The Cretaceous/Tertiary boundary: sedimentology and micropalaeontology at El Mulato section, NE Mexico

L. Alegret,[1] I. Arenillas,[1] J. A. Arz,[1] C. Liesa,[1] A. Meléndez,[1] E. Molina,[1] A. R. Soria[1] and E. Thomas[2,3]

[1]*Departamento de Ciencias de la Tierra, Universidad de Zaragoza, 50009 Zaragoza, Spain;* [2]*Department of Earth and Environmental Sciences, Wesleyan University, Middletown, CT 06459-0139,* [3]*Center for the Study of Global Change, Department of Geology and Geophysics, Yale University, New Haven, CT 06520-8109, USA*

ABSTRACT

In the El Mulato section (NE Mexico), the Upper Cretaceous marly Méndez and the Lower Palaeogene marly Velasco Formations are separated by a clastic unit. Benthic foraminifera from both marly formations indicate lower bathyal depths. The clastic unit, in contrast, contains platform sands, muddy pebbles and neritic (shallow) faunas mixed with microspherules, indicating that it was allochthonously deposited into the deep basin. The diversity and the variability in origin of the components in the clastic unit, and its sedimentological features, support a model of deposition by turbidity currents related to mass-wasting processes triggered by the Cretaceous/Tertiary (K/T) boundary impact. Planktic foraminifera were affected by a catastrophic extinction at the K/T boundary, whereas benthic foraminifera show reorganization of the community structure rather than significant extinction. The benthic faunal turnover may have resulted from the drop in primary productivity after the asteroid impact at the end of the Cretaceous.

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Introduction

Numerous researchers have focused investigations on Cretaceous/Tertiary (K/T) sections because of the controversy about the origin of the characteristic K/T deposits, the global mass extinction in terrestrial and marine environments and the hypotheses regarding its causes. Most accept the theory that the deposition of the controversial 'Clastic Unit' (containing impact-derived spherules) at the K/T boundary in many sections in Mexico resulted from a bolide impact on the Yucatan Peninsula (e.g. Bohor, 1996; Smit *et al*., 1996; Bralower *et al*., 1998; Klaus *et al*., 2000), which destabilized the continental margin (e.g. Bourgeois *et al*., 1988; Smit *et al*., 1992; Soria *et al*., 2001). Some (Keller and Stinnesbeck, 1996a; López-Oliva and Keller, 1996; Stinnesbeck *et al*., 1996; Keller *et al*., 1997), however, propose an origin related to relative sea-level changes, or regional tectonics and therefore formation over a long period of time.

Bolide impact is also the most widely accepted explanation of the catastrophic mass extinction of planktic foraminifera at the K/T boundary (Smit, 1982; Olsson and Liu, 1993; Molina *et al*., 1998). Deep-sea benthic foraminifera lack significant extinction at the end of the Cretaceous (e.g. Thomas, 1990a,b), and changes in their community structure have been interpreted to be the result of collapse of pelagic food webs (Coccioni *et al*., 1993; Kuhnt and Kaminski, 1993; D'Hondt *et al*., 1998; Alegret and Thomas, 2001).

Mexican K/T boundary sections are of special interest owing to their proximity to the impact crater. The present contribution offers a micropalaeontological and sedimentological analysis of this transition at the El Mulato section (NE Mexico), in order to infer the little-known local palaeoenvironmental evolution across the K/T boundary, as well as the sedimentary processes.

Methods

The El Mulato section (24°54′N; 98°57′W) is 500 m North of El Mulato village, in Tamaulipas State, NE Mexico (Fig. 1). Between the marly Upper Cretaceous Méndez Formation and the marly Lower Palaeogene Velasco Formation, there is a ~ 2-m-thick Clastic Unit. Stratigraphical and sedimentological analysis were based on the main section (Figs 2 and 3A), and a partial outcrop of the Clastic Unit a few metres away (Fig. 3B).

Fifty-six samples were collected from the Méndez and Velasco Formations (Fig. 2), at 2-cm intervals close to the K/T Clastic Unit, and at decimetric intervals well below and above. Samples were disaggregated in water with diluted H_2O_2 and washed through a 63-μm sieve. At least 300 benthic and 300 planktic foraminifera from the > 63 μm fraction were picked, identified to species level and counted in each sample.

Morphotypic analysis of benthic foraminifera was performed to infer the benthic palaeocology (Jones and Charnock, 1985; Corliss and Chen, 1988). Additional information on morphological similarity to recent benthic foraminifera was used in order to distinguish epifaunal (living in the upper 2 cm of sediment), and deeper infaunal species (Mackensen *et al*., 1995; Widmark and Speijer, 1997; Thomas *et al*., 2000; Alegret *et al*., 2001).

Stratigraphy

Analysis of the upper 4 m of the Méndez Fm. revealed grey, massive marls, in tabular, metre-scale-thick bodies, with a cm-thick, tabular bed of ochre, fine-grained sandstones, with asymmetric ripples, at 1.8 m below the Clastic Unit. The lower 9 m of the Velasco Fm. consists of ≤ 3.5-m-thick tabular beds of massive marls, with interlayered grey marly limestones in

Correspondence: L. Alegret, Departamento de Ciencias de la Tierra, Universidad de Zaragoza, 50009 Zaragoza, Spain. Tel.: +34 976 761080; fax: +34 76 761088; e-mail: laia@posta.unizar.es

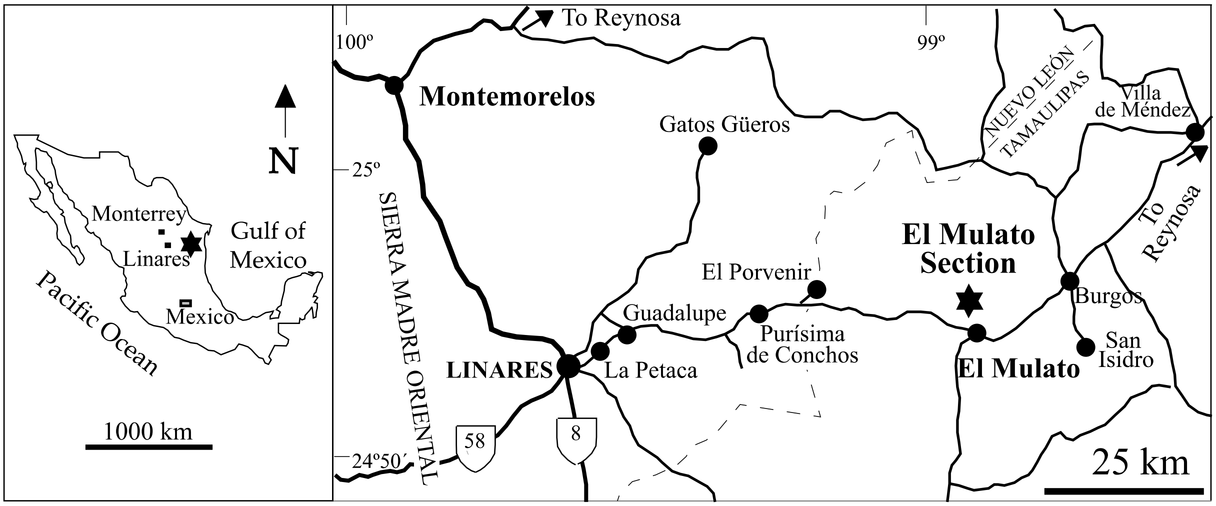

Fig. 1 Location of the El Mulato section (NE Mexico).

tabular beds up to 10-cm thick. The lower 3.5 m of the Velasco Fm. were studied in detail. Both formations are typical marine hemipelagic deposits with abundant planktic foraminifera.

The K/T Clastic Unit is ~ 2-m thick. The lower part is a 8–10-cm-thick tabular bed containing abundant spherules (Fig. 3A, subunit 1) with a diameter of 2–5 mm, and marly muddy pebbles from the Méndez Fm. The microspherules are recrystallized into calcite, but show the typical tektite morphology (Figs 2 and 6–8), as documented in many K/T Mexican sections (Smit *et al*., 1992). This bed is overlain by a fining-upward 30-cm-thick bed of medium-to coarse-grained ochre sandstones (Fig. 3A, subunit 2), with cm- to dm-thick lenticular and tabular layers bounded by internal erosive surfaces, which occasionally contain basal lags of Méndez muddy pebbles. The bed shows common parallel lamination and low-angle cross-lamination. Cross-lamination and asymmetric ripples occur toward its top.

This bed is overlain by a 50-cm-thick tabular body of medium-grained ochre sandstones with parallel and undulate lamination (Fig. 3A, subunit 3). Above these, there are three beds 15-, 15- and 10-cm thick, of medium- to fine-grained ochre sandstones (Fig. 3A, subunits 4, 5 and 6). The upper and lowermost bodies consist of cm-thick tabular and lenticular layers, containing cross-lamination and abundant stream ripples, the intermediate body has parallel lamination. The deposit continues with two tabular beds comprising 35-cm-thick medium- to fine-grained sandstones with parallel lamination, and asymmetric ripples toward the top of each bed (Fig. 3A, subunit 7). Laterally, subunit 7 (Fig. 3B) consists of a 5-cm-thick sandy level with convolute lamination. The Clastic Unit is topped by fine-grained ochre sandstones in three dm-thick, tabular bodies (Fig. 3A, subunit 8). The lowermost contains in-phase climbing-ripples, whereas those of the intermediate body are out of phase. The uppermost body displays cross-lamination and asymmetric ripples. Laterally, subunit 8 shows sets of cm-scale cross-lamination and asymmetric ripples, as well as in phase climbing ripples and flaser bedding toward the top (Fig. 3B).

Biostratigraphy and planktic foraminiferal mass extinction

In the Méndez marls, 60 Cretaceous planktic foraminiferal species were identified that are typical for low-latitude assemblages, dominated by the cosmopolitan *Heterohelix*, but also typical for end-Maastrichtian polytaxic assemblages with globotruncanids and complex heterohelicids. The Clastic Unit contains Upper Cretaceous species with very poor preservation at much lower abundance than in the Méndez Fm. The first marly layer overlying the Clastic Unit contains scarce reworked Cretaceous specimens and abundant Tertiary planktic foraminifera. This finding is in disagreement with Keller *et al*. (1994, 1997), who propose a latest Maastrichtian age for this marly layer.

The six biozones proposed by Molina *et al*. (1996) were recognized at El Mulato (see Fig. 2). The lowest known record of *P. hantkeninoides* is only 40 cm below the K/T boundary, which does not necessarily indicate a significant unconformity or hiatus, because *P. hantkeninoides* is very rare in Mexican K/T sections (Arz *et al*., 2001a). The lowest records of the *Pv. eugubina*, *Ps. pseudobulloides* and *Gl. compressa* occur 30, 95 and 595 cm above the top of the Clastic Unit, respectively. The Clastic Unit has been included in the *G. cretacea* Biozone by Molina *et al*. (1996), according to its biozonal definition. A possible hiatus is suggested at the base of the Velasco Formation, because the evolutionary radiation of the first Tertiary species is not recorded.

Only *Archaeoglobigerina cretacea* and *Gublerina acuta* disappear significantly below the base of the Clastic Unit, i.e. at the K/T boundary. If reworked specimens are not taken into account, up to 90% of planktic foraminiferal species became extinct at the K/T boundary. Biostratigraphical data in other Mexican sections support that the planktic foraminiferal mass extinction occurred at the base of the Clastic Unit (Arz *et al*., 2001a,b).

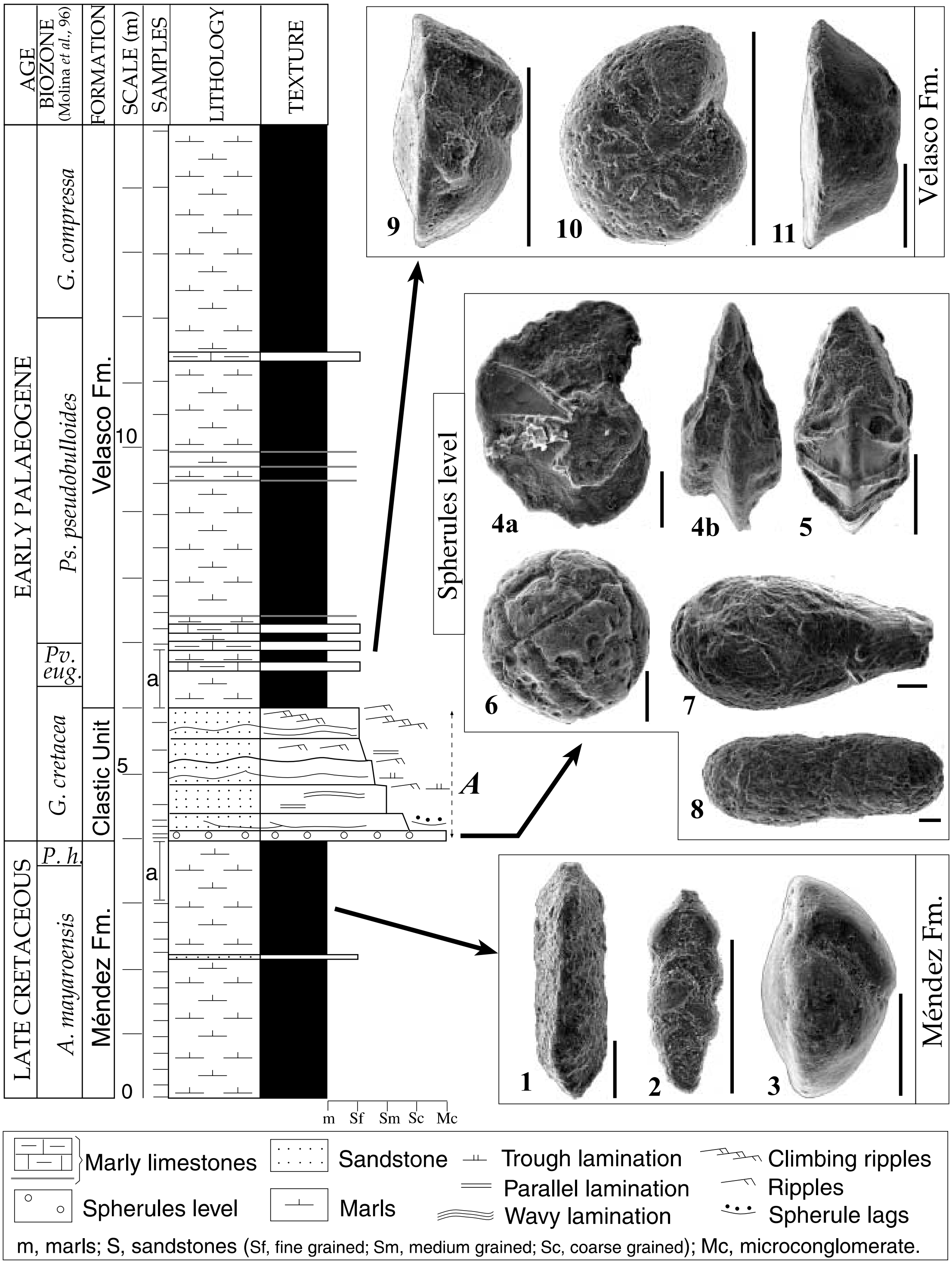

Fig. 2 Upper Cretaceous and Lower Palaeogene sediments of the El Mulato section, and some of the most important benthic taxa. 1, *Clavulinoides trilatera*; 2, *Eouvigerina subsculptura;* 3, *Gyroidinoides beisseli*; 4a, b, *Lenticulina spissocostata*; 5, *L. navarroensis*; 6, 7 and 8, tektite-like components; 9, *Globorotalites* sp. A (Alegret and Thomas, 2001); 10*, Stensioeina becariiformis*; 11, *Nuttallinella florealis*. *P. h., Plummerita hantkeninoides* Biozone; *Pv. eug., Parvularugoglobigerina eugubina* Biozone.

Palaeobathymetry

The El Mulato section was deposited well above the calcite compensation depth, as indicated by the presence of abundant calcareous (70–80%) and calcareous-agglutinated species. The planktic:benthic ratio is high (90%). Benthic foraminiferal assemblages contain common species typical of the Velasco Fauna (Berggren and Aubert, 1975), such as *Stensioeina*

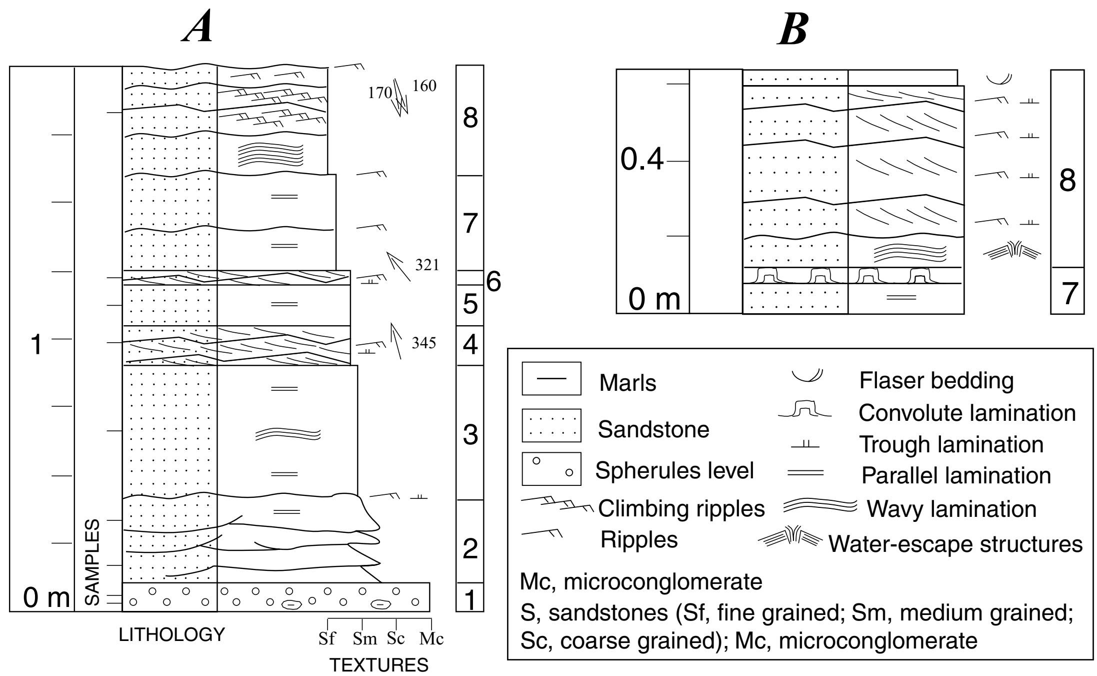

Fig. 3 Sedimentological features of the Clastic Unit in the main section (A) and in a partial outcrop (B) at El Mulato.

beccariiformis, Nuttallides truempyi, Aragonia sp., *Osangularia velascoensis*, gyroidinids and anomalinids (Fig. 4), as well as other deep-water taxa such as *Aragonia velascoensis*, *Bulimina trinitatensis*, *B. velascoensis*, *Cibicidoides hyphalus*, *Clavulinoides trilatera*, *Gaudryina pyramidata*, *Gyroidinoides globosus*, *Marssonella oxycona*, *Nuttallinella coronula*, *Nt. florealis*, *Osangularia velascoensis* and *Spiroplectammina spectabilis*. Some of the most common species (e.g. *B. trinitatensis, N. truempyi, O. velascoensis, Sp. spectabilis* and *S. becariiformis*) have upper depth-limits at 500–700 m, and some (*B. velascoensis* and *Pullenia coryelli*), upper depth limits at 1000 m (Van Morkhoven *et al*., 1986). *Aragonia* sp., *C. hyphalus* and *G. globosus*, as well as other *Gyroidinoides* species, are common at lower bathyal depths (Tjalsma and Lohmann, 1983). *Clavulinoides amorpha* and *Cl. trilatera* are common in abyssal to lower bathyal environments (Kaminski *et al*., 1988). *Coryphostoma incrassata* is rare to absent at abyssal depths (Van Morkhoven *et al*., 1986), and suggests deposition at lower bathyal rather than abyssal depths. The high planktic:benthic ratio, the low abundance of macrofauna, and the assemblage composition suggest a lower bathyal (1000–1500 m) depth of deposition for El Mulato sediments. This deduction is in strong disagreement with the interpretation of outer shelf to upper bathyal (200–500 m) environments (Keller and Stinnesbeck, 1996b).

In contrast to the lower bathyal Méndez and Velasco Fms., the K/T Clastic Unit contains shelf species (Fig. 2), such as *Lenticulina navarroana*, *L. spissocostata* and *Planulina* sp. These species appear toward the base of the Clastic Unit, mixed with microspherules and bathyal species such as *Cibicidoides velascoensis, Cl. trilatera* or *Gaudryina pyramidata*.

Allochthony of the Clastic Unit

The sedimentology of the Clastic Unit indicates deposition under very different conditions than the Méndez and Velasco marls. The Clastic Unit contains elements from shallower depths, such as coarse-grained siliciclastic sediments, microspherules, muddy pebbles and reworked shallow benthic (Figs 2 and 4) and planktic foraminifera. The general fining-upward sequence and the sedimentary structures suggest deposition at a high sedimentation rate, from decelerating turbidity currents changing from high to low energy. The presence of intervals with parallel and cross-lamination suggests local accelerations in a general energy-decreasing trend of the turbidity flow. Surges are normal in turbidity flows (Lowe, 1982), and have been suggested to occur in the nearby El Tecolote section (Soria *et al*., 2001). The presence of the allochthonous neritic components supports the hypothesis that deposition of the Clastic Unit on the lower slope was triggered by a unique and geologically instantaneous event, the K/T impact (Bohor, 1996; Smit *et al*., 1996; Arenillas *et al*., 2001; Arz *et al*., 2001a; Soria *et al*., 2001), in contrast to Stinnesbeck *et al*. (1996), who suggest a Maastrichtian age and long-term sedimentation of the Clastic Unit.

Benthic foraminifera and environmental turnover

Benthic foraminiferal assemblages from the Méndez Fm. contain up to 70% of shallow infaunal species such as *Clavulinoides trilatera, Eouvigerina subsculptura, Gyroidinoides beisseli* (Fig. 2, 1–3). The abundance of *Cl. trilatera* decreased drastically at the K/T boundary. In the uppermost *G. cretacea* Biozone its ecological niche was occupied temporarily by

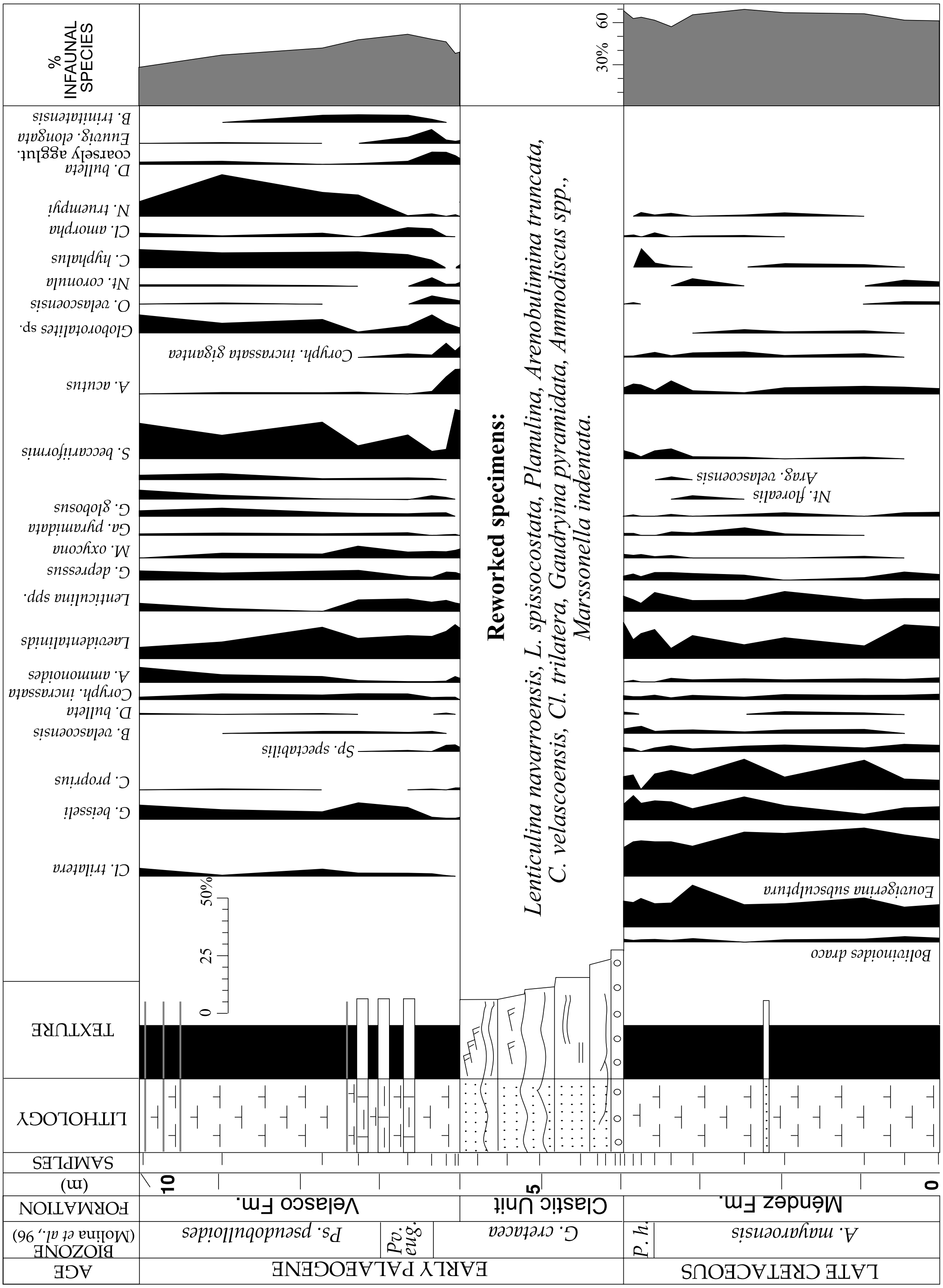

Fig. 4 Benthic foraminiferal turnover across the K/T boundary at El Mulato section. *P. h.*, *Plummerita hantkeninoides* Biozone; *Pv. eug.*, *Parvularugoglobigerina eugubina* Biozone.

other infaunal species such as *Coryphostoma incrassata* forma *gigantea*, *D. bulleta* coarsely agglutinated and *Spiroplectammina spectabilis*; in the lower *Pv. eugubina* Biozone by *Euuvigerina elongata* and *Cl. amorpha*, and in the lower *Ps. pseudobulloides* Biozone by *Marssonella oxycona*.

After the deposition of the Clastic Unit, the percentage of infaunal benthic foraminifera decreased to 30%, and the lowermost samples from the Velasco Fm. (*G. cretacea* Biozone) are dominated by epifaunal groups (up to 60%), such as *Anomalinoides acutus, Cibicidoides hyphalus, Globorotalites* sp. and *Stensioeina beccariiformis*. According to the model proposed by Jorissen *et al.* (1995), this faunal change may be the consequence of a decrease in food supply at the K/T boundary, which has been related to the collapse in primary productivity at the end of the Cretaceous (Zachos and Arthur, 1986; Thomas, 1990a,b; Widmark and Malmgren, 1992a,b; Kuhnt and Kaminski, 1993). The K/T planktic mass mortality thus affected the amount and the character of the food supply to the benthos (d'Hondt *et al.*, 1998). Only two infaunal species, *Bolivinoides draco* and *Eouvigerina subsculptura* have their last appearance at the K/T boundary. Alegret and Thomas (2001) argue that the lack of significant extinction of deep-sea benthic foraminifera at the K/T boundary indicates that many of the taxa in Mexican sections were detritus-feeders rather than users of fresh phytoplankton. The mass wasting at the end of the Cretaceous deposited the Clastic Unit (consisting of organic-poor, sandy sediments) in the lower-bathyal region, thus further decreasing the food supply. Benthic foraminiferal assemblages do not suggest the occurrence of low oxygen conditions at El Mulato, or other Mexican sections (Alegret *et al.*, 2001).

The increase in abundance of *Nuttallides truempyi* in the *Pv. eugubina* and *Ps. pseudobulloides* Biozones may reflect oligotrophic conditions (Nomura, 1995; Thomas *et al.*, 2000), indicating that primary productivity had not fully recovered at that time. The decrease of *N. truempyi*, together with a slight increase in infaunal species towards the end of the *Ps. pseudobulloides* Biozone and through the *Gl. compressa* Biozone suggest recovery of the food supply to the sea floor, but not to the levels of the Late Cretaceous.

Conclusions

Sedimentological and micropalaeontological data on the Upper Cretaceous–Lower Tertiary transition at the El Mulato section indicate that sudden depositional and environmental changes occurred at the K/T boundary. Upper Cretaceous Méndez sediments consist of hemipelagic, lower-bathyal marls; benthic foraminiferal assemblages are dominated by infaunal species and indicate a moderate to high food supply to the seafloor. The deposition of the Clastic Unit was triggered by the K/T boundary impact, and elements from the platform and upper slope (foraminifera, sand, microspherules, marly pebbles) were geologically instantaneously redeposited by turbidity currents on the lower slope. The first marly layer overlying the Clastic Unit belongs to the Velasco Formation, contains Tertiary taxa, and represents normal sedimentation in a hemipelagic lower bathyal environment.

Whereas planktic foraminifera data suggest a catastrophic mass extinction at the K/T boundary, benthic foraminifera were not strongly affected. However, a decrease in abundance of infaunal morphogroups as well as community restructuring indicate a sudden decrease in the food supply to the seafloor. This is consistent with a collapse in primary productivity at the K/T boundary event, aggravated by the downslope transport of food-poor, clastic material. The nutrient depletion prevailed during the *G. cretacea, Pv. eugubina* and *Ps. pseudobulloides* Biozones, with some increase in food supply toward the end of *Ps. pseudobulloides* Biozone through the *Gl. compressa* Biozone. Primary productivity did not return completely to Late Cretaceous values.

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