# Slumping and a sandbar deposit at the Cretaceous-Tertiary boundary in the El Tecolote section (northeastern Mexico): An impact-induced sediment gravity flow

Ana R. Soria*
Carlos L. Liesa — Departamento de Ciencias de la Tierra, Universidad de Zaragoza, E-50009, Spain
Maria Pilar Mata Facultad de Ciencias del Mar, Departamento de Geología, Universidad de Cádiz, Puerto Real, E-11510, Spain
José A. Arz Facultad de Ciencias de la Tierra, Universidad Autónoma de Nuevo León, Linares, MEX-67700, Mexico
Laia Alegret
Ignacio Arenillas
Alfonso Meléndez — Departamento de Ciencias de la Tierra, Universidad de Zaragoza, E-50009, Spain

## ABSTRACT

**Slumps affecting uppermost Méndez Formation marls, as well as the spherulitic layer and basal part of the sandy deposits of the Cretaceous-Tertiary (K-T) boundary clastic unit, are described at the new K-T El Tecolote section (northeastern Mexico). These K-T clastic deposits represent sedimentation at middle-bathyal water depths in channel and nonchannel or levee areas of reworked materials coming from environments ranging from outer shelf to shallower slope via a unidirectional, high- to low-density turbidite flow. We emphasize the development and accretion of a lateral bar in a channel area from a surging low-density turbidity current and under a high-flow regime. The slumps discovered on land and the sedimentary processes of the K-T clastic unit reflect destabilization and collapse of the continental margin, support the mechanism of gravity flows in the deep sea, and represent important and extensive evidence for the impact effects in the Gulf of México triggered by the Chicxulub event.**

**Keywords:** K-T boundary, slumping, sand bars, gravity flows, Mexico.

## INTRODUCTION

The Cretaceous-Tertiary (K-T) boundary in northeastern Mexico is characterized by a 1–7-m-thick clastic deposit, consisting of a basal unit of calcareous marls rich in millimeter-size spherules and a sandstone (litharenite) complex cemented by calcite. Both the spherule-bearing unit and the sandstone unit display similar characteristics around the Gulf of Mexico. Bralower et al. (1998) called these distinctive materials the K-T boundary "cocktail" and proposed that they can be used to recognize boundary sections.

The sedimentary processes causing the clastic unit are still in debate. Two models have been proposed. (1) The clastic unit is the result of one geologically instantaneous event clearly related to the Chicxulub impact coinciding with the K-T boundary, and the unit corresponds to the deposit generated by megatsunami waves (Bourgeois et al., 1988; Maurrasse and Sen, 1991; Smit et al., 1992, 1996) or to gravity-flow deposits such as turbidites and debris flows (Bohor, 1996; Bralower et al., 1998). (2) The clastic unit is not related to the K-T event; instead, the unit represents the deposition during several thousands of years of eroded sediments from deltaic to inner neritic environments (Stinnesbeck et al., 1993; Keller et al., 1994). In the second model, the deposit originated during successive falls of sea level during the latest Maastrichtian.

In the first model, involving impact-related sediment, Bohor (1996) and Bralower et al. (1998) suggested that slumping processes might have taken place right after the impact as a consequence of the instability of continental margins. Smit et al. (1996) reported slumping at Moscow Landing (Alabama), but it is related to normal fault activity. Klaus et al. (2000) showed, from seismic reflection data combined with results from ocean drilling, regional-scale slumping in the western North Atlantic, connecting these effects with the K-T impact. However, field examples of slumps have not been previously described.

In this paper we document slumping genetically related to the deposition of the K-T clastic unit from the new El Tecolote K-T section (northeastern Mexico, Fig. 1). We present and discuss new results of K-T boundary clastic sediments, including a sandbar deposit not reported in other K-T sections until now. These features and other sedimentological and paleobathymetric findings allow us to identify the sedimentary processes that took place during deposition of this K-T clastic unit.

*E-mail: E-mail: anasoria@posta.unizar.es.

## K-T BOUNDARY IN THE EL TECOLOTE SECTION

### Stratigraphic Features

In the El Tecolote section (Fig. 1), the K-T sandstone complex crops out on hilltops overlying the marls of the Cretaceous Méndez Formation. Quaternary conglomerates overlie the clastic unit in angular unconformity, so the relationship between the clastic unit and the Paleocene Velasco Formation is not known. Three physically correlatable K-T stratigraphic columns and other partial outcrops have been studied. According to the stratigraphic features of the K-T clastic unit, two areas can be differentiated, northwestern and southeastern (Fig. 1). The stratigraphic column of the northwestern area is reconstructed from two partial columns.

The K-T clastic sediments (Fig. 1) begin with commonly chaotic, 4–4.5 m of gray massive marls, white and green spherule-rich levels, and gray marls with spherules (unit 1). In the northwestern area, a spherule-bearing level defines a good example of a recumbent fold trending northeast (050°), and overturned to the southeast, that continues some meters without changing attitude (Fig. 2A). This fold is surrounded by marls containing Late Cretaceous planktonic and benthic foraminifera and echinoderm fragments. It locally includes the sandy facies of the clastic unit in its core (Fig. 2B). This example and other field observations are consistent with a slumped unit involving mainly Méndez marls and the spherule-bearing basal unit (Fig. 1). In some outcrops, the spherule layer (Fig. 2C) displays parallel lamination and fining-upward grain size. Backscattered scanning electron study shows that spherules (Fig. 3) have an average size of 2–3 mm and typical vesicular texture. Energy-dispersive spectra analysis indicates that they are made of calcite and probably chlorite (Fig. 3A), with minor potassium feldspar, barite, and iron oxides (spinel). Spinels occur as micrometer-size octahedral crystals (Fig. 3A) and sporadic crystals with a Ni-rich

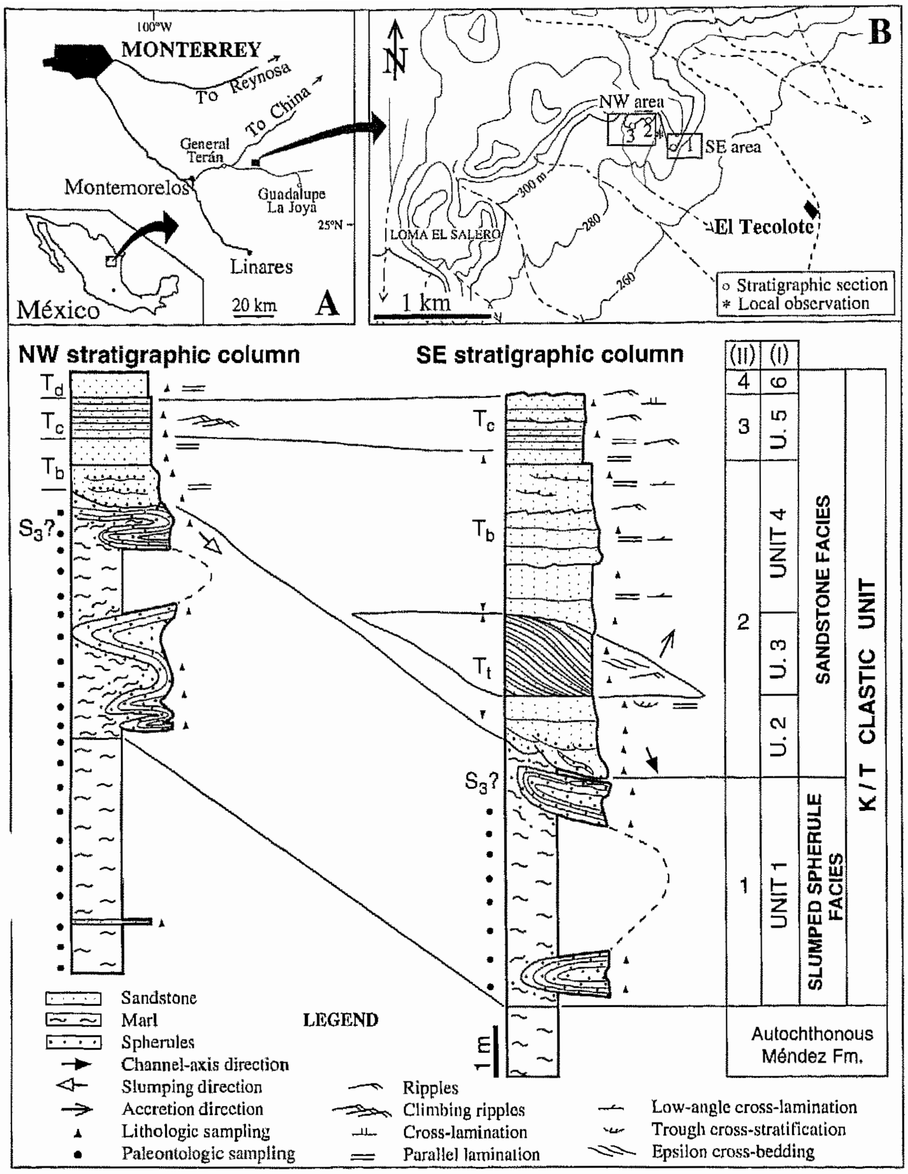


**Figure 1. Stratigraphy and sedimentology of Cretaceous-Tertiary boundary stratigraphic columns of El Tecolote section displaying distinguished units (1), their bed to bed correlation, and their correlation with units of Smit et al. (1996) (2), general geometry of sandbar deposit, and its relationship to channel margin. Inset A shows location of El Tecolote study area (25°15.1′N, 99°32′W). Inset B shows schematic map of El Tecolote section displaying location of northwestern and southeastern areas.**

core. Combined X-ray diffraction and energy-dispersive analyses show that the spherule marly matrix is made of quartz, chlorite, calcite, Na-feldspar, and rare apatite.

In the southeastern area, the slumped unit underlies an 8-m-thick sandy complex. Four units have been differentiated. The first sandy unit (unit 2) consists of a single 1.3-m-thick coarse-grained sandstone body of channelized geometry (channel axis 160°), with internal erosion surfaces (Fig. 2D). Toward its base, this unit also displays some centimeter- to decimeter-size lenticular sandstone layers with abundant spherules. Trough cross-stratification and parallel lamination were observed toward its upper part. Unit 3 is a 1.35-m-thick body with epsilon cross-bedding (Fig. 2E) formed by 20–30-cm-thick strata with fining-upward internal evolution. These strata display parallel lamination (Fig. 2F) and ripple surfaces on top. The cross-bedding planes provided an accretion direction toward the north-northeast (028°). Unit 4 consists of 4.6 m of decimeter- to meter-scale tabular layers with fine- to medium-grained sandstones displaying parallel lamination and low-angle cross-lamination. Its base has a channelized geometry, but it does not represent erosion because the sediments filled a channel-type paleotopography as determined by the sandbar deposit. Toward its top, there are some internal erosion surfaces with basal lags containing spherules. Unit 5 is 1 m thick and consists of 20–30-cm-thick tabular strata with fine-grained sandstones showing cross- and parallel lamination, asymmetric ripples, and climbing ripples.

In the northwestern column, the sandy complex is significantly thinner (2–2.5 m). Unit 3 is absent, although a new unit (unit 6) crops out (Fig. 1). The succession begins with a 70-cm-thick body of medium- to coarse-grained brown sandstones with gently channelized geometry that pinches out to the west (unit 2). Internal erosion surfaces and basal lags containing spherules are present. The overlying unit (unit 4) is a 50–70-cm-thick tabular body of medium-grained sandstones displaying parallel- and low-angle cross-lamination. This bed is succeeded by as much as 80 cm of fine- to medium-grained sandstones with tabular geometry showing cross-lamination and climbing ripples (unit 5). The clastic succession is capped by 40 cm of fine- to medium-grained sandstones (unit 6) in 15-cm-thick tabular strata displaying abundant parallel lamination that locally contain intercalated centimeter-scale marly beds.

### Micropaleontologic Data: Age and Paleobathymetry

Foraminiferal assemblages in allochthonous and autochthonous marl samples (see Fig. 1) indicate that 88% of the specimens correspond to planktonic foraminifera in typical low-latitude assemblages. As a whole, the age of the planktonic foraminifera is late Maastrichtian (*Abathomphalus mayaroensis* biozone), but older reworked specimens have also been found. The absence of *Plummerita hantkeninoides,* marker of the last Maastrichtian biozones in low latitudes, may be controlled by paleoecological causes, but seems to suggest a very probable stratigraphic gap (hiatus and/or erosion) on top of the upper Maastrichtian.

Autochthonous Méndez marls contain 36%–48% of middle-bathyal benthic foraminiferal species such as *Eouvigerina subsculptura* or *Stensiöina beccariiformis,* whereas deeper species (*Clavulinoides trilatera, Cibicidoides hyphalus, Gyroidinoides* spp.) constitute to 9% of the assemblages. Several identified species (*Bulimina velascoensis, S. beccariiformis, Spiroplectammina spectabilis*) have their upper depth limit at 500 m (Van Morkhoven et al., 1986). The high percentage (81%–93%) of foraminifera with calcareous tests and the paleobathymetric distribution of the identified species suggest deposition at middle-bathyal depths. Species collected from the allochthonous slump facies indicate the presence of reworked material coming from outer neritic to upper bathyal depths.

## SEDIMENTOLOGICAL INTERPRETATION OF K-T DEPOSITS

K-T clastic facies are extensively represented across the Gulf of Mexico, except for

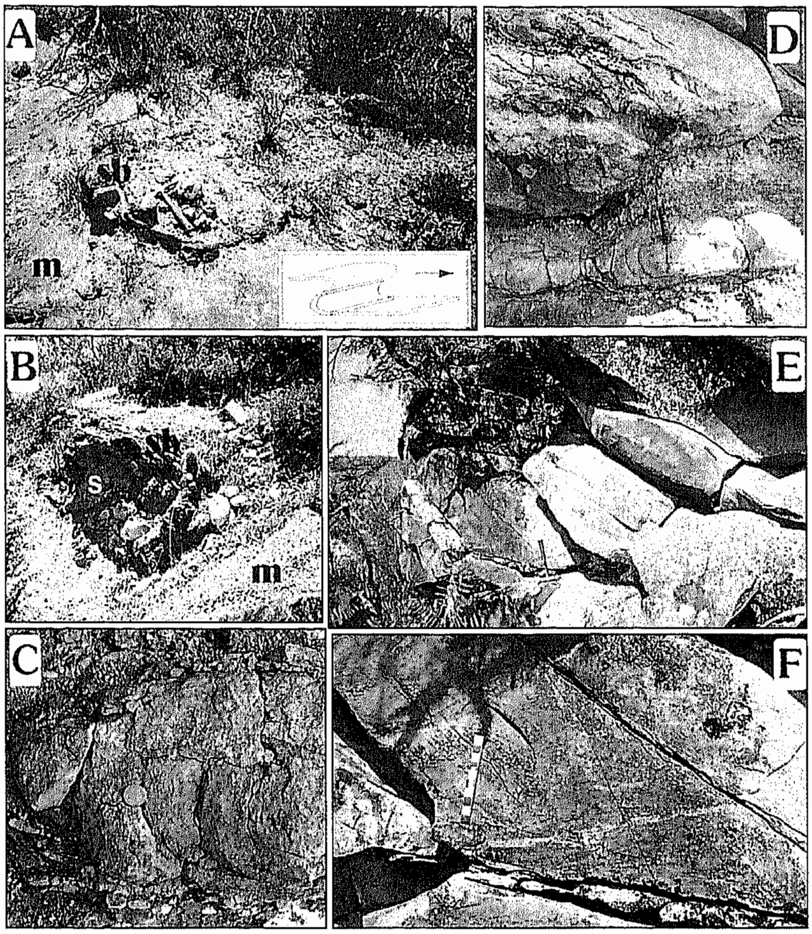


**Figure 2. Outcrop photographs of Cretaceous-Tertiary (K-T) boundary clastic unit at El Tecolote. A, B: Panoramic view of slump, looking northeast and southwest, respectively, in northwestern area of El Tecolote section. Inset in A shows slump reconstruction, where arrow indicates sense of overturning; sb—spherule bed, m—marls, s—sandstone. C: Spherule bed in southeastern area. D: Channel deposit (unit 2) showing internal erosion surfaces with spherule lags. E: Epsilon cross-bedding of unit 3 with accretion direction toward north-northeast. F: Detail of strata in E showing laminae parallel to strata.**

units 2 (channel facies) and 3 (sandbar deposit), which have been recognized only in the El Tecolote section (Fig. 1). Moreover, the spherule-bearing unit 1 was involved here in slumps. The sands, echinoderms, and benthic foraminifera, as well as the spheroid particles of this clastic deposit, came from the outer platform and upper slope areas. According to the interpretation of Smit et al. (1996), and others, the spherules represent altered impact ejecta. Facies, geometry, and thickness of the clastic deposit from the southeastern and northwestern El Tecolote areas suggest sedimentation in shallow channels and nonchannel and levee areas, respectively. Moreover, benthic foraminiferal data indicate that this deposit formed at middle bathyal water depths.

The fining-upward sequence, the textural divisions, and the sedimentary structures recognized in the northwestern column allow us to interpret the K-T clastic unit as the product of a surging, high- to low-density turbidite flow, according to the interpretations of Bohor (1996) and Bralower et al. (1998) in other K-T sections of the Gulf of Mexico. We next focus on the analysis and sedimentological interpretation of the peculiarities described, such as slumping related to the K-T deposit and channel facies, including the sandbar deposit.

## Slumping at the K-T Boundary

Slumping processes involved the spherule level and the uppermost Méndez Formation marls, but they did not affect the upper parts of the clastic unit. Thus, slumping took place after the ejecta's deposition and before the sandy unit deposition. Nevertheless, the basal part of the sandy unit is locally involved in slumps (Fig. 2B), suggesting several phases of slumping during a short period. Micropaleontological data indicate that sediment transport associated with slumping did not produce large changes in sediment depth.

The spherule layer displays important deformation that includes mainly folding and stretching of beds. Bed disruption could be re-

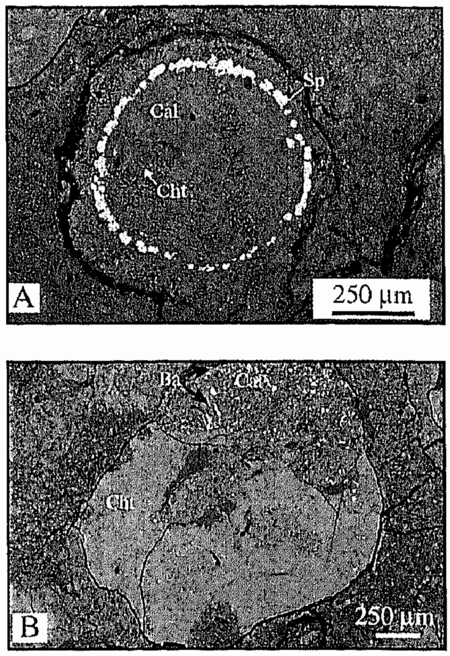


**Figure 3. Photomicrographs of circular to elliptical spherules in marly matrix. A: Backscattered scanning electron (BSE) image of altered spherule filled with calcite (Cal) and chlorite (Cht) that has external rim of spinel (Sp) crystals. B: BSE image of clay spherule with minor chlorite, barite (Ba), and spinel crystals.**

sponsible for local mixture of spherules with marls, indicating semisoft- and soft-sediment deformation. Structural data of the slump fold of Figure 2A indicate a direction of slumping toward the southeast. This interpretation agrees with the paleoslope of the Méndez basin that deepened to the south-southeast (Keller et al., 1994). Moreover, the 160° direction of the channel axes in the El Tecolote southeastern area and the north-northwest trend of channel axes from other K-T sections (Keller et al., 1994; Bohor, 1996) also support the slope orientation.

## Channel and Sandbar Deposits Related to Channelized Turbidites

Units 2 (channelized facies) and 3 (sandbar facies) described in the southeastern area were deposited in a shallow channel. The paleodepth of the deposit and the presence of slumps indicate a channel in the upper middle part of the continental slope.

The channel geometry of the base of unit 2 (Fig. 2D) may represent erosion associated with the transition from high- to low-density turbidity flow (Lowe, 1982). The normal grading and parallel lamination of the spherule-bearing layer and the spherule size suggest a deposit by direct-suspension sedimentation from a high-density turbidity flow ($S_3$ term of Lowe, 1982). The deposition of the coarse-grained spherules left a residual current forming a true low-density flow. According to

Lowe (1982), such a flow can erode or rework the upper part of the $S_3$ (i.e., the spherule level) term, leaving sediments exhibiting traction structures (parallel lamination and large-scale cross-stratification) that are not part of the normal Bouma sequence ($T_t$ term). Units 2 and 3, and probably unit 4, represent the deposit formed under these conditions, during a tractive stage in the upper flow regime. Thus, unit 2 corresponds to the deposits of channel fill, and unit 3 (Fig. 2F) comprises the sediments deposited by migration of a sandbar across the channel.

The excellent outcrop conditions allowed us to observe the close spatial relationship between the epsilon cross-bedding body and the channel margin (see reconstruction of this deposit in Fig. 1). This fact, the epsilon cross-bedding geometry of the strata (Fig. 2E), and their accretion to the north-northeast—nearly perpendicular to the 160° channel direction—allow us to conclude that the sandbar is a lateral bar in a sinuous realm of the channel. The internal parallel laminae of the different epsilon bodies (Fig. 2F) suggest deposition by traction in a high-flow regime. This sandbar left a paleotopography that became fossilized by the laminated textures of unit 4, which are also typical of high current strength (upper flow regime) and rapid sedimentation ($T_b$ term of Bouma sequence). In these units, the internal surfaces reflect flow-regime changes, including surging during waning of the current.

## DISCUSSION AND CONCLUSIONS

The stratigraphic, sedimentologic, biostratigraphic, paleobathymetric, and structural data from the El Tecolote section support the interpretation that the K-T clastic unit represents sedimentation in middle bathyal water depths (upper to middle slope) in a high- to low-density turbidity current containing sediments coming from the outer shelf and uppermost slope areas.

Furthermore, the data suggest a close relationship between slumping and deposition of K-T boundary sediments. The main slumping processes took place between the deposit of the spherule layer and unit 2. Our results cannot be directly correlated with the main impact-induced phase of slumping reported by Klaus et al. (2000), which preceded deposition of ejecta, but they may be correlated with the remobilization of ejecta, shortly after it was initially deposited, as inferred by Klaus et al. (2000).

However, El Tecolote slumps cannot explain the stratigraphic gap on top of the upper Maastrichtian strata. As a tentative explanation, we suggest an earlier mass wasting directly related to the impact, which could have produced the sliding of the uppermost slope sediments toward more basinal positions, and/or the erosion associated with the head of the turbidity flow. Thus, seismic disturbances or tsunami-like waves due to the K-T impact event mobilized spherules and sands from the shelf (Bohor, 1996), and these materials were redeposited by sediment gravity flows in slope and basinal areas. This high-density sediment flow going to basinal environments and the local load of the initial deposits (spherule bed) could destabilize slope areas again and produce new phases of slumping incorporating the new sediments. In any case, slumping reflected the destabilization and collapse of the continental margin directly or indirectly triggered by the Chicxulub impact event. Our data represent important and extensive evidence for the impact effects in the Gulf of Mexico. Moreover, slumping supports the mechanism of gravity flows in the deep sea (e.g., Bralower et al., 1998).

According to our data, the appearance of the spherule-bearing level several times in the stratigraphic columns only represents its recurrence by folding and other bed-disruption processes (thrusts, balls, bed rotation, reworking) related to slump development. Similar observations in other K-T sections must be taken with caution, particularly in areas that lack good exposures. Thus, the discovery of these slumps emphasizes the need to reexamine outcrops elsewhere with multiple exposures of spherules to test for slumps. Moreover, future paleontologic studies, both sampling and interpretations, should consider and evaluate the possible presence of slumps.

Sediments coming from the platform overflowed onto the continental slope to form an extensive gravity flow, which in slope and basinal environments scoured multiple shallow channels trending nearly parallel to the paleoslope (Bohor, 1996). These channels fed basinal areas where final sedimentation from turbidity currents took place (Bohor, 1996; Bralower et al., 1998). The gradual waning of turbidity-current strength left sediments in channel and nonchannel or levee areas of the slope, with typical textural and structural features. We have described a lateral bar that developed in a sinuous realm of a channel. This bar formed under the upper flow regime in a low-density turbidity flow. Slumping and deposition of the K-T clastic unit were triggered by destabilization of the continental margin of the Gulf of México because of the Chicxulub impact event.

## ACKNOWLEDGMENTS

We thank J. López-Oliva for providing the outcrop location. We are grateful to G. Pardo, A. Pérez, and J.L. Simón for discussions and suggestions and to D.R. Peacor and the Electronic Microscopy Analysis Laboratory of the University of Michigan for the technical support in the acquisition of backscattered scanning electron images. We thank F. Maurrasse and W. Stinnesbeck for careful reviews. This work was funded by projects PB97-1016 (Spanish Ministry of Education) and J32473T (National Council for Science and Technology of Mexico).

## REFERENCES CITED

Bohor, B.F., 1996, A sediment gravity flow hypothesis for siliciclastic units at the K-T boundary, northeastern México, *in* Ryder, G., et al., eds., The Cretaceous-Tertiary event and other catastrophes in Earth history: Geological Society of America Special Paper 307, p. 183–195.

Bourgeois, J., Hansen, T.A., Wiberg, P.L., and Kauffman, E.G., 1988, A tsunami deposit at the Cretaceous-Tertiary boundary in Texas: Science, v. 241, p. 567–570.

Bralower, T.J., Paull, C.K., and Leckie, R.M., 1998, The Cretaceous-Tertiary boundary cocktail: Chicxulub impact triggers margin collapse and extensive sediment gravity flows: Geology, v. 26, p. 331–334.

Keller, G., Stinnesbeck, W., Adatte, T., MacLeod, N., and Lowe, D.R., eds., 1994, Field guide to Cretaceous-Tertiary boundary sections in northeastern México: Houston, Texas, Lunar and Planetary Institute Contribution 827, 110 p.

Klaus, A., Norris, R.N., Kroon, D., and Smit, J., 2000, Impact-induced mass wasting at the K-T boundary: Blake Nose, western North Atlantic: Geology, v. 28, p. 319–322.

Lowe, D.R., 1982, Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents: Journal of Sedimentary Petrology, v. 52, p. 279–297.

Maurrasse, F.J.-M.R., and Sen, G., 1991, Impacts, tsunamis and the Haitian Cretaceous-Tertiary boundary layer: Science, v. 252, p. 1690–1693.

Smit, J., Montanari, A., Swinburne, N.H.M., Álvarez, W., Hildebrand, A.R., Margolis, S.V., Claeys, P., Lowrie, W., and Asaro, F., 1992, Tektite-bearing, deep-water clastic unit at the Cretaceous-Tertiary boundary in northeastern México: Geology, v. 20, p. 99–103.

Smit, J., Roep, T.B., Álvarez, W., Montanari, A., Claeys, P., Grajales-Nishimura, J.M., and Bermudez, J., 1996, Coarse-grained, clastic sandstone complex at the K-T boundary around the Gulf of México: Deposition by tsunami waves induced by the Chicxulub impact?, *in* Ryder, G., et al., eds., The Cretaceous-Tertiary event and other catastrophes in Earth history: Geological Society of America Special Paper 307, p. 151–182.

Stinnesbeck, W., Barbarin, J.M., Keller, G., López-Oliva, J.G., Pivnik, D.A., Lyons, J.B., Officer, C.B., Adatte, T., Graup, G., Rocchia, R., and Robin, E., 1993, Deposition of channel deposits near the Cretaceous-Tertiary boundary in northeastern México: Catastrophic or "normal" sedimentary deposits?: Geology, v. 21, p. 797–800.

Van Morkhoven, F.P.C.M., Berggren, W.A., and Edwards, A.S., 1986, Cenozoic cosmopolitan deep-water benthic foraminifera: Bulletin des Centres Reserches Exploration-Production Elf-Aquitaine, Memoir 11, 421 p.

Manuscript received July 20, 2000
Revised manuscript received November 20, 2000
Manuscript accepted December 4, 2000

Printed in USA