal communication, 1991; Mimbral and Brazos River).

# THE K/T BOUNDARY SEQUENCE IN THE GULF OF MEXICO AREA

Although the details may differ locally, there appears to be a consistent depositional sequence in all outcrops of the K/T sandstone complex (Fig. 2). The K/T sandstone complex can be subdivided into four lithologic units. The lower three were defined earlier (Smit et al., 1992b) and can be recognized in most outcrops. However, in some outcrops (e.g., Brazos River) a fourth unit occurs on top of the sequence.

- The basal Unit I consists of poorly sorted, coarse-grained sediments, usually pebbly sandstones, filling irregular scours and channels in the topmost Cretaceous formations. Unit I is principally characterized by and locally rich in a peculiar type of spherules. The most common forms are spherules and droplets with an internal bubbly texture, interpreted as altered impact ejecta. The various sublayers of Unit I are laminated and contain variable mixtures of spherules, small limestone clasts, ripup clasts and boulders from underlying formations, planktic and benthic foraminifers, and-rarely-phosphatic and glauconitic debris. Size grading within Unit I is often not apparent. Lithic grains occur but are less abundant than in the overlying units. The most common texture is large-scale, channel-fill cross-bedding. Some larger channels display accretion-type lateral infilling. Burrowing has not been observed within the basal Unit I or extending from it at the bottom.
- 2. Unit II usually displays a stack of shallow lenses (or channels?) filling in shallow erosional depressions or blankets of fining-upward medium- to fine-grained sandstones, displaying a wide variety of sedimentary structures, such as parallel lamination associated with primary current-lineation, two- and three-dimensional—lunate and linguid—ripples, in-drift and inphase climbing ripples of variable dimensions, and rare antidune-like ripple structures. In the case where Unit I is absent and Unit II is directly in contact with the underlying finegrained sediments, flute- and groove-casts occur at the base. Current directions inferred from such sedimentary structures indicate variable—often 180° different—current directions in successive sublayers. The sandstones are highly variable in composition but usually form a mixture of foraminifers and lithic grains, with minor plant debris. Armored mudballs frequently occur at the base, with an armor of the above-mentioned bubbly spherules and lime clasts.

3. Unit III consists of thinning- and fining-upward, small-scale cross-bedded, fine sandstone layers alternating with thin layers of silt/mud draping over the sand layers.

In particular the thin silt layers contain anomalous iridium concentrations (Smit et al., 1992b) and Ni-rich spinels (Robin et al., 1994). The top ripple layers of Unit III are burrowed but mostly at the upper surface. The topmost rippled sandstone layer is often severely bioturbated. The ichnofabric of the trace fossils is usually tiered. Different types of burrows occur at different levels.

4. Unit IV overlies Unit III, sometimes gradually, sometimes more abruptly. In thin section the very base of Unit IV

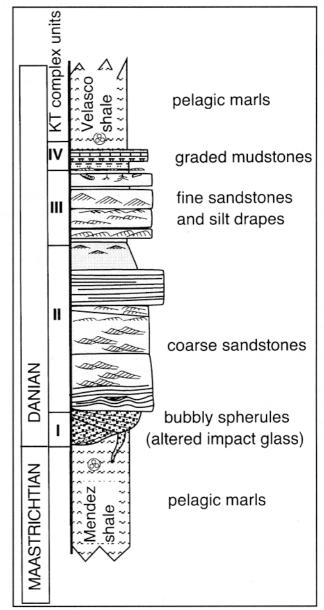


Figure 2. Lithologic column of the K/T sandstone complex (La Lajilla, northeastern Mexico), showing the main lithological subdivisions (Units I through IV), and the position of the K/T boundary.

still shows alternations of millimeters-thin fine sand and silt layers, passing upward into siltstones. The most conspicuous lithologic feature of Unit IV is a 5- to 10-cm-thick calcareous siltstone or mudstone layer (limestone unit F of Hansen et al., 1987), which can be traced over most K/T outcrops in northeastern Mexico and at Brazos River.

# THE STRATIGRAPHIC POSITION OF THE K/T BOUNDARY IN THE GULF COAST AREA

The placement of the K/T boundary in the Brazos River sections in Texas and in sections in eastern Mexico containing the K/T sandstone complex is controversial, as mentioned in the introduction (Smit et al., 1994a; Stinnesbeck et al., 1994b). Some place the K/T boundary above the complex (Beeson et al., 1994; Jiang and Gartner, 1986; Keller et al., 1993, 1994b; Stinnesbeck et al., 1993, 1994b) and some at the base of the clastic beds (Bourgeois et al., 1988; Hansen et al., 1987; Montgomery et al., 1992; Olsson and Liu, 1993; Smit et al., 1992b; Smit and Romein, 1985). Formally, the Global Stratotype Section and Point (GSSP) of the K/T boundary is defined (Cowie et al., 1989) in the El Kef section in Tunisia. At El Kef the K/T boundary is defined at the base of the boundary clay, directly above marls with an abundant and diverse Cretaceous planktic flora and fauna. The boundary clay at El Kef includes at its base a few-millimeters-thick-often rusty-clay layer, anomalously enriched in iridium. The layer also contains crystalline spherules (altered microkrystites; Smit et al., 1992a), Ni-rich spinels, and shocked minerals and is regarded by many as a distal ejecta-or fallout-layer. In other words, the K/T boundary in its type section is defined directly below a thin layer with impact ejecta. Given the hypothesis that this layer is globally produced by one near-synchronous impact event, it would make most sense to chronostratigraphically place the K/T boundary at the beginning of the event that produced the ejecta layer. Consequently, all deposits with the ejecta from the K/T impact event are Paleocene in age.

When locating the K/T boundary in sections other than the type locality, one can choose among several tools to make the correlation to the K/T boundary stratotype section at El Kef. Biostratigraphically, the correlation can best be achieved by using the mass-extinction-mass-mortality horizon, although that level may often be blurred by reworking. Using the first appearance datum (FAD) of the new Paleocene planktic species such as Globigerina minutula (=Globoconusa conusa sensu [Keller, 1988]) is more ambiguous. At El Kef, the FAD of G. minutula is 23 cm, and the FAD of Globigerina eugubina-a widely used biomarker for the basal Paleocene—is about 25 cm above the K/T boundary at El Kef. According to work currently underway by H. Vonhof and J. Smit, this means that the FADs of these species are at least 5 k.y. above the K/T boundary in the Kef section, using the average sedimentation rate of 40 m/m.y. of the Upper Cretaceous and Paleocene at El Kef. Another way to locate the K/T boundary is by means of the worldwide dispersed ejecta, including iridium-rich dust, shocked minerals, and spher-

ules produced by the presumed K/T impact event. The K/T boundary should be placed at the base of all these ejecta. We intend to demonstrate in this chapter that the sandstone complex at the K/T boundary postdates the planktic mass mortality and was deposited in one complex but coherent event and that the ejecta found in the base of the sandstone units (altered impact glass, shocked minerals) and at the top of the sandstone complex (iridium anomaly), although separated by a few meters, are easiest to explain as products of one and the same impact event. If this option is followed, the K/T boundary in the Gulf Coast outcrops should be placed at the base of the ejecta-bearing clastic deposits. When using a single tool such as the iridium anomaly, one could favor the K/T boundary being drawn just below the Ir anomaly, well above the base of the sandstone unit. However, the iridium anomaly in the Gulf Coast outcrops is dispersed and usually consists of multiple peaks. Because the Ir carrier is very fine grained (a particulate "carrier" for the iridium has yet to be found), it is not surprising that Ir settled more slowly through the atmosphere and water column than the coarse ejecta and that both occur in separate levels in the K/T sandstone unit. The mass-extinction horizon in the Gulf Coast outcrops, that is, the level where the abundance of Cretaceous planktic foraminifers drops by an order of magnitude, locates the K/T boundary again at the base of the clastic (ejecta) deposits: The last (hemi)pelagic sediments with abundant Cretaceous planktic faunas invariably occur below the K/T sandstone unit. The FAD of Paleocene foraminifers may be used as proxy for the K/T boundary as well. The FAD of Paleocene foraminifers in the Brazos River sections (Keller, 1989a; Beeson et al., 1994) is about 25 cm above the highest rippled sandstone layer. However, as said above, it should be kept in mind that the FAD of unequivocal Paleocene foraminifers is several thousands of years above the type K/T boundary in the Kef section and probably also in the Brazos River sections.

# SECTIONS CONTAINING K/T SANDSTONE COMPLEX IN THE U.S. GULF COAST AND MEXICO

# Moscow Landing, Alabama

The easternmost outcrop studied containing the K/T sand-stone complex is at Moscow Landing, Alabama. The K/T sand-stone complex occurs here as a series of discontinuous lenticular sandstone bodies, known as the Clayton basal sands of the Clayton Formation, overlying the fossiliferous upper Maastrichtian Prairie Bluff Chalk with an erosional contact. The Prairie Bluff Chalk is a gray sandy fossiliferous chalk, containing about 1 m below the K/T boundary a conspicuous phosphatic macrofossil lag bed, interpreted as  $\alpha$  condensed section (Mancini et al., 1989). Bedding planes dip slightly to the south (2°), but as a result of repeated offsets by small normal faults, the K/T boundary remains exposed for more than 1 km along the east bank of the Tombigbee River.

The basal Clayton sands are usually interpreted in sequence stratigraphic terms (Habib et al., 1992; Mancini and Tew, 1993;

Mancini et al., 1989) as early Danian low-stand channel-fill deposits, overlain by a transgressive surface with a Thalassinoides burrow-fabric and transgressive deposits, respectively. However, the situation is more complex, as illustrated in Figures 3 and 4. Over most of the outcrop, the Danian transgressive surface overlies paraconformably the Prairie Bluff Chalk, but the same surface also overlies the coarse-grained basal Clayton sand bodies (Fig. 3). Within the 200- to 400-m-wide tilted blocks, bounded by the small normal faults mentioned above, the bedding planes of the Prairie Bluff Chalk are not disturbed and remain mostly parallel. However, near the faults, bedding is chaotic, displaying a mixture of soft and semisoft sediment deformation. In some rotated, about 5-m-wide, domains, the bedding planes are tilted vertically and are truncated by the Danian transgressive surface (Fig. 4). Some of these faults also offset the basal Clayton sands but do not offset the early Danian transgressive surface. Drag along these faults plastically deforms—even overturns—the basalmost layers of the Clayton basal sands. In some of the faults Clayton sands have been injected. The next coarse sand deposit of a younger part of the Clayton Formation again truncates the tilted bedding planes of the basalmost Clayton layers, showing that movements along the fault plane occurred during deposition of the Clayton basal sands.

The lowermost infillings of <3-m-wide and <1-m-thick "pockets" of the basal Clayton sands consist of a poorly sorted conglomerate containing Cretaceous macrofossils and Prairie Bluff chalks clasts, in a matrix of coarse sands. Some of the chalk clasts are plastically deformed, in particular near the base. Characteristic components of the sand matrix are green, sparry calcite-filled spheroids and droplets, 2 to 3 mm in diameter, with an external lining of clay minerals (Fig. 5A). The spheroids contain internal cavities, also filled with sparry calcite.

Identical spheroids were found in the nearby outcrops of

Shell Creek and Lynn Creek, and those were interpreted as altered splashform tektites, by analogy with spheroids from Beloc and Mimbral filled with bubble-cavity—rich glass (Pitakpaivan et al., 1994).

The basal conglomerate has the appearance of a mass-flow and is found only at those places where the Prairie Bluff Chalk is slumped and deformed. The bottom of the "pockets" follows the slump structures of the deformed Prairie Bluff Chalk. The conglomerate is overlain and truncated by 10- to 50-cm-thick lenticular layers of very poorly sorted, poorly graded, parallellaminated coarse sandstones and pebbly sandstones, rich in Cretaceous macrofossils and chalk clasts. The laminated textures are typical for high current strength (upper flow-regime) and rapid sedimentation. The sand matrix dominates, but the typical bubbly spheroids of the underlying conglomerate matrix were not found. As mentioned above, the lowermost layers were drag-tilted near the faults and truncated by the overlying sand layers. The geometry of the sand bodies filled with conglomerates and sandstones is asymmetrical. They appear as triangular wedges in cross section, with their thickest part at the southern end, near the faults (Fig. 4). The pockets with spheroid-rich conglomerate occur only at the southern—thickest end of the wedges. At none of the bedding surfaces or in the sandstone layers were borings or Thalassinoides-type burrows observed other than those penetrating down from the Danian transgressive surface.

A few symmetrical channels filled with graded conglomerate and nonlaminated coarse sand—with chalk boulders as large as 90 cm—are also paraconformably overlain by the Danian transgressive surface. The infilling layers are not deformed in contrast to the triangual wedges and are thus presumably younger. Those channels are incised into the underlying chaotically bedded part of Prairie Bluff Chalk and presumably also

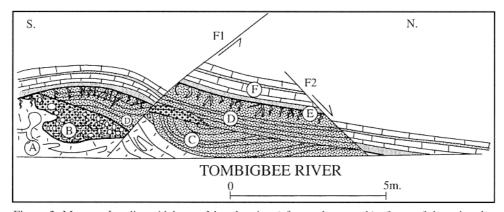


Figure 3. Moscow Landing, Alabama. Line drawing (after a photograph) of one of the spherule-(altered tektites—) bearing K/T complex channels. A, Deformed chalks of the Prairie Bluff Formation. B, Spherule-bearing conglomerate "pocket," or deformed channel. C, Coarse-grained pebbly sandstone—filled channel, upturned near fault F1. D, Subsequent coarse laminated pebbly sandstone and coarse sandstone layer, truncating the upturned end of channel C. E, Transgressive surface truncating B–D channels as well as a symmetrical channel (not shown) of the preceding low-stand incision. Borings penetrate into the upturned end of channel D. F, Clayton Formation graded sandstones, limestones, and phosphatic lag deposits.

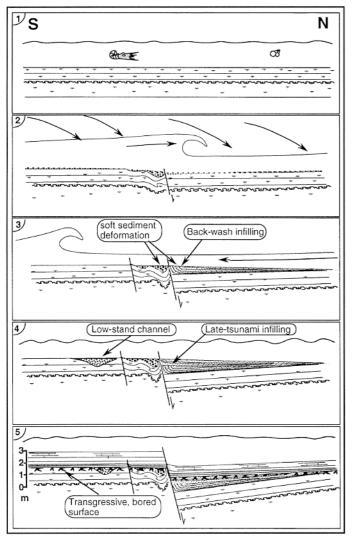


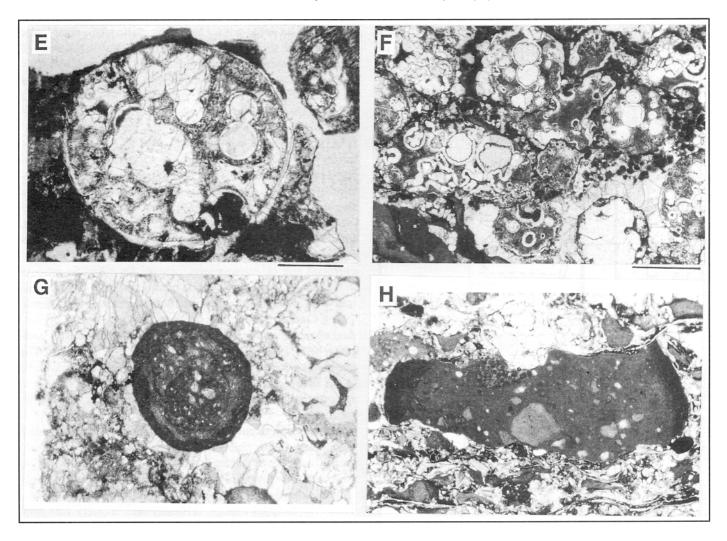
Figure 4. Cartoon of the sequence of events at the K/T boundary in the Moscow Landing, Alabama, outcrop. Only locally, at the downthrown side of the faulted blocks, has an almost complete sequence of the K/T clastic beds been preserved. 1, Situation just before the K/T boundary. The Prairie Bluff chalks are undisturbed and parallel bedded and contain a phosphatic lag bed, interpreted as maximum flooding surface. 2, Arrival of large waves, possibly preceded by earthquakes, causes slumping and faulting. The ejecta from the Chicxulub impact arrive at about the same time and are reworked into conglomerate pockets loaded into the slumped parts. 3, Continued faulting causes deformation of the edge of the sandstone channel infill. Some channels appear to originate as a result of the faulting and are infilled with coarse terrigenous (backwash?) sands. 4, Triangular wedges caused by continued faulting are further filled with pebbly sandstones, and the early Danian sea-level fall-caused low-stand channels are filled with basal Danian sediments. 5, The low-stand phase and subsequent transgression erodes part of the low-stand channel, the tsunami deposits (Units II-IV), and the top of the Cretaceous and leaves a bored hard ground. Continued faulting causes offset of the transgressive surface and the subsequent Clayton Formation deposits.

into the basalmost Clayton sand wedges, although this could not be clearly observed in the outcrop. Habib and Talvirska (1994) demonstrated the presence of earliest Danian dinoflagellate cysts in one of the symmetrical channels. We, however, did not observe any Danian foraminifers or dinoflagellate cysts in the underlying triangular sand wedges.

The trangressive surface overlies the Prairie Bluff Chalk, the basalmost wedges, and the symmetrical channels. The Thalassinoides-type burrows extending down from the Danian transgressive surface penetrate a few decimeters into the top of the Prairie Bluff Chalk as well as into the top of both types of channels. The burrows penetrate parallel to the bedding planes where the basal Clayton sands were tilted vertically, showing that the transgressive surface postdates deformation of the basal Clayton sand bodies. The burrow-fillings contain Morozovella pseudobulloides (Mancini et al., 1989), demonstrating a hiatus of at least 50 k.y. (Groot et al., 1989) between the sandstone channels underlying the transgressive surface and the marlstones and limestones of the upper part of the Clayton Formation overlying the transgressive surface. The Clayton marlstone contains at the base a 10-cm-thick lag bed with quartz grains, phosphatic pebbles, and reworked Cretaceous fossils (Mancini et al., 1989). This layer is continuous over the entire outcrop but thickens over the slumped parts of the Prairie Bluff Chalk, filling up shallow depressions. The next overlying layers are two continuous 15-cm-thick limestone beds separated by a 10-cm-thick sandy marl. The thickness of these layers is independent of the underlying type of lithology. Mancini et al. (1989) reported a similar phosphatic lag bed in the Braggs and Mussel Creek sections, overlying a transgressive surface on top of the Prairie Bluff Chalk (Braggs) or a transgressive surface with associated *Tha*lassinoides burrows (Savrda, 1993) on both the Prairie Bluff Chalk and basal Clayton sands (Mussel Creek). The basal Clayton sands at Mussel Creek fill more or less symmetrical channels, similar to the symmetrical channel at Moscow Landing described above, and are reported to contain Danian microfossils (Mancini et al., 1989) and several tiers of Thalassinoides burrows (Savrda 1993). Bubbly spheroids were not reported, nor have we found those. Thus sediments comparable to those in the triangular wedges at Moscow Landing seem to be lacking in these outcrops.

Laterally, from north to south along the outcrop, a consistent sequence is observed across several of the K/T sandstone wedges (Fig. 3). The upthrown, not deformed part of the Prairie Bluff Chalk ends with a series of normal faults. In between the faults the intensity of deformation increases until the chalk layers are completely slumped. The basal mass-flow conglomerates were deposited against, and partially upon the slumped chalk, partially upon the nondeformed downthrown end of the next Prairie Bluff Chalk block. The lenticular pebbly sandstone layers were deposited against and partially upon and farther to the north of the basal conglomerates, gradually pinching out to the north.

In general we agree with the interpretation of Mancini et al.



waves. Those deposits are followed by deposition of mass-flows and coarse sandstones with coarse (?near-shore) terrigenous material (K/T sandstone Unit II). Any later fine-grained phases (K/T sandstone Units III and IV), as observed in other K/T sections around the Gulf of Mexico that may also have been associated with tsunami waves, were removed during low-stand erosion, preceding the burrowed Danian transgressive surface.

The next phase is infilling of incised lowstand channels, with early, but not earliest, Danian material.

## Brazos River, Texas

The many studies of the Brazos River sections have led to publication of numerous papers that convey a variety of interpretations. The controversy about the placement of the K/T boundary in the Brazos sections has already been mentioned. At low-water level of the Brazos River, the K/T sandstone complex can be traced over a considerable distance in the river bed. In the Brazos 1 section the lithologic sequence across the K/T sandstone complex has been subdivided into units A through J (Hansen et al., 1987), a subdivision that we will follow herein

(Fig. 6). The lower unit (unit A, Corsicana Fm, >15 m thick as exposed in the river bed) consists of fossiliferous upper Maastrichtian mudstones deposited at mid- to outer-shelf depths (75 to 200 m; Bourgeois et al., 1988). Occasional shell stringers in the Corsicana Formation about 10 m below the K/T boundary and the low-diversity planktic foraminiferal fauna suggest a water depth closer to the lower estimate, near storm wave base (50 to 75 m). Unit B/C (0 to 45 cm thick) is a laminated, poorly lithified, graded skeletal—shell hash—sandstone, rich in phosphate, glauconite, shell debris, and small clay clasts, resting with a scoured contact on unit A. At several places the basal part of unit B/C contains boulders of black claystone and micritic limestone.

Recently, we have found abundant green spheroids in the basal coarse-grained sandstone (unit B/C) in the Darting Minnows Creek outcrop, about 3 km southwest of the Brazos 1 outcrop (Bourgeois et al., 1988). The spheroids are dominantly composed of dull olive-green clay minerals. As at Moscow Landing, they contain numerous internal cavities filled with calcite (Fig. 5B). Those spheroids were earlier probably mis-

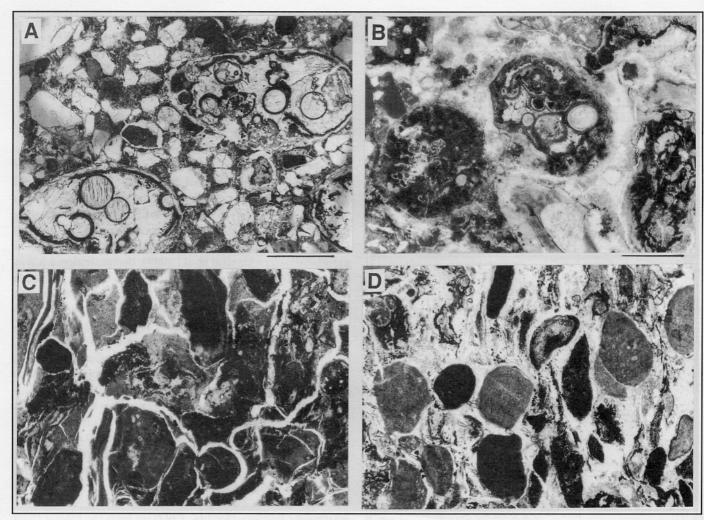


Figure 5 (on this and facing page). Micrographs of thin sections of the bubbly spherules and limestone fragments, interpreted as ejecta. A, Bubbly calcitic spherule (Moscow Landing). B, Bubbly spherule (Darting Minnows Creek, near Brazos River, Texas). C, Remnant of a bubbly spherule from Brazos 1 section. D, Limestone fragment (Darting Minnows Creek). E, F, Bubbly spherules (Mimbral, Mexico). G, H, Concentric banded limestone fragment, with some bubble? cavities (Mimbral, Mexico). (Bar = 0.5 mm.)

(1989), Mancini and Tew (1993), and Savrda (1993) that most of the sequence at Moscow Landing and all of the sequences found at Mussel Creek and Braggs can be explained in a sequence stratigraphic scheme. However, we interpret the Moscow Landing basal Clayton sands as two different types of deposits: a basal sequence consisting of several nonburrowed, rapidly deposited, partially mass-flow—type deposits (K/T sandstone Units I and II), followed by low-stand ravinement valleys filled with Danian low-stand deposits. The interpretion of the Moscow Landing K/T sequence is best illustrated with the cartoon of Figure 4. We assume that faulting and associated slumping of the Prairie Bluff Chalk started just before and remained active during deposition of the Clayton basal sands. Because the thickness and texture of the Prairie Bluff Chalk layers are not influenced by these faults, the faults were presumably not active

in the Upper Cretaceous. The major faults were later rejuvenated, because the major tilting phase—offsetting the K/T
boundary as described above—took place after formation of the
Danian transgressive surface and deposition of the Clayton Formation. During and immediately following the initial phase of
faulting and slumping the mass-flow conglomerates with green
bubbly spheroids and the laminated pebbly sandstone layers
were rapidly deposited. Some sandy material (without bubbly
spheroids) is even injected into open faults. The above-mentioned faulting phase and subsequent slumping and deposition
of these mass-flow units may be explained by seismic shaking
resulting from the Chicxulub impact event, followed by deposition of the spheroid-rich ejecta. The ejecta are mixed with rip-up
chalk clast (K/T sandstone Unit I) and redeposited by strong
currents, believed to be induced by passage of large tsunami

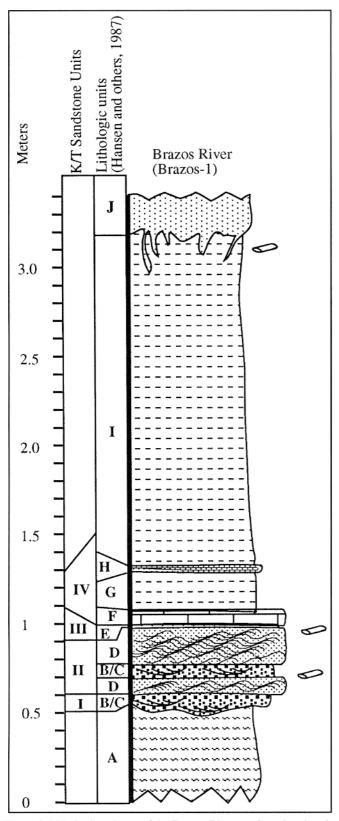


Figure 6. Lithologic column of the Brazos River section, showing the subdivision A–J of Hansen et al. (1987) (see text) and the subdivision into K/T sandstone complex units I–IV.

taken for glauconite grains. However, glauconite grains-also present in the shell hash—can be easily distinguished by their bright green colors, irregular outline, and absence of spherical cavities. Reexamination of earlier thin sections of the coarse "shell hash" of the Brazos 1 and 3 and Cottonmouth Creek (CMC) outcrops (Hansen et al., 1987) reveals that spheroids occur frequently also in those outcrops, in the lower B/C units (Fig. 6). However, the spheroids are strongly corroded and hardly recognizable. Often only an aggregate of the calcitefilled cavities remains (Fig. 5C). Another characteristic component of the basal sandstone is abundant, rounded carbonate fragments, 1 to 5 mm in diameter (Fig. 5D). These fragments often display irregular, concentric banding and contain rare, internal spherical cavities. The fragments are coarsely crystalline in the interior and have a <0.1-mm-thick, darker, oftencorroded rim of micro-sparry calcite. An 87Sr/86Sr ratio of 0.707564 (K. Beets, personal communication, 1992) is consistent with a Campanian age of the carbonate (MacDougall, 1988). Carbonate fragments of the same size and with an identical texture were found in all other Gulf Coast basal K/T sandstone beds, including DSDP site 540 and Beloc, Haiti. The fragments are easily identifiable in thin section (Fig. 5D, G, H) in the basal sands of all Brazos River sections and appear to have better survived diagenetic alteration than the bubbly spheroids.

A salient lenticular layer of well-lithified, current-rippled medium- to fine-grained sandstone (unit D, 0 to 35 cm thick) quite sharply overlies the basal sands (unit B/C). The ripple structures are invariably asymmetrical and include steeply climbing ripples, climbing ripples-in-drift, and linguoid ripples. These ripple types change vertically and laterally into each other. Oscillation-type ripple structures, hummocky cross-stratification, or other symmetrical or asymmetrical wave ripple structures have not been observed, although it is often hard to distinguish the ripple structures observed in a section perpendicular to the current direction from wave ripple structures.

Current directions measured in unit D of the Brazos 1 and 3 outcrops are dominantly toward N100–110E but shift to N180 near the top of the layer. The basal sands and rippled sandstone (units B through D) repeat up to three times stratigraphically in the outcrops in the Brazos river bed, Brazos 3, CMC, and Darting Minnows Creek (DMC) (Hansen et al., 1987; Bourgeois et al., 1988). The second sequence (units B through D) is more continuous, and the second current-rippled sandstone (unit D) is often the thickest. The Brazos 1 section contains only one unit B through D sequence, but it could not be observed whether the first or second (units B through D) sequence outcrops in the Brazos 1 section.

Conspicuous, 1-cm-diameter, tubelike, branching (Ophio-morpha?) burrows occur on the top surface of both the first and the second rippled sandstone (unit D). These burrows were not observed in the interior of the rippled sandstone. It is not clear whether these burrows penetrated from above and spread out at these particular surfaces after deposition of the entire sandstone

sequence or were produced shortly after deposition of the rippled sandstone layers.

The rippled sandstone (unit D) is overlain—in ascending order—by a thin silt layer (unit E, 1 cm thick), a weathering-resistant silty limestone (unit F, 8 cm thick), and a silt/mudstone (unit G, 20 cm thick) (Fig. 6). The first (rare) Paleocene biota appear at the top of the mudstone (unit G) (Jiang and Gartner, 1986; Hansen et al., 1987). A single laminated fine sand layer (unit H, 2 to 3 cm thick) follows, overlain by fossiliferous mudstones, containing extremely rare Paleocene planktic foraminifers in the upper part (unit I, 2.5 m thick) capped by a burrowed transgressive surface. Large *Ophiomorpha*-type burrows associated with the transgression extend downward for 0.5 m into the mudstones of unit I. The Littig Member of the Kincaid Formation, a sandy, glauconitic, phosphatic lag bed containing reworked Cretaceous fossils (unit J, >30 cm thick), overlies the transgressive surface.

It has been suggested by some authors that the silty limestone and mudstone (units F, G) represent either the grading settling "tail" of the tsunami disturbance (Bourgeois, 1991; Bourgeois et al., 1988) or low-energy sedimentation after a storm (Hansen et al., 1987). Alternatively, it has been suggested that no size grading is apparent in those units and that they represent a homogeneous background sedimentation, not related to the deposition of the sandstone units (Beeson et al., 1994; Keller, 1989b; Keller et al., 1993; Keller et al., 1994a; Stinnesbeck, et al., 1993; Stinnesbeck et al., 1994a).

To verify these hypotheses, the grain-size distribution of the HCl-insoluble and  $H_2O_2$ -treated residue of 60 samples across the K/T boundary sequence of the Brazos 1 outcrop (units A through I) was analyzed. HCl-insoluble residues were used to eliminate biases that could be caused by such factors as the difference in size between Cretaceous and Paleocene foraminifers. Samples from the Corsicana mudstones, the basal skeletal sandstone, and the rippled sandstone (units A through D) were taken from the outcrop in the Brazos river bed, and the remaining samples (units E through I) came from the Brazos 1 outcrop in the west bank of the river, about 20 m to the northwest. The silty limestone and overlying mudstone (units F, G) above the last sandstone ripples were sampled in detail (on average every 0.8 cm) (Fig. 6).

The grain-size distributions are presented as histograms (Fig. 7). Percentages of the 60 histograms, arranged in ascending stratigraphic order, were contoured at 1% intervals (Fig. 8). The detailed sampled interval of units E through G is presented in Figure 9.

Several trends can be observed in the grain-size distributions that are not easily visible in outcrop. The Corsicana mudstones (unit A) can be subdivided into a slightly siltier lower part (0.5 to 10 m below the K/T boundary) and a more clay-rich upper part (0 to 0.5 m below the K/T boundary). The rippled sandstone (unit D) is fining upward, consistent with inferred settling from suspension-rich currents decreasing in strength. Above unit D no fine sand has been stirred up anymore, with

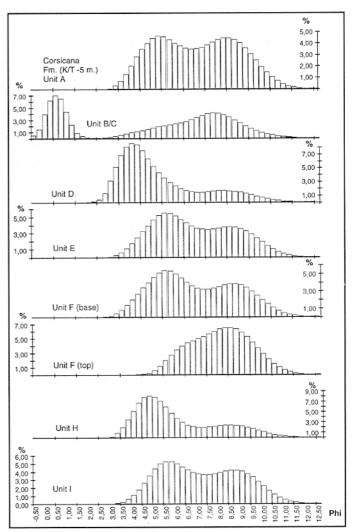


Figure 7. Selected histograms of the grain-size distribution of the different lithological units (see Fig. 6). Grain size in Phi units.

the exception of one 1- to 2-cm-thick very fine sand layer (unit H). The silt, silty limestone, and mudstone (units E through G) above the rippled sandstone (Figs. 7 through 9) show a bimodal size distribution, with peaks in the silt (Phi 5.75 to 6.5) and clay (Phi 9) size-fraction (Fig. 9). The silt fraction gradually decreases upward while the clay fraction (Phi 9) gradually increases, until near the top of unit G the clay fraction dominates. In the silty limestone (unit F) the modal grain size of the silt fraction shifts gradually from Phi 5.75 to Phi 6.5 (19 to 11µ, Fig. 9). The graded grain size distribution through units E through G strongly suggests that a suspended cloud of silt and clay settled out during low-energy conditions to form those units, directly on top of the K/T sandstone units, contradicting the suggestion (Beeson et al., 1994, Keller et al., 1993) that these silt-mudstones are part of normal background sedimentation. The grain-size distributions of the unit A mudstones are comparable to those of units E through G, suggesting

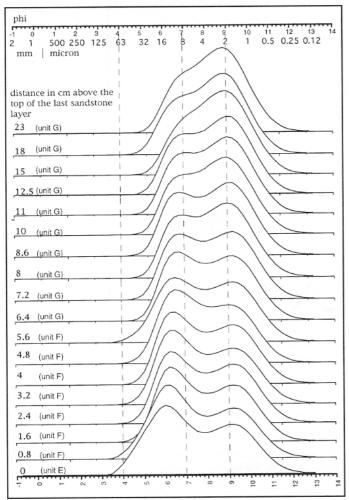


Figure 9. Brazos 1 outcrop. Detail of Units E–G (K/T sandstone complex Unit IV). Grain-size histograms are in stratigraphic order, showing the gradual shift of a bimodal distribution, with a dominating silt component, to a distribution with a dominant clay fraction.

that resuspended Corsicana Formation mudstones could have deposited units E through G. All iridium peaks found in the Brazos 1 section (Asaro et al., 1982), occur in this graded interval (units E through G, Fig. 10).

The thin, very fine sandstone (unit H) layer at 25 cm above the rippled sandstone indicates an increase of energy, with or without connection with the K/T sandstone beds. Near the top of the mudstones of unit I (Fig. 8) grain size is coarsening upward toward the transgressive surface. The settling time for the graded units E through G can be estimated using Stokes law. In Figure 10 the percentile scores of a few selected grainsize classes are plotted against stratigraphic thickness. The grain sizes with diameter >63µ (Phi 4) have settled within 1.5 cm from the base of unit E. Grain size 32µ (Phi 5) decreases to a minimum at 13 cm above the base of unit E. Assuming a homogeneous silt/clay suspension cloud of 50-m thickness (Table 1)—the minimum estimated water depth—the first

13 cm of units E through G could have been deposited in about 20 hs. The settling time of the finer tail (Phi >6) of the graded units E through G is harder to estimate. However, the fine suspended particles (Phi 8 to 9.5, 4 to  $1.4\mu$ ) apparently continued to settle, as the clay fraction at the top of unit G and base of unit I (Fig. 8) dominates the size distribution. If this interval is still part of the settling phase, the fraction of 4 to  $16\mu$  might have settled between 1 week and a few months. Figure 10 shows that all of the iridium peaks occur within this graded interval.

# Arroyo de Mimbral, Mexico

The K/T sandstone complex crops out in the south bank of the Arroyo de Mimbral, about 4.5 km east of the electric power lines (Fig. 11). Thirty-five m of well-bedded upper Maastrichtian (*Abathomphalus mayaroensis* Zone) Mendez Formation marls are exposed below the K/T sandstone unit. Bedding planes in the last meter below the K/T sandstone complex are barely visible.

The K/T sandstone complex in the eastern, best-exposed, part of the outcrop is depicted in Figure 11, showing the meter markings (m.mk.) that were painted on the outcrop. Unit I is deposited in four separate shallow depressions or scours along the outcrop, with a maximum width of 20 m and a depth of 1.2 m at m.mk. 28. A 2-cm-thick bentonite bed that occurs between 10 and 50 cm below the base of the depressions in the Mendez shales was never breached but runs parallel to the base of the depressions. This shows that the depth of scouring was less than 1.2 m, and that the depressions were accentuated by loading. The depressions are channel-like, and the axis of the best exposed, middle channel (m.mk. 18-38) strikes more or less north-south, as determined with the orientation of the basal scours at m.mk. 24 and 36-38. This channel is laterally infilled from the west. The lateral accreting layers are inclined to as much as 15° with respect to the overlying Unit II layers and are truncated by the overlying Unit II sandstones at m.mk. 32-38, giving the (false) impression of an angular unconformity (Hay, 1960). The different layers of the sideward shifting channel fill are composed of a variable mixture of spherules, droplets, and other splash forms (some with a glass interior; Fig. 5E, F), small subrounded microsparitic limestone clasts (Fig. 5G, H), foraminifers, terrigenous grains, and flat Mendez rip-up clasts containing Maastrichtian foraminifers. Texture and sorting differ from layer to layer. Some layers have the character of a poorly sorted debrisflow, with clasts supported in a sand matrix. Others are slightly better sorted, displaying low-angle to very low angle large-scale cross-bedding, probably due to channel-migration. Some layers are a well-sorted packstone of foraminifers, spherules, and a few detrital quartz grains. Such layers are well cemented and weather out. In some layers rip-up clasts of the Mendez dominate. These rip-up clasts are strongly deformed and commonly fused together. The boundary between the Mendez clasts is often outlined by thin stringers of spherules. The fused clasts seemingly

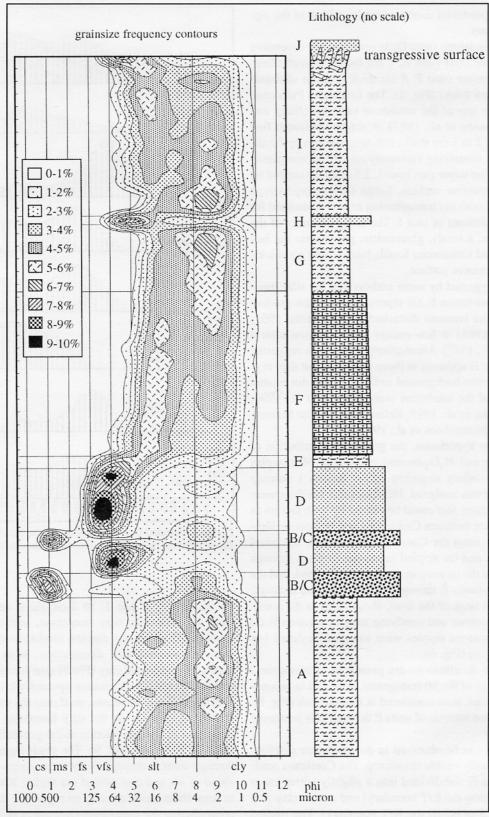


Figure 8. Contour plot of grain-size distribution in 60 samples across the K/T boundary in the Brazos 1 section. The samples are plotted in stratigraphic order but note that the true sample spacing is different. Therefore, the lithologic column represents lithologic expression of the samples in the correct stratigraphic order but has no vertical scale. The contours are at 1% spacing, and scores are computed for each 1/4 Phi class. A–J, lithologic units of Hansen et al. (1987). Abbreviations: cs = coarse sand, ms = medium sand, fs = fine sand, vfs = very fine sand, slt = silt, cly = clay.

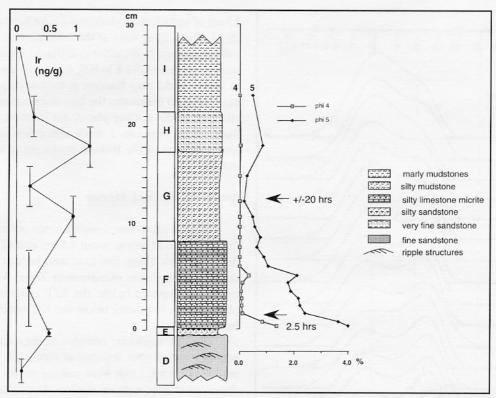


Figure 10. Profiles of percentile score of two grain-size (Phi) classes from the histograms of Figures 7 through 9, in true stratigraphic thickness. Ir concentrations in ng/g (nanogram/gram) are from Asaro et al. (1982). The duration in hours is taken from Table 1 and estimates the settling time of silt of Phi 4 and 5 from a 50-m-thick water column, after the deposition of the last sandstone (unit D). The clay fraction would settle after weeks (Table 1). The Ir carrier is apparently fine grained, because it settles down together with the finest clay fraction, several days to weeks after the impact.

TABLE 1. SETTLING TIME OF FINE SEDIMENT SUSPENDED IN THE WATER COLUMN COMPUTED FOR DIFFERENT WATER-COLUMN THICKNESS

Size	Micron	Settling Velocity (m/h)	Water-column Height in Meters							
Class (phi)			2	5	10 (time	25 - hours)	50	500		
3	125.00	57.60	0.03	0.09	0.17	0.43	0.87	8.68		
4	64.00	19.08	0.10	0.26	0.52	1.31	2.62	26.21		
4.5	40.00	3.60	0.56	1.39	2.78	6.94	13.89	138.89		
5	32.00	2.52	0.79	1.98	3.97	9.92	19.84	198.41		
6	16.00	0.61	3.27	8.17	16.34	40.85	81.70	816.99		
7	8.00	0.18	11.11	27.78	55.56	138.89	277.78	2,777.78		

form "continuous" layers and can give the impression of normal hemipelagic sedimentation alternating with coarse-grained sand layers. This impression has led to estimates of the duration of sedimentation of the K/T sandstone complex of tens of thousands of years (Lyons and Officer, 1992).

The Unit I channels are progressively deformed toward the edges of the channels (m.mk. 34–38 and 44–48). The dip of the lateral accreting layers increases, and near m.mk. 38 and 45 those layers are even overturned. The underlying Mendez shale follows a similar deformation pattern. The disappearance of bedding planes in the Mendez shales just below the sandstone

units could be due to soft-sediment deformation of the Mendez marls. The above-mentioned bentonite bed enclosed in the Mendez shale is folded at several places, showing that the shales were deformed. Near m.mk. 36–46 the Mendez shales are strongly deformed and contain frequent slickensides, without obvious preferred orientations. We infer that the Mendez shales at time of deposition of the K/T sandstone complex were still extremely soft and could be easily deformed. As a result of uneven loading of the rapidly accumulating incipient channel fills, the soft Mendez oozes were pushed away from the center of the channels into the large flamelike or diapirlike structures

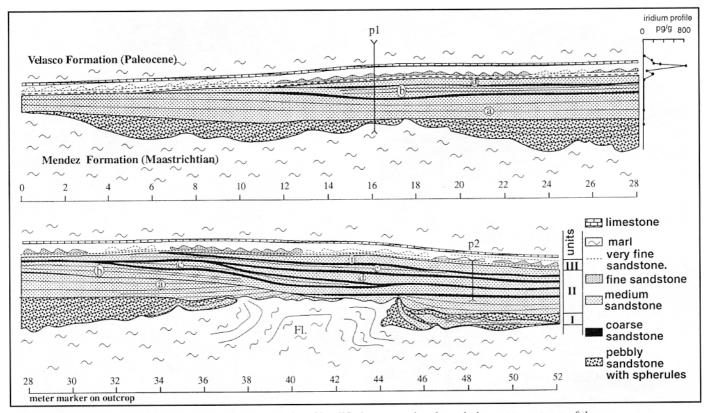


Figure 11. Arroyo de Mimbral, Mexico. Simplified cross section through the eastern outcrop of the K/T sandstone complex. Meter markings (see text) are painted on the outcrop. Ir abundances (pg/g = picogram/gram) (Table 3; Smit et al., 1992b) are measured at the section p1. The petrographic thin-section analysis (Table 2) is at p1 and p2. F1 = Mendez shale "diapir" or large, deformed flame structures between two channels. A–F, different lenticular parallel-laminated layers of Unit II, each with a scoured, coarse base. Note that near the shale "diapir" F1, the edges of Units I and II are upturned and that each successive channel or layer is less deformed and either "onlaps" on or truncates the steeper, previously deposited one.

observed between the channels (m.mk. 38–44). The sand layers near the depression rims (m.mk. 38 and 44) were dragged along and were oversteepened or even overturned by this diapiric movement. One can infer that the diapiric movements continued during the infilling of the channels, because successive layers onlap on more steeply inclined previously deposited layers (m.mk. 44–48). A spectacular example of such large flames or "diapirism" can also be observed at the Rancho Nuevo, Mexico, site (Alvarez et al., 1992b).

Current velocities involved in deposition of Unit I are apparently variable and mostly high, based on the coarse grain size. Unit I lacks adequate current-direction indications. The direction of lateral accretion shows infill from the west in one channel near m.mk. 28–38 and from the east in the next channel near m.mk. 44–48.

Unit II is made up of at least six fining-upward, stacked, thinning-upward lensing calcareous sandstone bodies (Fig. 11, a through f). Often the base of a higher sandstone body scours into the top of the lower ones and truncates the bedding. The latter is most obvious between m.mk. 36–42, because the angle of dip

of the laminations of the lower (Fig. 11, a) sandstone body has been increased in a way similar to that of Unit I near the Mendez "diapir." Unit II differs petrographically and texturally from Unit I. The sandstone is pervasively parallel laminated and is well sorted, except in the axial, basal parts of the basal (Fig. 11, a) sandstone body. In Unit II detrital terrigenous grains are increasingly more common. In some laminae the sand-fraction is dominated by foraminifers identical to those in the Mendez shales; other laminae are rich in detrital quartz grains (Fig. 12A, B). Minor amounts of biotite crystals and charcoal fragments (Kruge et al., 1994) occur as well. Spherule remains similar to those found in Unit I also occur in the coarse basal part of several Unit II (Fig. 11b, c) sand bodies. Other components of Unit II, in particular in the basal part of sandstone body (Fig. 11a) near m.mk. 22-26, include rare siliceous sponges, plant debris, and rounded clasts of Mendez shale, some of which are 80 cm in size (m.mk. 29).

The axial part of the basal Unit II channels contains multiple layers rich in plant debris and pieces of wood. Some of the wood fragments have borings and were probably water satu-

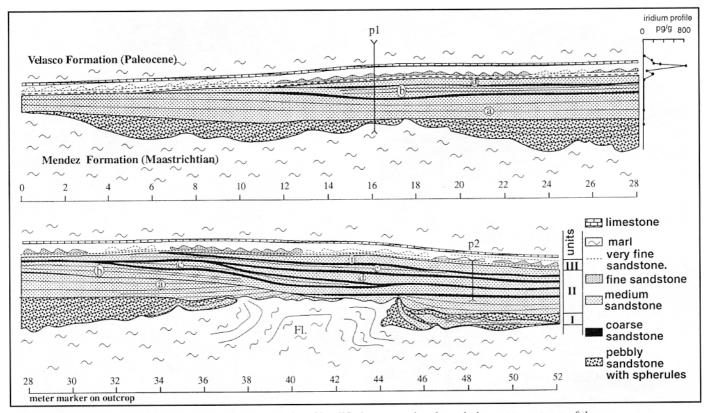


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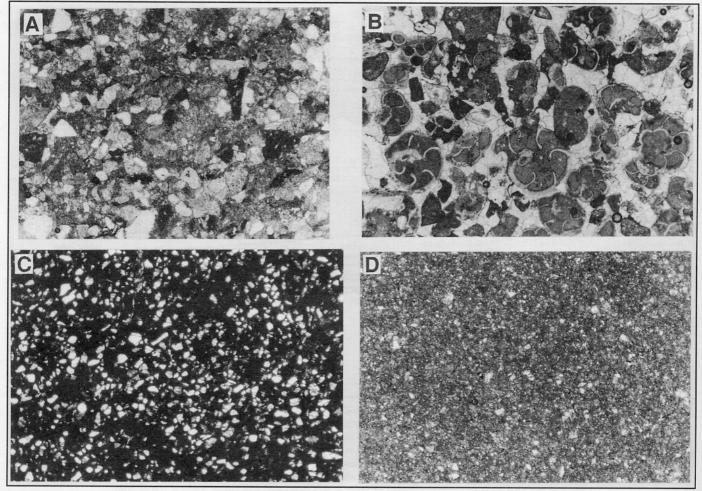


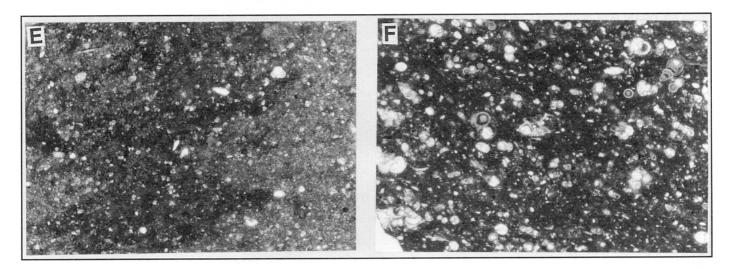
Figure 12 (on this and facing page). Thin-section micrographs of the Mimbral, Mexico, section. A, Unit II (Sample M5) terrigenous sandstone with "dirty" matrix. B, Foraminiferal grainstone with sparry calcite matrix, Unit II (sample M18). C, Fine sandstone flaser from top of Unit III (see Fig. 13). The matrix is entirely composed of iron oxides, falsely resembling the impact fallout layer, or "fireball" layer (Stinnesbeck et al., 1993) of distal K/T sections. D, Micrite (cf. Fig. 13, level 300 cm). E, Basalmost Velasco shale, poor in Cretaceous planktic foraminifers. F, Mendez shale, 5 to 10 cm below the K/T sandstone Unit I, rich in Cretaceous planktic foraminifers.

rated before they were transported. They are not the remains of fresh plants. Small charcoal fragments occur in increasing numbers in the higher sandstone bodies (Kruge et al., 1994).

Unit II overlies Unit I and the Mendez diapirs with a sharp contact at most places and truncates the layers of Unit I. However, in the middle of the Unit I channels, the transition from Unit I to II is rapid but gradual and nonerosive (between m.mk. 22–30) over a thickness of about 15 cm. The uppermost layers in Unit I show changes leading up to Unit II. In the transition zone detrital quartz content increases, and the Mendez shale rip-up clasts are progressively more rounded and often armored with a peppering of impact spherules. The rip-up clasts preserve internal layering and apparently were more resistant to deformation than the Mendez clasts within Unit I. We assume that these "armored mudballs" are eroded from deeper,

more-compacted Mendez beds. Sedimentary structures in Unit II are dominated by semiparallel laminae associated with primary current lineations on the bedding-plane surfaces, having different orientations at different levels (N75°E–N180°E). A single 2-cm-thick layer with low-angle cross-bedding occurs at m.mk. 12 (current direction N120°E  $\pm$  15°). Flute-casts were observed near m.mk. 38–42 where Unit II directly overlies the Mendez marls. These flute-casts show a N350°E  $\pm$  10° current direction.

Unit III conformably overlies Unit II, where the first thin (1 cm thick) silt layer indicates the beginning of a series of alternating silt and thin current-rippled fine sandstone layers (Fig. 13). The first silt layer is also the first layer enriched in Ir. The rippled layers consist of asymmetric, unidirectional current ripples. Symmetric ripples or ripples with bidirectional internal



structure indicative of oscillation (wave) ripples were not observed. Some ripples bear a resemblance to hummocky cross-stratification structures on the rock-face cut at right angles to the current direction (Lyons and Officer, 1992), but at a rock-face cut parallel to the current direction they show their unidirectional cross-bedded character. The top surface of the highest rippled layer is bioturbated. Some *chondrites* burrows also occur at the top of the next-to-last ripple and in the silt layer in between. We have not observed any traces of burrows in any of the lower ripples or ripple surfaces of Unit III or in Units I and II.

The highest ripples are overlain by a 4-cm-thick silt layer, containing a 2- to 5-mm-thick flaserlike fine sandstone layer that is most enriched in Ir (Fig. 13; Table 2). This layer can be traced over the entire outcrop, and at the westernmost outcrops of the K/T sandstone complex (outcrop Mimbral 2 of Stinnesbeck et al. [1994]) the thin flaserlike sandstone layer is red stained by iron-oxides. Stinnesbeck et al. (1994a) and Hildebrand et al. (1991) termed this layer as "red K/T layer" and "fireball layer," respectively, but in thin section (Fig. 12C) it is clearly a sandstone with goethite matrix, not compatible with an interpretation as a K/T red ejecta or fireball layer. The 4-cm silt layer is overlain by a 7-cm-thick micritic limestone layer, still silty and graded (Fig. 12D; Fig. 13). This layer appears correlative with the graded silty limestone layer (unit F of Hansen et al., 1987) at Brazos River. The first small Danian foraminifers (G. eugubina?) appear about 12 cm above the silty limestone layer in shales of the Velasco Formation that are somewhat darker than the Mendez shales. The first fine-grained sediments above the rippled layers and all of the subsequent Velasco shales are highly impoverished in Cretaceous planktic foraminifers (Fig. 12E) in comparison with the uppermost Mendez shales underlying the clastic beds (Fig. 12F). Those few present are probably reworked.

#### Petrography of the Mimbral sandstone sequence

Twenty-nine thin sections were analyzed from samples taken every 10 cm in Units II and III in a vertical section at

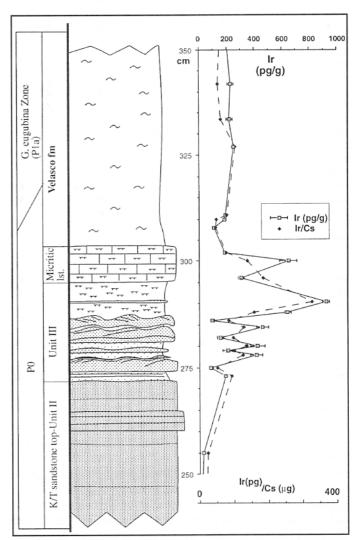


Figure 13. Mimbral, northeastern Mexico. Detail of the top of the K/T sandstone complex near meter mark 16 (cf. Fig. 11). Lithological column traced from a photograph. Ir and Cs data from Table 3 (F. Asaro, personal communication, 1991). Ir is normalized to Cs to eliminate dilution effects by carbonate.

TABLE 2. GRAIN-SIZE TRENDS IN THIN SECTIONS FROM UNIT II
OF THE MIMBRAL K/T SANDSTONE COMPLEX

	Genera Muddy Matrix				al Sparry Calcite Cement		Limeclasts			Terrig. Detritus		
Samples	Crs sand/fine gravel	Crs-med sand	Med-fine sand	Fine sand	Terr. sand	Foram grainst.	Crs	Med	Med-fine	No 1st grains	Med	Med-fine v fine
M29 M28 M27 M26 M25 M24 M23 M22 M21 M20 M19 M18 M17	x				x x x	x x x x x	x	x x x x x	x x x x		X X X X X X X X X X X X X X X X X X X	
M15 M14 M13 M12 M11 M10 M9 M8 M7 M6 M5 M4 M3 M2 M1	x	x x	X X X X X X	X X X			X X	X X X X	X X X X	x	x	x x x x x x x x x x

m.mk. 16, supplemented at m.mk. 48 for the part of Unit II missing there. The most common composition is a foraminiferal grainstone with abundant lime-clasts and with minor amounts of terrigenous grains, alternating with layers rich in terrigenous detritus. A basic twofold subdivision could be made of Unit II sandstone (Table 3). The basal part has essentially a "dirty muddy matrix" (Fig. 12A); the upper part is a clean, bettersorted sandstone with a sparry calcite matrix (Fig. 12B). Petrographically, three different groups of sediment can be distinguished. The first group—the lower part of Unit II (M2 through 15)—has a "dirty" aspect due to smeared, lime-mud matrix. The sand is a polymict mixture of medium-fine to fine-grained terrigenous sand, with foraminifers. Lime-mud grains occur, roughly fining up from coarse grained at the bottom to medium and fine grained at the top. The second group—Sam-

TABLE 3. Ir, Fe, AND Cs ABUNDANCES IN THE MIMBRAL SECTION

Position (m)	Ir (ppt)	Fe (%)	Cst (ppm)	
-0.14	13 ± 4	2.90	3.55	
+0.13	18 ± 5	4.96	0.30	
+0.15	4 ± 9	12.95	0.73	
+0.78	16 ± 4	1.09	0.98	
+1.48	$7 \pm 4$	1.41	0.36	
+1.83	8 ± 9/7	1.19	0.54	
+1.98	$25 \pm 32/20$	1.01	1.06	
+2.01	192 ± 12	1.72	2.04	
+2.03	$83 \pm 15$	1.22	1.58	
+2.06	414 ± 44	2.34	3.26	
+2.07	206 ± 36	1.72	2.04	
+2.08	$423 \pm 50$	2.28	3.05	
+2.1	153 ± 24	1.29	1.57	
+2.125	457 ± 44	2.14	3.52	
+2.14	92 ± 18	0.79	1.07	
+2.16	642 ± 24	2.16	4.05	
+2.185	921 ± 23	1.61	2.80	
+2.24	306 ± 21	1.34	1.64	
+2.28	$650 \pm 63$	2.22	4.67	
+2.3	187 ± 9	1.86	2.40	
+2.36	$109 \pm 22$	1.34	2.26	
+2.38	184 ± 7	0.67	3.68	
+2.39	191 ± 8	1.17	2.36	
+2.55	$250 \pm 12$	1.58	2.40	
+2.615	$218 \pm 20$	2.62	3.46	
+2.7	$228 \pm 23$	2.80	4.17	
+2.84	22 ± 4	0.82	1.16	
+3.39	$79 \pm 8$	2.82	4.17	
+4.49	41 ± 6	2.57	3.98	

ples M16 through 29 (=upper part of Unit II, starting with a small erosive channel with spherules)—have a cleaner and better-sorted aspect, with a sparry calcitic cement. Mediumgrained calcareous sandstones with medium-grained terrigenous grains alternate with foraminiferal grainstones. The foraminifers have an infilling of greenish clay. The third group—samples M30 through 42 (Unit III)—shows a crude grading from laminated and cross-bedded silty and very fine sandstones to silt-stones. The topmost samples contain burrows.

# La Lajilla, Mexico

At La Lajilla (Alvarez et al., 1992b) the K/T sandstone complex crops out at both sides of the overflow channel of the Lajilla reservoir dam. The upper Mendez shales are rich in Upper Maastrichtian foraminifers (Fig. 14A). The well-developed planktic fauna and high planktic/benthic foraminifer ratio suggest deposition at upper bathyal (±500 m) water depth. Bedding is not visible in the top 0.5 m of the Mendez Formation, possibly as a consequence of soft sediment deformation, similar to that in the Mimbral outcrop. The Lajilla K/T sandstone complex can also be subdivided into three units (Fig. 15). Unit I fills shallow (<50 cm) scours in the top Mendez. Unit I sands with K/T spherules are locally "injected" into the top Mendez beds. Unit I

displays a crude low-angle cross-bedding with alternating layers of pebbly sandstone and sandstone, dominantly composed of a mixture of spherules (Fig. 14B) and Cretaceous foraminifers. Internal truncations occur, but measurement of current directions was not possible. Unit II sharply overlies Unit I and has locally truncated Unit I. The beds of Unit II are well lithified and are more continuous than at Mimbral; individual layers (e.g., the parallel laminated bed at 60 cm) could be traced over 150 m, and a strongly eroded outcrop at the other side of the dam (300 m southwest) shows the same lithostratigraphic subdivisions. Unlike Mimbral, Unit II displays a wide variety of (current) ripple structures that allow a large number of paleocurrent measurements (Figs. 15 through 18). Where possible, the direction of migration of the ripples was measured on bedding planes, and otherwise a three-dimensional view of the ripples was obtained, using vertical sections at a perpendicular angle to each other (Fig. 16). The ripple structures observed are all compatible with origin as current-ripples. Ripples indicative of oscillation (waves) were not found. The ripple types observed vary from straight crested to linguoid, possibly lunate, ripples-in-drift to climbing ripples, with transitions in between. The basal 10 cm of Unit II displays ripple structures—associated with parallel-laminated beds—somewhat reminiscent of standing-wave- (antidune?-) type ripples (Fig. 17). A prominent, well-lithified bed, similar to the Mimbral Unit II beds, occurs at 55 to 62 cm. This bed is parallel laminated, and in thin section it shows an alternation of foraminifer-rich and darker lithic grain-rich laminae. Unit III begins at 78 cm, where the first thin silt layer appears. Unit III further consists of fine-sand layers with ripple structures alternating with (draping) thin silt layers. The top of Unit III (105 to 107 cm) displays a very fine scale flaserlike alternation of silts and millimeter-sized ripples (Fig. 19). Iridium concentrations are high in this interval (0.8 ng/g, R. Rocchia, personal communication, 1994). The top layers of Unit III are burrowed (Fig. 15). Unit III is capped by a silt layer 4 cm thick, overlain by a lithified silty micritic limestone layer (Fig. 14C), again similar to the one at Brazos River and Mimbral. This silty limestone layer is followed by a rhythmically bedded series of gray hemipelagic shales of the Velasco Formation, containing basal Danian foraminifers. The silty limestone and the first few centimeters of the Velasco Formation contain high iridium concentrations (R. Rocchia, personal communication, 1994). Although the silty limestone layer is greenish gray as is the Mendez Formation, the limestone layer is greatly depleted in Cretaceous foraminifers compared with the Mendez (compare Figs. 14A, B). Danian foraminifers have not been observed in the silty limestone, but they appear in the Velasco shales just above it. Therefore, we infer that the silty limestone layer is not Maastrichtian in age, as believed by some (Keller et al., 1994), but basal Danian (P0 Zone) in age.

The paleocurrent directions measured are shown in Figures 15 and 18. The current directions are bidirectional when integrated over the entire thickness of the K/T sandstone unit. The dominant directions are away and toward the Chicxulub

crater, but that may be a coincidence. Within individual layers the current directions appear stable and unidirectional (Fig. 15), as they do when measured at different places in the same layer. Those opposite current directions demonstrate that the individual sandstone layers are deposited by currents repeatedly changing direction in almost 180°. The bidirectional currents are somewhat reminiscent of tidal-cycle currents, but such currents are difficult to explain in a semienclosed-basin environment and at a water depth of 500 m.

The sedimentology of Unit II at first glance makes one think of turbidity currents with repetitive Bouma sequence (A)B-C alternations. The opposing current directions then could be explained by reflected turbidites (Best and Bridge, 1992). The general setting of these opposing cross-beds of Unit II in the large-scale energy decreasing-up sequence I through III and in the smaller-scale energy decreasing-up sequence of Unit II is thought to be too small and gradual compared to energy differences between a supposed initiating turbidity current and a reflected one. Also Unit III is quite different from a turbidite setting, regarding the preservation of the ripple forms sharply overlain by a mud drape, contrary to the more gradual transition from Bouma C to D in a true turbidite.

A better explanation seems to be an origin by landward-breaking wave surges alternating with the seaward return flow of a series of large tsunami waves. Gravity flows may have helped to transport clastic material from the coast, ~70 km to the west, into the deeper basin but are not directly involved in the deposition of the K/T sandstone unit. The general thinning-and fining-upward trend shows the decreasing energy of tsunami waves, and in the final stages current velocity sufficiently decreases in between individual wave arrivals to allow the settling of the fine silt and clay of Unit III.

## El Peñon, Mexico

El Peñon is located on a hilltop where the "flagstones" covering the dam of the Porvenir reservoir were quarried, mainly from Units II and III of the clastic complex. These units are therefore exposed over several acres, allowing investigation of the sedimentary structures preserved on the surface of the sandstone layers (Figs. 20, 21).

As at Mimbral and Lajilla, current measurements demonstrate periodic changes in current direction, consistent with the previously mentioned hypothesis of deposition by breaking tsunami waves.

El Peñon may be important for the correct interpretation of the many burrow structures that occur on and in the top of the K/T sandstone complex in almost every outcrop of the Gulf Coast. Most burrows (*Zoophycos, Chondrites*) occur in the topmost sand layers only, and all those seem to penetrate from above *after* deposition of the K/T sandstone unit. The burrow fabric show a distinct tiering; different types of burrows occur on different bedding planes. This tiering leads to alternation of more intensively burrowed beds and hardly burrowed beds, a

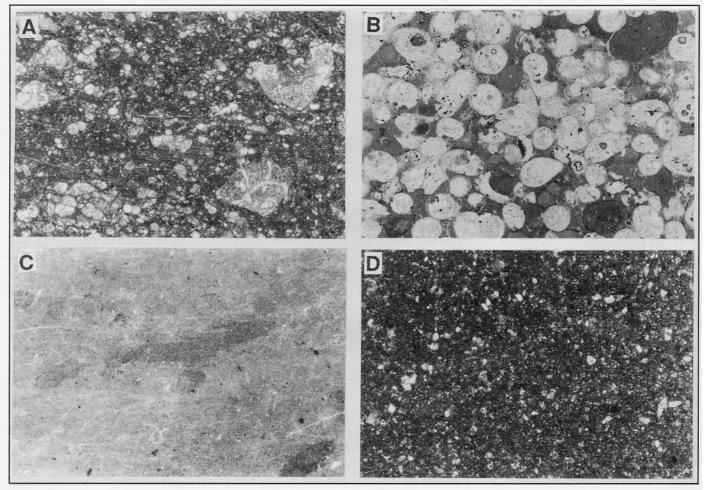


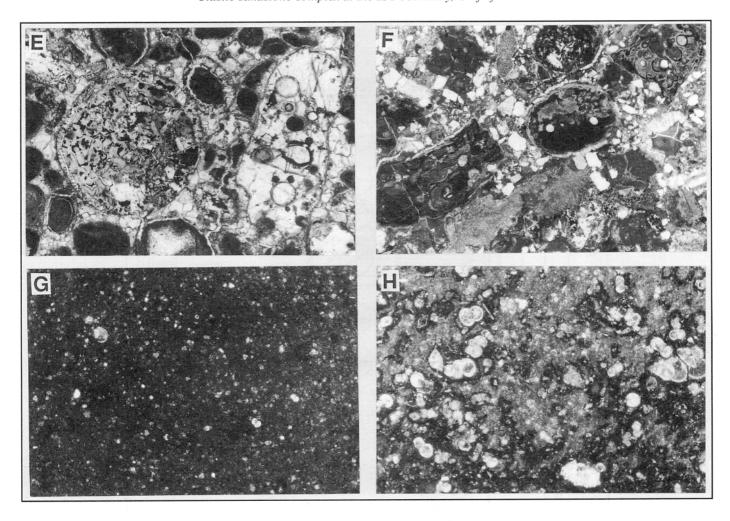
Figure 14 (on this and facing page). Thin-section micrographs. A, La Lajilla, upper Maastrichtian Mendez shale. B, La Lajilla, bubbly calcite spherules and limestone fragments (Unit I). C, Basalmost Velasco shale. D, Silty limestone (cf. Fig. 15, 112 cm) poor in foraminifers. E, Coxquihui, Mexico. Calcitic, bubbly spherule. F, La Ceiba, Mexico. Bubbly spherule composed of clay minerals with tar filling. Matrix is rich in coarse quartz grains and orbitoid fragments. G, H, Beloc, Haiti. G, Lowermost Paleocene chalk, poor in foraminifers. H, Uppermost Cretaceous chalk, rich in planktic foraminifers.

situation that might easily be mistaken for repeated sedimentdepositional events followed by longer periods of burrowing. An Ophiomorpha-type burrow penetrates up to 50 cm below the top of the clastic complex (Fig. 21). These burrows consist of 1-cm-diameter, up to 3 m long, frequently branching, usually straight horizontal tubes, which follow the thin silt layers in between Unit III rippled sandstone layers. The horizontal tubes radiate from a central bundle of vertical burrows, observed at El Peñon to penetrate through several sandstone layers. The burrowing shrimplike animal is apparently capable of penetrating 50 cm down through sand layers before spreading out. Thus as far as we can establish, these burrows also postdate the deposition of the K/T sandstone unit. We assume that similar Ophiomorpha-type burrows at the same position in the Brazos River K/T clastic layer originate the same way, although there we did not observe the vertical central tubes.

The basal 2.75 m of Unit II at El Peñon are characterized by massive bedding, without any clear sedimentary structures except some water-escape structures and faint parallel laminations. A similar lack of sedimenary structures is also common in Unit II of nearby K/T outcrops Las Bruselas, Porvenir, Rancho Nuevo, La Sierrita, Loma las Rusias, and Los Ramones (Alvarez et al., 1992b). Apparently this massive bedding is shared by K/T outcrops in the northeastern Mexico area but is absent farther south. The water-escape structures indicate rapid deposition of massive sand or leading to massive sand by obliterating the earlier sedimentary structures.

#### Mesa de Llera, Mexico

A few hundred meters east of the microwave tower on the Mesa de Llera, next to the road between Ciudad Victoria and



Ciudad Valles, the K/T sandstone complex crops out in several small clearings in the mesquite chapparal bushes, below cappings of Eocene basalts (23° 21.8′N, 98°59.9′W). The K/T sandstone complex is only 3 cm thick and consists of bioturbated ripples of very fine sand of Unit III. Unit I and II are absent and also could not be traced in nearby outcrops. The K/T sandstone complex overlies indurated Mendez marls of *A. mayaroensis* Zone age and is directly overlain by a 5-cm-thick silty limestone layer. This limestone layer is overlain by *G. eugubina* Zone age marls of the Velasco Formation. Although the Velasco and Mendez marls crop out at many places along the Mesa de Llera, evidence for thick K/T sandstone layers has not yet been found.

#### La Ceiba, Mexico

About 7 km south of La Ceiba (20°19.8'N, 97°41.0'W), along the road from La Ceiba to Tlaxcalaltongo, the K/T sandstone complex crops out over several tens of meters and is also exposed 200 m farther to the north in a dirt road. The sandstone complex changes in thickness from 1.2 m in the roadside outcrop to 0.25 m along the dirt road (Fig. 22). The sequence consists of a channelized lower Unit I downcutting in foraminifera-rich

Mendez marls of *A. mayaroensis* Zone age. Unit I contains bubbly spherules altered to green clay minerals (smectite?), frequently filled with tar, and abundant (>50%) large detrital quartz grains and mica-crystals (Fig. 14E). Unit I also contains bioclasts of shallow-water origin (Orbitoid foraminifers, bryozoans). The thickness of Unit I varies from 1 to 25 cm. Unit II, as in other sections in northeastern Mexico, is a graded sandstone displaying climbing ripples indicating bidirectional currents. Unit III consists of fine sand ripples alternating with silt layers, overlain by Velasco shales containing a P0 Zone and *G. eugubina* Zone fauna. Only the top sandstone ripples contain burrow traces.

#### Coxquihui, Mexico

Just 30 km southeast of La Ceiba, a badly weathered K/T sandstone complex crops out in the roadside, just east of the village of Coxquihui. The K/T sandstone complex is 88 cm thick and overlies 90 cm of exposed red marls of *A. mayaroensis* Zone age. The K/T sandstone complex is poorly graded and faintly layered. Two graded layers, 50 and 38 cm thick respectively, are separated by a layer in which a few cobbles of whitish Upper Cretaceous micritic limestone are intercalated in a spherule-rich

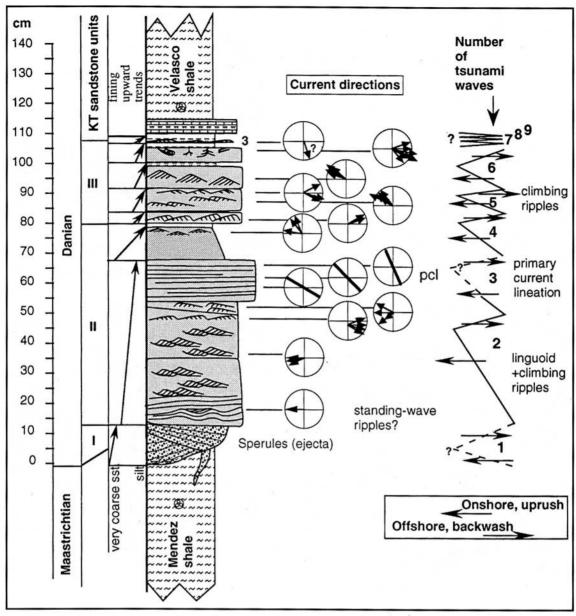


Figure 15. La Lajilla, Mexico. Stratigraphic column through the K/T sandstone complex at La Lajilla, Mexico. 40 km east of Ciudad Victoria. Measured paleocurrent directions are plotted next to the stratigraphic level. At right the total number of current reversals is indicated, inferred to indicate the number of passages of tsunami waves. Pcl = primary current lineation.

matrix. In contrast to the other K/T clastic beds, no Units II and III could be distinguished; almost the entire bed consists of bubbly spherules. The spherules are composed of sparry calcite (Fig. 14F); unfortunately, we have found no relict glass in a sample of 800 g dissolved in HCl. Red pelagic sediments directly overlying the K/T sandstone complex are of *G. eugubina* Zone age. In contrast to the other K/T outcrops in eastern Mexico, the K/T sandstone complex is intercalated in red marls that may indicate deposition in deep (>600 m) water, below the oxygen minimum zone. Although we have not found preserved glass, the K/T sandstone complex is reminiscent of the Beloc outcrop on Haiti, in that it is essentially composed of Unit I.

#### OTHER OUTCROPS IN THE GULF OF MEXICO

Other outcrops of the K/T sandstone complex are known from the literature, and we have also studied them. We report

here some of our observations, in particular those that have a bearing on interpretations in the literature.

# Beloc, Haiti

The K/T boundary sandstone complex crops out along the road from Carrefour Dufort to Jacmel, within rhythmically bedded pelagic chalks of the Beloc Formation (Maurasse et al., 1979). The K/T sandstone complex is exposed at several places along the road, because the road descends almost at the same angle as the local dip of the layers. The Beloc Formation is gently folded but not severely deformed, although many minor faults occur. However, package-sliding and slumping also occur at many horizons, and the intensity of synsedimentary deformation differs from place to place. None of the K/T sandstone outcrops has escaped synsedimentary deformation, and each

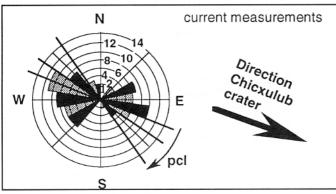


Figure 16. La Lajilla, Mexico. Rose-diagram of all paleocurrent direction measurements of Units II and III. The dominant measured directions are toward and away from the Chicxulub crater.

outcrop therefore has a different lithological sequence and expression. The K/T sandstone complex at Beloc at most places essentially has only Unit I preserved, a layer characterized by bubbly spherules and other splash forms and limeclasts similar to the clasts observed in Unit I in Gulf Coast outcrops. The spherules have a glass interior preserved only in the two southernmost outcrops, which appear least weathered (outcrops B and M; Jéhanno et al., 1992). The northern two outcrops (outcrops A and H; Jéhanno et al., 1992) have the thickest Unit I spherule layers (15 to 30 cm) deposited in shallow channels

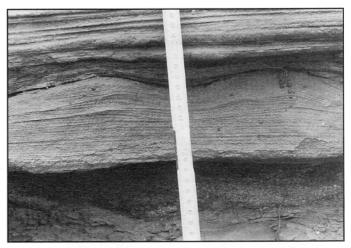


Figure 17. Photograph of Unit II standing wave(?) ripples 5 to 10 cm above the top of Unit I (visible at the bottom, resting on Mendez shales).

showing crude mega—cross-bedding. The spherule layer is size graded. The size grading continues into a fine sand-silty calcarenitic layer of about 20 cm thickness, which shows low-angle cross-bedding. Near the top of the limestone layer several 1- to 2-mm-thick lenses of fine sandstone occur that are locally stained by iron oxides and are rich in iridium and Ni-rich spinels (Jéhanno et al., 1992). In view of the continuous grading

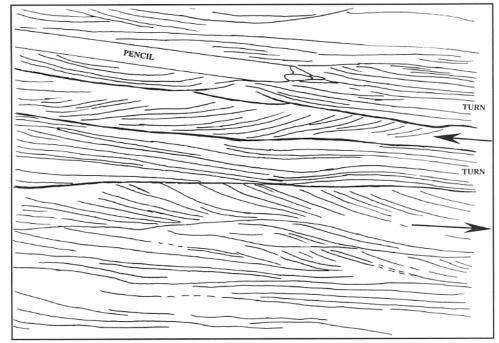


Figure 18. La Lajilla, Mexico. Drawing after a photograph showing two changes in migration of climbing ripples in Unit II, between 35 and 49 cm (cf. Fig. 15). Pencil for scale. Near the bottom current direction is approximately N270°E, just below the pencil approximately N90°E, and at the top again approximately N270°E.

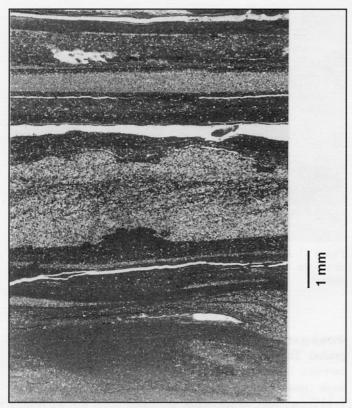


Figure 19. La Lajilla, Mexico. Thin section of topmost part of unit (III) at cm 108 (Fig. 15). At least three 0.2- to 2-mm thick (crossbedded) fine sandstone flasers alternate with fine mud and silt, showing evidence for changes in current strength.

and pervasive cross-bedding we believe that all these units were rapidly deposited in one depositional sequence, not interrupted by periods of slow background sedimentation.

Jéhanno et al. (1992) also have described the lithology of these sections. Sigurdsson et al. (1991), Izett (1991), and Koeberl (1992) discussed the chemistry of the relict glass from the interior of the K/T spherules and concluded that the glass is of impact origin. Jéhanno et al. (1992) prefer a volcanic origin of glass based on two arguments: the high Fe<sup>3+</sup>/Fe<sup>2+</sup> ratio in the glass and the stratigraphic position of the K/T sandstone unit, supposedly below the K/T boundary. Although the high Fe3+/Fe2+ is not yet explained, Jéhanno et al. (1992) did not discuss the extremely low volatile content of the glass (Koeberl, 1992), which is not consistent with volcanic origin. We have performed a few simple crushing experiments of glass fragments with relatively large (0.5 mm) fresh bubble cavities inside the glass. Ten glass fragments were crushed immersed in glycerine under a microscope. When the glass was crushed, the glycerine almost completely filled the bubble cavities in all fragments. This means that the gas pressure inside the bubble cavities is extremely low, consistent with a tektite glass origin.

Jéhanno et al. (1992) positioned the K/T boundary at the thin iron-oxide-stained, Ir-rich sand laminae and thus

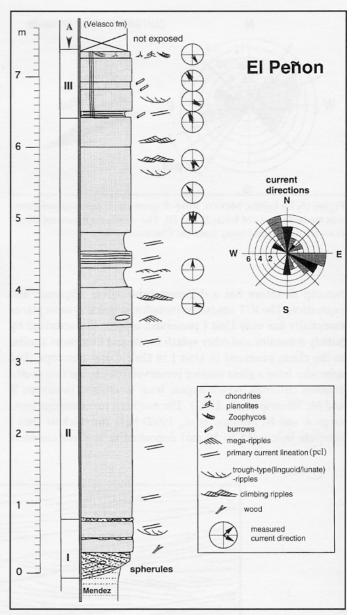


Figure 20. El Peñon, northeastern Mexico. Stratigraphic column through the K/T clastic complex. Paleocurrent directions of individual levels are plotted on the right-hand side and combined in the rose-diagram. The top and contact with overlying Velasco shale are not exposed here.

believed the K/T sandstone complex to be below the K/T boundary. The chalks directly below the K/T sandstone complex are rich in Maastrichtian planktic foraminifers (Fig. 14H), and the cross-bedded limestone and following sediments above the spherule layer are extremely poor in Cretaceous foraminifers (Fig. 14G). This interval is moreover rich in calcispheres (*Pithonella*) reworked from shallowerwater sediments. These are thus part of the K/T sandstone unit and not of Cretaceous age because the Cretaceous fossils are clearly reworked.

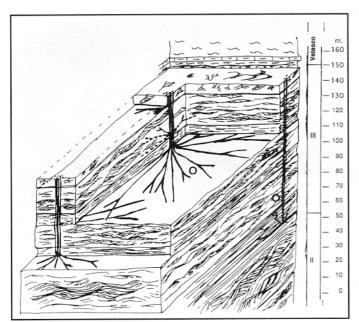


Figure 21. El Peñon, northeastern Mexico. Reconstruction of the top-most rippled sand and silt layers of Unit III, showing the tiered deep and shallow burrow types. The star-shaped, 5-m diameter *ophiomorpha*-type burrow structures follow the interbedded silt layers, up to a depth of 50 cm below the top of the K/T sandstone complex. In the middle of the "star" they are connected to a number of vertical tubes, observed to penetrate from above through at least 20 cm of sandstone above the star-structure and here interpreted to reach all the way to the surface, although that has not yet been observed.

# Bochil, Chiapas, Mexico

The K/T sandstone complex crops out along a dirt road to the PEMEX well Soyalo-1, 9.4 km from the turnoff from the road between Bochil and Tuxtla Gutierrez (Montanari et al., 1994). The K/T sandstone complex occurs within a sequence (from bottom to top) of >80 m Campanian-Early Maastrichtian platform limestones with rudists, 30 m of late Maastrichtian pelagic marls containing several turbidites and debris flows, a >50-m-thick debris flow, and >15 m pelagic Paleocene marls. The Maastrichtian debris flows contain, among others, limestone cobbles, orbitoid foraminifers, and rudists. The K/T sandstone complex is underlain by a graded, >50-m-thick polymict mass-flow containing platform limestone blocks as large as 10 m. Those blocks consist of rudist-limestones, orbitoid limestones, and miliolid (lagoonal) limestones of the same composition as the cobbles in the Maastrichtian mass-flows. These components are thus locally derived and unlikely to be coarse ejecta from the Chicxulub impact. The matrix of the mass-flow contains loose orbitoids (Fig. 23A) and rudists.

The mass-flow grades into a 105-cm-thick, laminated and crudely cross-bedded sandstone with lime and bioclasts (orbitoids, rudist fragments, miliolids [Murciella sp.]; Fig. 23B). Remains of bubbly spherules have not yet been identified in the sandstone. The sandstones are overlain by a 5-cm-thick marl

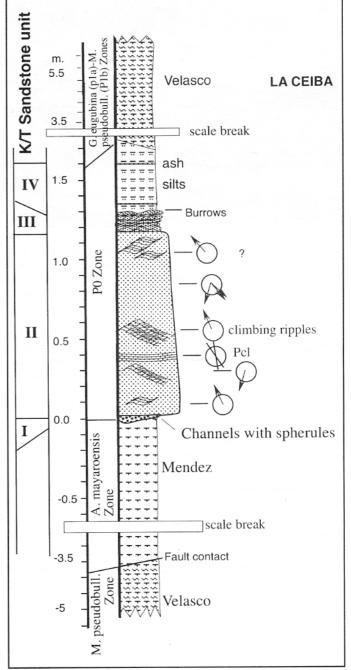


Figure 22. Stratigraphic column of the K/T sandstone complex at La Ceiba, east-central Mexico, with measured current directions. Pcl = primary current lineation. Unit II contains dominantly climbing ripple structures.

enriched in iridium, containing fine sand laminae locally stained by iron oxides (Montanari et al., 1994). Some poorly defined burrows occur in the marl. The marl is overlain by a 10-cm-thick silty limestone, similar to other outcrops in the Gulf Coast, followed by marls containing *G. eugubina*. The 50-m-thick massflow underlying the K/T sandstone complex may actually

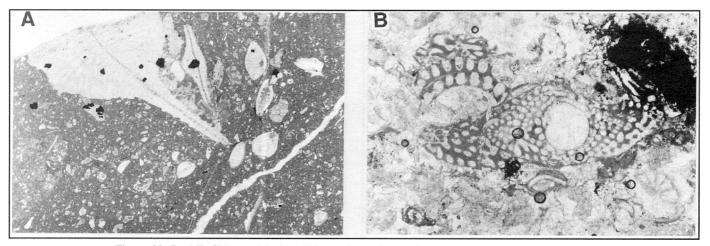


Figure 23. Bochil, Chiapas, Mexico. Thin sections of mass-flow components. A, Loose orbitoid foraminifer, from base of 50-m-thick mass-flow, underlying the K/T sandstone complex. B, Loose, *Murciella* sp., an upper Maastrichtian miliolid (lagoonal) foraminifer. These *Murciella* appear at the top of the K/T sandstone, as in nearby outcrops in Guatemala (Hildebrand et al., 1994), and may have been flushed from lagoons on the nearby carbonate platform.

belong to the depositional sequence of the K/T sandstone because it appears to be grading into the K/T sandstone. However, mass-flows that are similar but thinner, containing the same components, occur already in the Maastrichtian.

Apparently the Bochil area was at a slope setting at K/T boundary time, near a carbonate ramp, where thick mass-flows could have been triggered by the seismic shaking of the Chicxulub impact.

# Los Ramones, Mexico

A small K/T sandstone complex outcrop occurs in the east bank of the Rio Pesqueria (Alvarez et al., 1992b). Unit I is almost absent and contains very few bubbly spherules at the base, mostly as armoring of the many clay pebbles. On some of the mud-clasts oriented current-crescents occur upstream of the spherules of the armoring. Unit II is massive, contains many stringers of clay pebbles, and fills a single channel (max. 440 cm thick, axis strikes N140°E) that is loaded into the Maastrichtian Mendez Formation. A Unit III is absent, but the flat top of the sandstone complex is marked by several 30-cm-large crescent scours (direction N140°E), with superimposed current ripples (N230°E) running at an oblique angle to the channel axis.

Overlying sediments are not exposed for over 5 m; the first sediments exposed are Velasco shales, containing *M. pseudo-bulloides*.

#### Rancho Nuevo, Mexico

Two adjacent channels, ~7 m wide (strike of channel axis N130°E), are exposed on the east bank of the Rio San Juan (Alvarez et al., 1992b). Unit I is 0 to 15 cm thick, channelized, almost entirely composed of bubbly spherules. Unit II is mas-

sive, maximum 6.5 m thick in the center of the channels, reduced to zero between the two channels. The massive sandstones display faint water-escape structures. Between the two channels (5 m apart) the Mendez shale is pushed up in large, deformed "flame-structures" or diapirs. At the base of Unit II frequent flute-casts occur, showing a current direction parallel to the channel axis (N110°–140°E), but some deviating directions were also measured (N80°E–N260°E). At the base imprints of siliceous sponges occur. Unit III is poorly exposed, but several (30 to 40 cm thick) fine sandstone layers with climbing ripples occur on top of Unit II. The transition from Unit III sandstone to the Paleocene marls is not exposed over 30 cm; then follow Paleocene Velasco marls containing *G. eugubina*.

## Parras basin, northeastern Mexico

The K/T boundary has been described by Kauffman and Hansen (1987), who described a chaotic sedimentary breccial conglomerate as a giant storm or tsunami bed within the dominant siliciclastic offshore to shoreface Maastrichtian-Danian siliciclastic sequence of the Parras basin. The K/T boundary was drawn between the sudden extinction of *Exogyra* and the appearance of a Paleocene mollusc (*Cucullea*) in a prominent middle shoreface sandstone bar, with abundant hummocky cross-stratification. We have investigated the outcrop, but we have not found any evidence for a chaotic breccia in the K/T interval. We found exfoliated sandstone boulders resembling a boulder bed. This site is clearly the shallowest, more or less continuous marine sequence across the K/T boundary, regarding the highly fossiliferous sequence of the wave-rippled offshore sandstone bars across the K/T boundary.

#### DISCUSSION

The sandstone layers occurring at the K/T boundary around the Gulf of Mexico are a complex deposit, size graded overall, with a distinct sequence of lithologies. We interpret this sequence to be the result of tsunami-wave activity initiated by the Chicxulub impact event on northern Yucatan. The K/T sandstone can be divided into four subunits, each one representing a different phase in the impact-tsunami scenario. We first discuss the tsunami-wave hypothesis, then alternatives given by other authors.

The basal Unit I invariably contains spherules and droplets, 0.5 to 10 mm in size, that we interpret as remains of molten ejecta-impact glass or (micro) tektites-because at Mimbral and Beloc some spherules contain a relict core of impact glass (Smit et al., 1992b). The tektites are invariably altered, but the same basic morphology is found in all K/T localities, including Beloc, and therefore can be easily recognized in the field and under a microscope. More than 99% of the tektites contain abundant bubble cavities, which are diagenetically infilled with clay minerals, or calcite. The bubble-cavity infillings may weather out, leading to interpretation as separate spherules, and the illusion of "accretionary lapilli," whereas they are actually bubble-cavity infillings enclosed in a spherule of clay minerals (Lyons and Officer, 1992). We also interpret the abundant rounded limestone fragments as ejecta, because invariably they are associated with the tektites and are highly similar in different places, whereas other detritus differs in composition from place to place, depending on the local source area. The ejecta are not primary deposits but are reworked into scours or channels gauged in the seafloor and mixed with local components, because the deposits are invariably cross-bedded.

Locally, we believe there is evidence for strong seismic activity, at least preceding the arrival of the first tsunami waves. At Moscow Landing, the ejecta deposits are associated with faults and soft-sediment deformation. The faults were active just before the deposition of the ejecta, because these deposits occur only near the faults and slumped areas. At Moscow Landing, La Lajilla, and El Peñon, material with ejecta is injected into fault planes below the K/T sandstone unit, indicating continued faulting during deposition of the K/T sandstone unit. At Bochil and in Guatamala (Hildebrand et al., 1994) the K/T sandstone complex is preceded by thick mass-flow conglomerates, probably triggered by seismic activity and moving downslope just before the arrival of the first tsunami waves, possibly before the arrival of the first ejecta. At Rancho Nuevo, Los Ramones, La Lajilla, and Mimbral, the Unit I and II channels are deeply loaded into the soft Mendez marls. Seismites—single, thick mass-flows of turbidites triggered by an earthquake have some of the same characteristics as the K/T sandstone complex (Kleverlaan, 1989). It is reported that the seafloor has been deformed as a direct result of the earthquake and the loading by the seismite.

Unit II usually displays a set of well-sorted lenticular sand-

stones, with a wide variety of sedimentary structures indicating currents that change direction several times up-section, often by 180°. The material of Unit II is a mixture of locally derived material and material from nearshore areas (plant debris, terrigenous grains, shallow-water foraminifers) and differs from place to place, although some of the Unit I ejecta still occur at the base of some layers. The sedimentary structures—strong parallel lamination, climbing ripples, water-escape structures—show that these sandstones were deposited rapidly by strong currents varying in strength and direction. In none of the localities investigated by us did we observe that the lenticular sandstone layers are interrupted by layers of normal hemipelagic deposition, or layers with burrows, that would represent long periods of time between deposition of the individual sandstone layers.

We interpret the repeated change in current directions to be a result of deposition by up-surge and back-surge of several large tsunami waves, best observed in the La Lajilla section. In some localities (Beloc, Coxquihui), Unit II does not occur. Since the bulk of the material is derived from nearshore material (shallow-water bioclasts, coarse terrigenous grains, and plant debris) and winnowed foraminifers, we infer that these localities are either too far from the shore or are at a water depth below tsunami wave-base.

Unit III is essentially a continuation of Unit II, but represents the phase in which tsunami waves decrease in strength to such extent that fine sediment is able to settle in between ripple layers of fine sand deposited during wave surges. These muddrapes are the first sediments to be enriched in iridium. Clearly, the deposition of iridium-rich phases is decoupled from the deposition of the coarse ejecta. Assuming a one-impact scenario, we infer that the iridium carrier particles are much finer grained and settle much more slowly than the coarse ejecta. Burrows occur in and at the top of the last sandstone ripples. Rare chondrites also occur on the surface of some of the lower sand ripples and the silt in between but not inside those lower sand ripples. Because the burrow-fabric is tiered, we conclude that the top surface was colonized after, not during, deposition of the sand ripples.

Unit IV represents the phase when currents induced by tsunami-waves are no longer capable of transporting fine sand at the seafloor, and silt and clay are able to settle on the seafloor. Regarding the large amount of winnowed foraminifers in the K/T sandstone unit, it is expected that most of the fine sediment has been washed out and remained suspended in the water-column during passage of the tsunami-waves. The mudstone interval is size graded, and we therefore infer that this graded interval represents an interval of days to weeks after the initiating tsunami event. The burrows present in this interval (which is not bioturbated) are difficult to interpret. These burrows could be due to a colonizing episode of weeks to months but could also be due to organisms trying to burrow back again in the seafloor sediment after being "uprooted" by the tsunami currents.

The K/T sandstone complex as a whole forms one contin-

uous overall size-graded sequence not interrupted by sediments or burrowed surfaces, indicating long periods of time in between the different sublayers.

This scenario has been challenged by several authors, who believe that the K/T sandstone complex can be interpreted differently. Stinnesbeck et al. (1993) conclude that the sandstone complex predates the K/T boundary and belongs to a normal turbidite system derived from the deltaic sediments of the Difunta group. Savrda (1993) interprets the sandstone complex as a normal low-stand sediment, because at Mussel Creek in Alabama bedding surfaces truncate burrow structures. Bohor (1994) interprets the K/T sandstone complex as an impact-triggered debris flow and turbidite.

At a first glance the K/T sandstone complex has many features in common with a turbidite fan, such as erosive base and channels, introduction of shallow marine benthos, plant debris and sands in a deeper marine environment, flute casts, loadings, plane beds with primary current lineation, and climbing ripples. However, comparing the K/T complex with generalized turbidite-fan models of Mutti and Normark (1987) and Walker (1978), it is clear that the K/T complex is not part of a distal outer fan or of the fan lobes. In the K/T complex none of the following occur: normal turbidites with Bouma sequences, separated by mud; thickening-up turbidite sequences (due to prograding lobes) and thinning-up compensation sequences (infillings between lobes); thicker mud intercalations between lobes (due to channel and lobe switch). The work of Mutti and Normark (1987) and Mutti and Ricci Lucchi (1972; their Fig. 16) enables us to quickly compare features, which they hold for characteristic of channels, lobes, and the transition zone in between.

Our K/T complex has the following in common with "channels of turbidite fans":

- erosional channels, in which infilling layers truncate against the scour (rarely occurring at Mimbral);
- depositional channels, in which infilling layers converge to the channel edge (at Mimbral in Units I and II and at Rancho Nuevo in Unit II);
- clast supported conglomerates (rare, except at Brazos River, Bochil, and Moscow Landing);
- thin-bedded overbank deposits (Unit III could be interpreted as such, but no wedging away from the channels is observed and instead opposing current directions or at Los Ramones even a winnowed channel top with current ripples moving at right angles to the channel); and
- · outsize mud clasts and armored mud clasts.

Not observed in the K/T sandstone complex were the following:

 massive, graded or inversely graded infillings of channels (instead, Unit I generally shows internally laminated fills, sometimes as at Mimbral with lateral accretion, indicating shifting channels); and  chaotic units pointing to sliding (instead vertical loading is seen, notably at Mimbral, Los Ramones, and Rancho Nuevo).

Our K/T complex unit has the following in common with "transition zone of turbidite fans":

- "zones of roughness" or levels with irregular scour, indicating bypass (such levels probably have been encountered at the base of the Unit 2 channel at Ramones and Rancho Nuevo, but that needs more study);
- low-amplitude megaripples (transition zone megaripples, according to Mutti and Ricci Lucchi [1972] are clast-supported parallel and cross-bedded units indicative of bypass); and
- stack of shallow channels (at Mimbral, Mulato, and Darting Minnows Creek; in our case, however, never with massive or graded fill and never with mud-drapes over a scoured surface).

Our K/T complex has nothing in common with "lobes of turbidite fans" except for the even parallel-bedded pattern (only at Lajilla) and repeating parts of the Bouma sequence B and C.

Concluding, we may say that our sandstone complex in some aspects resembles the channels and transition parts of a turbidite fan. The scarcity of mud-supported conglomerates, absence of chaotic masses, presence of bedded channel infillings, and indication of lateral migration of some of the channels of Unit I at Mimbral and Unit II at Mulato point to a low-gradient slope.

Having said this, we reject the hypothesis of the K/T sandstone complex as having been deposited as a turbidite-fan on the basis of the following arguments:

- 1. In all outcrops studied so far, the eventlike character is indicated by a general fining-up and thinning-up of our sand-stone unit. Fining-up is clearly indicated by the conglomeratic and spherule rich Unit I, overlain by the sandy Unit II and the current-rippled flaser/mud alternation of Unit III and grading of Unit IV. Despite repetition of beds and sedimentary structures with similar features, pointing to a strongly pulsating current, the vertical order is invariably such that a higher unit indicates progressive waning of the current. This can be deduced from upward thinning of similar beds or channels or from the size and steepening of climbing rippled intervals.
- 2. The presence of a relatively thin and lensing sandstone complex over a vast area of at least 2,000 km between Brazos River, Texas, and La Ceiba (Bochil) in Mexico with a consistent superposition of spherule-rich channels, sandstone layers, and a current-rippled sandstone/mud alternation. Over this vast area, the unit varies between only a few centimeters to 10 m, generally between 1 and 3 m. In turbidite fans such thicknesses occur only in the distal parts of the fan.
- 3. Common reversals of currents as revealed by the orientation of ripple cross-bedding and flutes and without the current sense from the orientation of channel axes and primary

current lineation. Such reversals also may be seen in turbidites reflected or deflected by fault scarps or in narrow basins (Pickering and Hiscott, 1985) but can hardly be expected to occur in the ancient Gulf of Mexico in turbidites over such a vast area.

- 4. The uniqueness of the sandstone complex within long tracts of Cretaceous marl and Paleocene marls without turbidites (or only very distal ones such as at Rancho Nuevo) between exactly the latest Cretaceous and earliest Paleocene marls and characterized by spherules at the base and high Ir concentration at the top of the sandstone unit.
- 5. The absence of longer time intervals between the beds as may be deduced from the lack of interbedded mud (except for Unit 3 at the top) and intercalated bioturbated levels. The only instance where we found two burrow levels separated by a scarcely burrowed sandstone bed was in the top of the K/T sandstone complex at El Peñon. However, we found that the horizontal star-shaped tube systems are connected to vertical tubes in the center, penetrating through several-decimeters-thick sandstone layers above the star-structure. Although we have not observed these vertical tubes to penetrate to the surface of the sandstone complex, there is no evidence to the contrary.
- 6. Channel cut and channel fill occurred directly after each other, as is indicated by only shallow downcutting in the order of 0.5 m, followed by meters-deep loading with upward-decreasing intensity of plastic deformations. Such fills were observed at Mimbral in Unit I and partially in Unit II and at Rancho Nuevo and Ramones in Unit II. Injection dikes with spherules in the Mendez Formation likewise point to connected cut-and-fill events at Lajilla and Moscow Landing. Rapid sedimentation is further indicated by water-escape structures and sand-in-sand loading at Rancho Nuevo, Ramones, and El Peñon.
- 7. The occurrence of mud clasts sparsely armored with spherules at the base of Unit II. These mud lumps just before sedimentation of Unit II sands were struck by the current, leaving minute, oriented current-crescents upstream of the spherules. These unique features were seen at Ramones, La Sierrita (Alvarez et al., 1992b), and Rancho Nuevo; they indicate a short time lapse between Units I and II. At Sierrita such an armored mud clast was picked up by the current and deposited in Unit II in a clear traction carpet (Lowe, 1982; Mutti and Ricci Lucchi, 1972) in the sandstone.

In conclusion, the general fining-up and thinning-up of the beds; the unique occurrence at the K/T boundary; the (impact-derived) spherules at the base of the unit, shelf-derived sand in the middle, and (cosmic) Ir concentration at the top; the relatively thin deposit but widespread occurrence; and rapid deposition by opposing and deviating currents cannot be explained by deposition in a turbidite fan or series of fans. On the contrary, these arguments fit well an impact scenario with associated tsunami deposits at the K/T boundary.

However, especially in the shallow-water areas of Alabama and Texas, other noncatastrophic factors such as eustatic sealevel changes have contributed locally to the final architecture of the sandstone units. An early, but not earliest, Danian sealevel lowstand may explain many features of the K/T boundary in the Gulf coastal plain and elsewhere. It is common knowledge that the K/T boundary at shallow-marine settings contains a hiatus due to erosion. Figure 24 shows the possible interactions of early Danian eustatic sea-level changes in the Gulf Coast sections (after Mancini and Tew, 1993). The onset of the sea-level drop is hard to estimate, but some biostratigraphic data are available. The burrows of the transgressive surface, in Brazos River and at Moscow Landing, are of M. pseudobulloides age. The low-stand phase has locally eroded down into earliest Danian, K/T sandstone complex, or Late Maastrichtian sediments, as shown at Moscow Landing. Some remnants of the low-stand (ravinement valleys, Habib et al., 1992; Habib and Talvirska, 1994) are still preserved in Moscow Landing and Mussel Creek but should not be confused with the K/T sandstone complex. These low-stand infills contain earliest Danian dinoflagellates. Also, as seen in the grain-size analysis of Brazos River (Fig. 7), there is a coarsening-upward trend in the top of the sequence, where the first G. eugubina appear and where Jiang and Gartner (1986) first found the basal Danian Crucoplacolithus primus.

Some have expressed doubts that the clastic beds are related to the Chicxulub impact, or have a bearing on the mass extinction of, among others, planktic foraminifers (Stinnesbeck et al., 1993, Keller et al., 1993; Jéhanno et al., 1992). Keller et al. (1994b) presented relative abundance plots of planktic foraminifers in the Mimbral section, suggesting the continuation of "thriving" planktic populations above the clastic beds. However, comparison of thin sections from pelagic marls just below (Figs. 12F, 14A, H) and above the clastic beds (Figs. 12E, 14C, G) clearly show that the Cretaceous planktic populations were decimated just above the clastic beds. The few Cretaceous specimens present are for the largest part most likely reworked, because they occur in cross-bedded sediments. But even if some of these were survivors, then their ecological significance in the planktic populations above the clastic beds is negligible.

#### CONCLUSIONS

The set of sandstone beds as found in intermediate water depths (50 to 500 m) in Gulf Coast outcrops from Alabama to Chiapas, Mexico—designated here as the K/T sandstone complex—is best explained as a deposit of large tsunami waves, caused by the impact of a large extraterrestrial body at Chicxulub, Yucatan, Mexico.

The resulting sequence of sedimentary events is as follows:

- 1. Seismic shaking of the Chicxulub impact locally caused faulting and slumping (Moscow Landing, La Lajilla, Mimbral) and triggered thick mass-flows (Bochil, Mexico, Guatemala).
- 2. During the earthquakes, or shortly afterward, coarse ejecta (tektites, limestone clasts) fell down around the Gulf of Mexico
- 3. These ejecta were immediately reworked with local (ripup) material into channel-like deposits by currents caused by

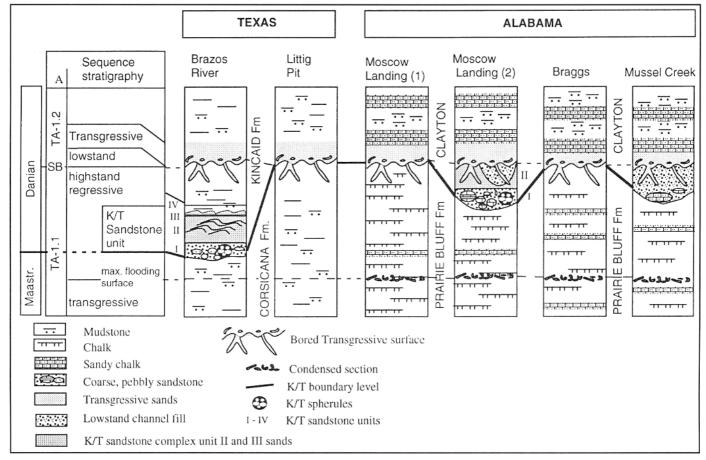


Figure 24. K/T boundary sections in Alabama and Texas, interpreting the K/T sandstone complex in a sequence stratigraphic context (after Mancini and Tew, 1993). We infer that the K/T sandstone complex occurs in a regressive sequence in all the outcrops, between a phosphatic lag-bed indicating a high stand and incised low-stand valleys and a transgressive surface. The channelized sands at Mussel Creek probably belong to incised channels from the early Danian sea-level fall but are not part of the tsunami deposits (Savrda, 1993). The conspicuous bored hard ground can be traced all over the U.S. Gulf coastal plain and is basal Danian (*M. pseudobulloides* Zone) in age. A similar hard ground occurs in the shallow water K/T sequences in Holland (Curffs quarry) and Denmark (Stevns Klint) at about the same biostratigraphic level. The K/T sea-level low stand was formerly considered to be K/T or latest Maastrichtian in age (Mancini et al., 1993). Only at the Brazos River has the sea-level low stand not removed (part of) the K/T boundary tsunami deposits.

the passage of large tsunami waves or were moved downslope by mass-flows (Beloc, Coxquihui). These channels loaded into the (?seismic-softened) seafloor sediments (Unit I).

- 4. Subsequent tsunami waves, possibly assisted by massflows, transported terrigenous sand, plant debris, and shallowwater fossils from nearshore areas into deeper basins, where they deposited a sequence of thick lenticular sandstone beds, showing evidence for currents from opposite directions, consistent with the water movements—upsurge and return-flow caused by large waves (Unit II).
- 5. The final waning tsunami waves only transported fine sand in the next deposits (Unit III), but fine mud was now allowed to settle that contained the first enrichments of iridium.
- 6. After the deposition of the last fine sandstone flaserlike layers, the suspended cloud of fine material settled out between a few hours and days, to form a graded mudstone deposit. The

bulk of the iridium was deposited in this graded interval. Apparently, this extraterrestrial material was fine grained, because it arrived more slowly than the coarse tektite ejecta. Based on the settling time of the fine muds in the Brazos River and the duration of several passages of the tsunami waves and their travel times across the Gulf of Mexico (1 to 6 hs), we estimate that the iridium settled between a few days and a week.

7. The first background sediments, deposited on top of the K/T sandstone complex, are greatly depleted in planktic foraminifers. This shows that the mass extinction coincided closely with the deposition of the K/T sandstone complex and thus most likely was caused by the consequences of the Chicxulub impact.

Placement of the K/T boundary sandstone complex in the top Cretaceous, below the K/T boundary (Stinnesbeck et al., this volume), is based on the use of the wrong criteria for correlation to the K/T boundary type-locality in El Kef, Tunisia.

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