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New evidence concerning the age and biotic effects of the Chicxulub impact in NE Mexico

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Abstract: In the 1990s the Chicxulub impact was linked to the K–T boundary by impact spherules at the base of a sandstone complex that was interpreted as an impact-generated tsunami deposit. Since that time a preponderance of evidence has failed to support this interpretation, revealing long-term deposition of the sandstone complex, the K–T boundary above it and the primary impact spherule ejecta interbedded in Late Maastrichtian marls below. Based on evidence from Mexico and Texas we suggested that the Chicxulub impact predates the K–T boundary. Impact-tsunami proponents have challenged this evidence largely on the basis that the stratigraphically lower spherule layer in Mexico represents slumps and widespread tectonic disturbance, although no such evidence has been presented. The decades-old controversy over the cause of the K–T mass extinction will never achieve consensus, but careful documentation of results that are reproducible and verifiable will uncover what really happened at the end of the Crectaceous. This study takes an important step in that direction by showing (1) that the stratigraphically older spherule layer from El Peñon, NE Mexico, represents the primary Chicxulub impact spherule ejecta in tectonically undisturbed sediments and (2) that this impact caused no species extinctions.

Of the five major mass extinctions in Earth's history, only the Cretaceous–Tertiary (K–T) mass extinction has been positively linked to an asteroid impact, based primarily on the presence of a global iridium anomaly coincident with the mass extinction of planktic foraminifers (Alvarez *et al*. 1980), the discovery of the Chicxulub crater in northern Yucatan (Hildebrand *et al*. 1991) and impact glass spherules at the base of a sandstone complex below the K–T boundary in NE Mexico (Smit *et al*. 1992; Stinnesbeck *et al.* 1993). Nevertheless, the cause for this mass extinction has remained contentious, mainly because stratigraphic data from NE Mexico, the Chicxulub crater on Yucatan and Texas indicate that the Chicxulub impact predates the K–T boundary by about 300 ka (Keller *et al*. 2003, 2004*a*,*b*, 2007).

Chicxulub impact spherules were originally discovered at the base of a thick sandstone complex, which infills submarine channels below the K–T boundary and Ir anomaly at El Mimbral in NE Mexico. To tie the widely separated Ir anomaly to the Chicxulub impact spherule layer, the intervening sandstone complex was attributed to an impact-generated tsunami (Smit *et al*. 1992, 1996; Smit 1999). In this scenario, the spherules rained from the sky within hours of the impact, followed by the tsunami waves, and the iridium settled during the subsequent weeks. This scenario became popular, but several problems arose from the very beginning.

For example, (1) at El Mimbral, El Peñon and other sections the impact spherules at the base of the sandstone complex are separated by a 15–20 cm thick limestone with occasional burrows that are infilled with spherules (Keller *et al*. 1997, 2003). This indicates that spherule deposition occurred in two phases separated by the considerable time it took to form the limestone layer. (2) The spherule layers contain a matrix of clastic grains, shallow-water foraminifers, plants and wood debris, which indicate erosion and transport from nearshore areas some time after the initial spherule deposition (Keller *et al*. 1994*a*,*b*; Alegret *et al*. 2001). (3) Several burrowed horizons were discovered in the fine-grained layers of the upper part of the sandstone complex, which indicate repeated colonization of the sea floor during deposition (Ekdale & Stinnesbeck 1998). (4) Mineralogical analysis revealed two zeolite-enriched layers that can be correlated throughout NE Mexico and indicate times of volcanic influx (Adatte *et al*. 1996).

Each of these discoveries reveals long-term deposition that is inconsistent with a tsunami interpretation. Adatte *et al*. (1996) and Stinnesbeck *et al*. (1996) proposed deposition during a sea-level lowstand with erosion from nearshore areas and transport into deeper waters via submarine channels along with occasional gravity slumps along the slope of the Gulf of Mexico (see recent reviews by Keller 2005, 2008*a*,*b*). Although the controversy over impact-generated deposits v. long-term deposition is still continuing, the evidence listed above in favour of long-term deposition and a pre-K–T age for the Chicxulub impact remains solid and has gained strong additional support from K–T sequences along the Brazos River in Texas (Yancey 1996; Gale 2006; Keller *et al*. 2007, 2008*a*, 2009). Opponents have argued that the Chicxulub impact marks the K–T boundary, which therefore must be placed coincident with the spherules at the base of the sandstone complex (Arenillas *et al*. 2006; Smit *et al*. 2004; Schulte *et al*. 2006, 2008). This is an ideological argument that also results in circular reasoning: Chicxulub is K–T age, therefore impact spherules define the K–T boundary (see Keller *et al*. 2008*a*). None of the impact-independent K–T defining criteria (e.g. mass extinction, evolution of first Danian species, $\delta^{13}C$ shift, boundary clay) or even the iridium and other PGE anomalies are present at the base of the sandstone complex (see review by Keller 2008*a*).

The evidence for long-term deposition of the sandstone complex in Mexico and Texas implied that the original Chicxulub impact spherule layer should be present in older marine sediments and that the spherule layers at the base of the sandstone are the results of subsequent reworking and redeposition. After an intensive search below the sandstone complex throughout northeastern Mexico, numerous outcrops were found with impact spherule layers in planktic foraminiferal zone CF1 (range of *Plummerita hantkeninoides*, Pardo *et al*. 1996), which spans the last 300 ka of the Maastrichtian. The most significant of these are at Mesa Juan Perez, Loma Cerca and El Peñon, where 1–2 m thick spherule layers were discovered in upper Maastrichtian sediments at 2 m, 9 m and 4 m below the sandstone complex, respectively (Keller *et al*. 2002, 2003, 2009; Schulte *et al*. 2003; Keller 2008*a*). Some workers interpreted this stratigraphically older spherule layer as slump, citing a small (60 cm) fold within the reworked spherule layer near the base of the sandstone complex at Loma Cerca (Soria *et al*. 2001; Schulte *et al*. 2003; but see Keller & Stinnesbeck 2002). The recent discovery in Texas of an older, primary Chicxulub spherule layer (now altered to cheto smectite) below the sandstone complex with up to three reworked spherule layers has lent new support to the hypothesis that the Chicxulub impact predates the K–T mass extinction (Keller *et al*. 2007, 2008*a*, 2009).

The controversy over the cause of the end-Cretaceous mass extinction has raged on for nearly three decades, supported by the popular consensus that the Chicxulub impact caused the mass extinction. Any evidence to the contrary is generally greeted with disbelief, citing the lack of consensus. However, any decades-old controversy will never achieve consensus, nor is consensus a precondition to advance science and unravel truth. What is necessary is careful documentation of results that are reproducible and verifiable. However, convincing scientists that a long-held belief in the impact theory is wrong will demand extraordinary documentation of verifiable evidence.

This study takes an important step in that direction by presenting new outcrops from the Maastrichtian below the sandstone complex along the hillside of El Peñon where we detail the physical stratigraphy, outcrop architecture and faunal turnover across the stratigraphically oldest Chicxulub spherule layer. Specifically, we (1) document the stratigraphy and lateral extent of the spherule layer that is 4–5 m below the sandstone complex; (2) detail the physical characteristics of the Chicxulub spherule deposit and contrast these with the reworked spherule layers at the base of the sandstone complex; (3) correlate El Peñon with the Loma Cerca and Mesa Juan Perez sections; (4) evaluate the biotic effects of the Chicxulub impact only *c*. 600 km from the impact crater on Yucatan based on planktic foraminifers; if this impact was as destructive as commonly assumed (i.e. caused the K–T mass extinction), then biotic effects in such close proximity should have been catastrophic; (5) for comparison, we illustrate the K–T faunal turnover and mass extinction at the stratigraphically higher La Parida and La Sierrita sections. Planktic foraminifers are highly sensitive to environmental changes and the only group for which about two-thirds of the species were extinct by the K–T boundary, with all but one of the remaining species disappearing within the first 200 ka of the Danian.

Location and palaeogeographical setting

El Peñon is located 40 km east of Linares, Nuevo Leon (24°58'N, 99°12.5'W, Fig. 1). At this locality, as elsewhere throughout northeastern Mexico, upper Maastrichtian marls of the Mendez Formation form low-lying hills, which are capped by a thick sandstone complex with reworked Chicxulub impact spherules at the base (see reviews by Smit 1999; Keller *et al*. 2003; Keller 2008*a*,*b*). In this study we concentrate on El Peñon and localities between 25 and 35 km to the NW, including La Parida, Loma Cerca, La Sierrita and Mesa Juan Perez (Fig. 1). The sandstone complex generally forms lenticular bodies that infill scoured submarine channels, and the K–T interval and younger sediments are eroded, except at La Parida and La Sierrita. To the south El Mulato, La Lajilla and El Mimbral also preserve good K–T intervals (Keller *et al*. 1994*b*, 1997; Lopez-Oliva & Keller 1996; Alegret *et al*. 2001). For this study we illustrate the K–T sequences at La Parida and La Sierrita. La Parida is located near the hamlet of La Parida *c*. 25 km NW of El Peñon (25°12.5'N, 99°31.1'W). About 100 m north of La Parida creek, the sandstone complex is 80 cm thick, and it thins out to the west over a distance of 50 m and disappears leaving a

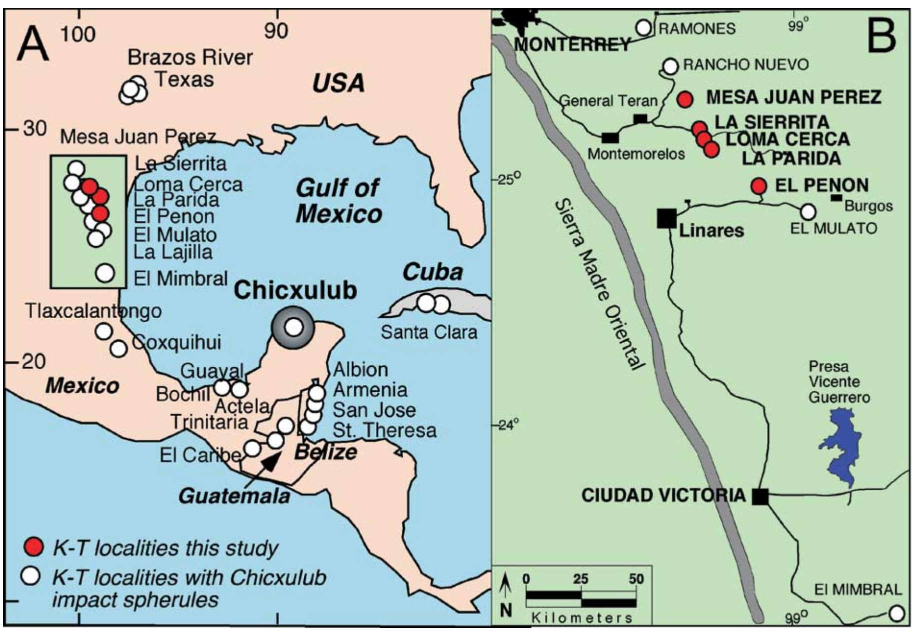

Fig. 1. (**a**) Location of localities studied that contain Chicxulub impact ejecta in Mexico, Guatemala, Belize, Cuba and Texas. (**b**) Locations of NE Mexico sections discussed in this study.

conformable contact between the Maastrichtian Mendez and Tertiary Velasco Formations (Stinnesbeck *et al*. 1996). Similarly, the La Sierrita section located 5 km south of La Parida is about 20 m beyond the channel infilling sandstone complex.

Upper Maastrichtian sediments in the El Peñon to Mesa Juan Perez area were deposited at >500 m depth (Alegret *et al*. 2001) along the continental slope of the Gulf of NE Mexico, which was cut by numerous submarine channels related to the uplift of the Sierra Madre Oriental (Galloway *et al*. 1991; Sohl *et al*. 1991). Sediments eroded from the Sierra Madre Oriental and nearshore areas around the Gulf of Mexico were deposited into these submarine channels, forming the lenticular bodies of the sandstone complex that are commonly found in NE Mexico. Deposition occurred during the latest Maastrichtian sea-level lowstand, which exposed nearshore areas to erosion and seaward transport into deeper waters (Adatte *et al*. 1996; Keller *et al*. 2003). The K–T boundary event occurred during the subsequent sea-level rise and is characterized by the mass extinction of tropical planktic foraminifers, the immediate first appearance of Danian species, and iridium anomaly, brown–red clay layer and ^{13}C shift (for recent review see Keller 2008*a*).

Methods

The classic El Peñon outcrop with the sandstone complex, labelled El Peñon 1 in this study, was first described in the field guide by Keller *et al*. (1994*a*; see also Smit *et al*. 1996; Stinnesbeck *et al*. 1996; Keller *et al*. 1997). At El Peñon 1 only about 1 m of the underlying marls is accessible by excavation and we sampled it at 10 cm intervals. About 80 m SW along the hillside, a 40–80 cm deep trench was dug from below the base of the sandstone complex to 9 m down the hillside, to clear debris and expose fresh rocks. A 2 m thick Chicxulub impact spherule layer was discovered about 4 m below the sandstone complex. This locality is labelled El Peñon 1B (Fig. 2). Subsequent fieldwork traced this spherule layer intermittently and with variable thickness over 50 m towards the El Peñon 1 outcrop. About 5–10 m from its disappearance we collected a sequence of horizontally bedded upper Maastrichtian marls (labelled El Peñon 1A, Fig. 2). At all three localities (El Peñon-1, 1A, 1B) sediments were examined for changes in lithology, bedding, bioturbation, structural disturbance and slumping. Samples were collected at an average of 15–20 cm intervals, and at 10 cm

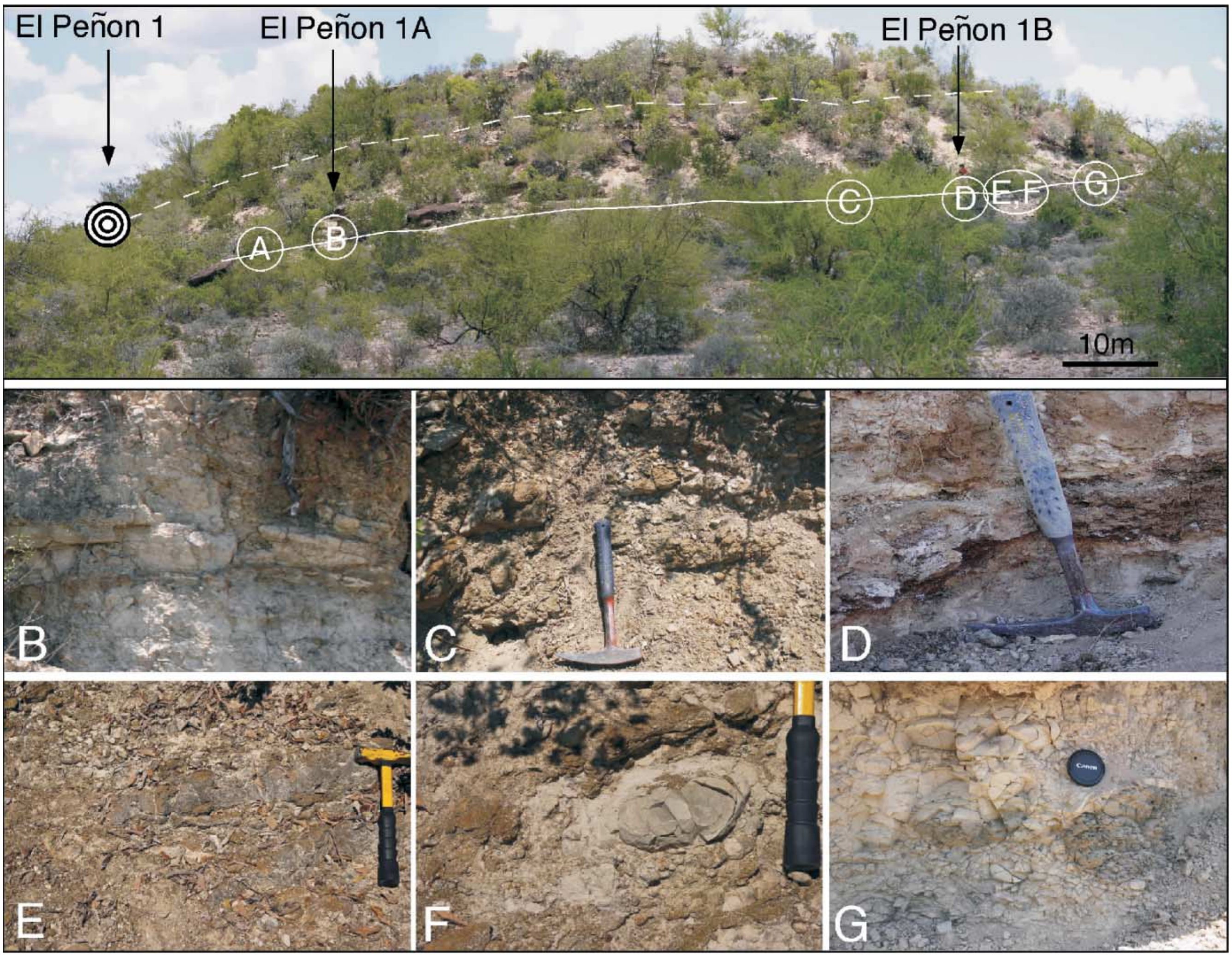

Fig. 2. El Peñon hill showing the base of the sandstone complex with reworked spherules (dashed line) dipping to the NE where the classic El Peñon 1 outcrop is located (circle). Parallel to the sandstone complex and 4–5 m below is the primary Chicxulub impact spherule ejecta layer (continuous line) interbedded in late Maastrichtian marls. Locations B–F mark exposures of the spherule layer, F and G show large clasts. Location A marks horizontally bedded marls above the primary spherule layer.

intervals above and below the 2 m thick spherule layer El Peñon 1B. Loma Cerca and Mesa Juan Perez sections were also sampled at 15–20 cm intervals. At La Sierrita and La Parida, samples were collected across the K–T boundary at 5 cm and 10 cm intervals.

Planktic foraminifers were processed by standard methods (Keller *et al*. 1995) and analysed quantitatively for small and large size fractions (38–63 μm, 63–150 μm, >150 μm) for El Peñon and >63 μm for Mesa Juan Perez. Quantitative counts were based on 300 specimens. All specimens were picked, mounted on microslides for a permanent record, and identified. The remaining sample residues were searched for rare species, which were included in the species census data. The planktic foraminiferal fauna is very rich and abundant at El Peñon and NE Mexico in general. Preservation is good, but calcite shells are recrystallized and therefore not useful for stable isotope analysis.

Lithostratigraphy of El Peñon

El Peñon consists of a series of low-lying hills that are topped by the sandstone complex (Fig. 1; Keller *et al*. 1997). The main hill is about 200 m long and strata dip 8° to the NE. The classic El Peñon 1 outcrop is located near the northeastern end where the sandstone complex overlies ground level (Fig. 2). In the up-dip direction to the SW, late Maastrichtian sediments are exposed beneath the sandstone complex (dashed line in Fig. 2). However, exposure is poor because the hillside is overgrown by cacti and shrubs, and strewn by large blocks and debris from the collapsing sandstone complex. Nevertheless, exposures of the Mendez marl Formation can be observed intermittently, including a spherule layer 4 to 5 m below the sandstone complex (continuous line, Fig. 2). This spherule layer was observed at five locations (B–F) and is of variable thickness ranging from a few centimetres to 2 m and absent in some intervals (A, G, Fig. 2). Vegetation cover and landslides prevent continuous tracing. Over about 80 m all exposures are at a constant 4–5 m below and parallel to the sandstone complex (continuous line, Fig. 2). No slumps or significant faults were observed, although recent rock slides from the overlying sandstone complex are common. The stratigraphic continuity and absence of slump features demonstrates that the spherule layer within the late Maastrichtian marls cannot be interpreted as the result of slumped sediments from the spherule layer at the base of the sandstone complex. Such an interpretation requires the sandstone complex to be part of the ‘slump’.

El Peñon 1

The classic outcrop at El Peñon 1 is most notable for its *c*. 8 m thick sandstone complex, which has been described previously (Keller *et al*. 1994*a*,*b*, 1997, 2003; Smit *et al*. 1996; Stinnesbeck *et al*. 1996). The lithology consists of three main units (Fig. 3). At the base, unit 1 is about 1 m thick and consists of the impact spherule layers separated by a 20 cm thick sandy limestone with occasional J-shaped and spherule-filled burrows that are truncated by erosion. In the middle, unit 2 consists of a 4–5 m thick massive sandstone with several disconformities and also occasional truncated J-shaped and spherule-filled burrows near the base. At the top, unit 3 consists of 2–3 m of alternating sand and laminated fine silt or shale layers that are burrowed by *Chondrites*, *Thalassinoides*, and *Zoophycos* (Keller *et al*. 1997, 2003; Ekdale & Stinnesbeck 1998). Two zeolite-enriched (volcanic) layers are present and can be correlated throughout NE Mexico (Adatte *et al*. 1996). These characteristics indicate times of

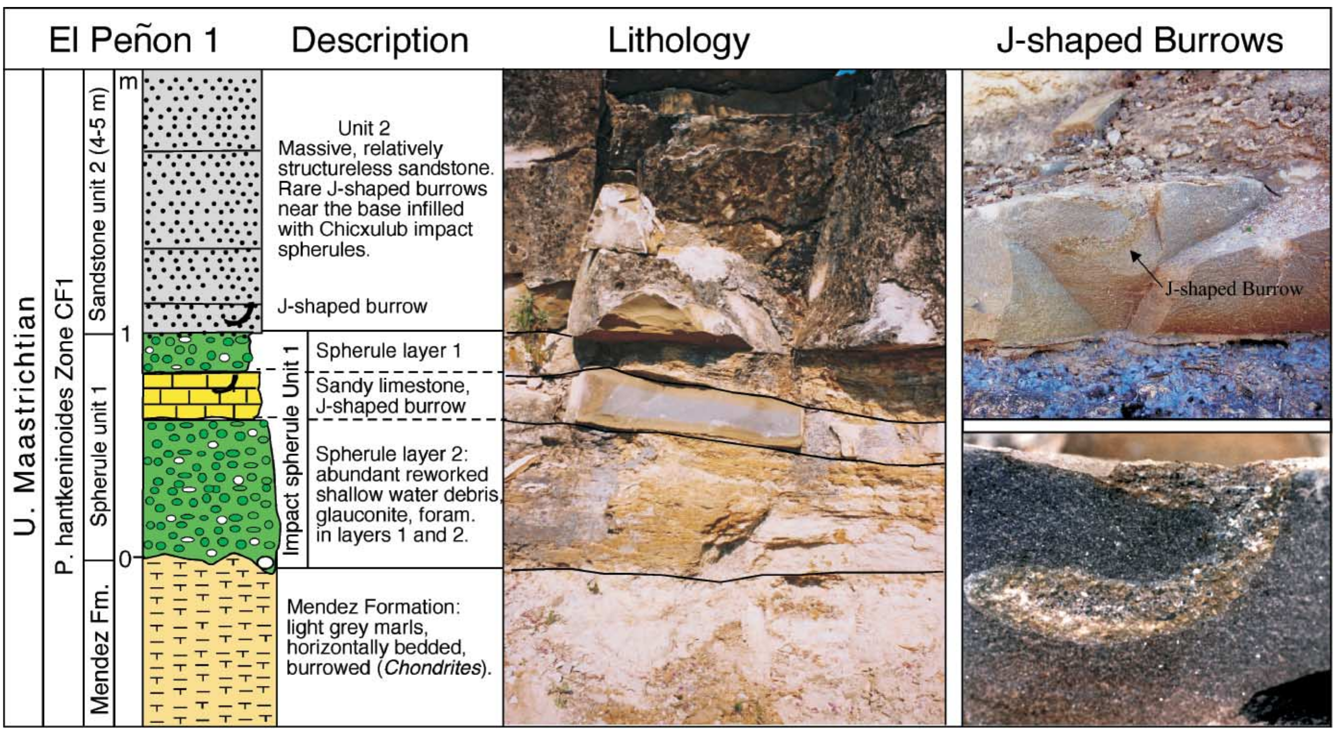

Fig. 3. The classic El Peñon 1 outcrop showing the reworked spherule-rich unit 1 at the base of the sandstone complex with two spherule layers separated by a sandy limestone layer. J-shaped burrows infilled with spherules and truncated at the top are present in this limestone layer and near the base of the sandstone unit 2. This marks two spherule depositional events separated by the considerable time it took to form the limestone layer.

volcanic influx and normal sedimentation with the ocean floor colonized by invertebrates alternating with times of rapid influx of sand (coarse-grained layers devoid of fossils).

Originally, the sandstone complex was interpreted as the Chicxulub impact-generated mega-tsunami deposit on the basis of the spherule unit 1 at the base and an Ir anomaly at the top at El Mimbral (e.g. Smit *et al*. 1992, 1996; Smit 1999). This view is still prevalent, but difficult to maintain given the sedimentary characteristics, trace fossils and zeolite layers of the sandstone complex, all of which reflect long-term deposition in a slope environment where rapid influx of clastic material (gravity flows, slumps) alternated with periods of normal sedimentation during the latest Maastrichtian sea-level fall (Adatte *et al*. 1996; Keller & Stinnesbeck 1996).

El Peñon 1A

El Peñon 1A has two outcrops, labelled A and B (Fig. 2), which are 10 m apart and about 20 m and 30 m from El Peñon 1, respectively. These two outcrops combined have good exposures of Late Maastrichtian marls of the Mendez Formation and the interbedded spherule layer (Fig. 2, outcrops A and B). In outcrop A exposure of the marl sequence between the sandstone complex and spherule layer is about 3.5 m. Vegetation and a recent rockslide obscure the uppermost metre and grading for road access covers the the lower part. The exposed part of the sequence clearly shows horizontally bedded marls and two marly limestone layers parallel to the sandstone complex at the top of the hill (Fig. 4). There is no evidence of structural disturbance or slumping. *Chondrites* burrows are common throughout the marl and marly limestone sequence and attest to normal marine deposition. Two thin (*c*. 1 cm) rust-coloured layers are present 40 cm apart (Fig. 4, layers B and C). Each layer overlies a strongly burrowed omission surface, which represents an interval of highly condensed sedimentation.

Rust-coloured layer B (sample Pe-11, Table 1) is mineralogically very similar to the marls above and below, which also contain unusually high iron hydroxide (goethite) contents. This layer represents a hardground with reduced sedimentation. Rust-coloured layer C differs from the marls by very high plagioclase (33%) and significant smectite and zeolite contents, but lower phyllosilicate contents. This mineralogical composition suggests a volcaniclastic origin. Such bentonite layers are commonly found in the Maastrichtian Mendez Formation of NE Mexico, including in the sandstone complex (Adatte *et al*. 1996).

The second El Peñon 1A outcrop (exposure B, Fig. 2) is less than 10 m from the marl sequence A, and reveals a 40 cm thick spherule layer exposed over 5 m (Fig. 5). The continuation of this spherule layer to the left is obscured by a recent rockslide and to the right by vegetation. The exposed 5 m long spherule layer forms a coherent unit parallel to the sandstone complex that is 4–5 m above and is easily recognized in the field (Fig. 5, locations A–C). The lower 5–10 cm of the spherule unit consists of dense, resistant melt rock and spherules. There is no evidence of slumping or faulting.

Lithostratigraphy of the two El Peñon 1A outcrops thus reveals a normal depositional environment during the late Maastrichtian, including a hardground and volcaniclastic influx all parallel to the sandstone complex 4–5 m above. This rules out any interpretation that the spherule layer could be the result of chaotic

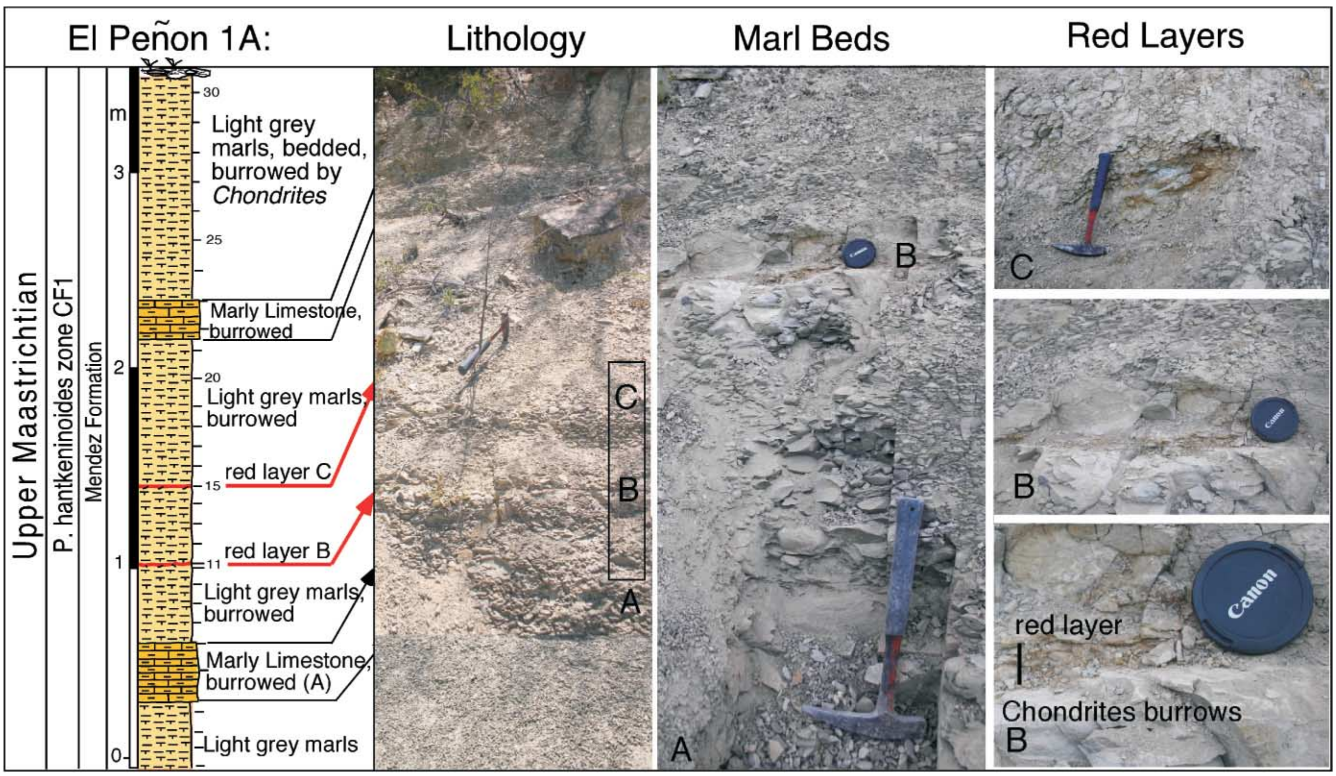

Fig. 4. Late Maastrichtian sequence at El Peñon 1A, exposed about 20 m from El Peñon 1, consists of horizontally bedded marl, two marly limestone layers (A) and two thin red layers (B and C). Red layer B marks condensed sedimentation; red layer C marks volcaniclastic influx. The stratigraphic layering is parallel to the overlying sandstone complex and shows normal marine sedimentation with abundant burrows. There is no evidence of tectonic disturbance.

Table 1. *Mineralogical data from the two red layers at El Peñon 1*A

Sample	Phyllosilicates	Quartz	K-feldspar	Plagioclase	Calcite	Goethite
Pe-9	22.53	21.61	0	7.34	48.52	0.00
Pe-10	22.58	23.59	0	6.17	47.67	0.00
Pe-11 (B)	27.97	25.60	0.00	2.89	36.78	6.76
Pe-12	20.89	13.87	0	4.79	60.45	0.00
Pe-13	23.48	19.45	0	6.65	50.43	0.00
Pe-14	27.56	20.99	0	4.52	46.94	0.00
Pe-15 (C)	14.78	17.47	0	33.56	34.19	0.00
Pe-16	21.30	17.75	0	4.43	56.52	0.00

slumping, tectonic disturbance, or tsunami deposition related to the Chicxulub impact. Deposition of marls and marly limestones occurred in a relatively deep (>500 m) upper slope environment inhabited by abundant *Chondrites*. Sedimentation was interrupted by rapid influx of spherules (Fig. 5), after which normal marl sedimentation resumed up to the hardground (rust-coloured layer B, Fig. 4). Above the hardground, normal marl sedimentation resumed, followed by volcaniclastic influx forming the second rust-coloured layer C.

El Peñon 1B

Between El Peñon 1A and 1B heavy vegetation and large boulders of the sandstone complex cover the upper Maastrichtian sequence (Fig. 2). Approximately 50 m from the El Peñon 1A outcrop we trenched the El Peñon 1B section (outcrop D in Fig. 2) to expose fresh rocks and examine the stratigraphic sequence (Fig. 6, layers A–C). Large blocks of the overlying sandstone complex cover the topmost 0.5–1.0 m. This interval was there-

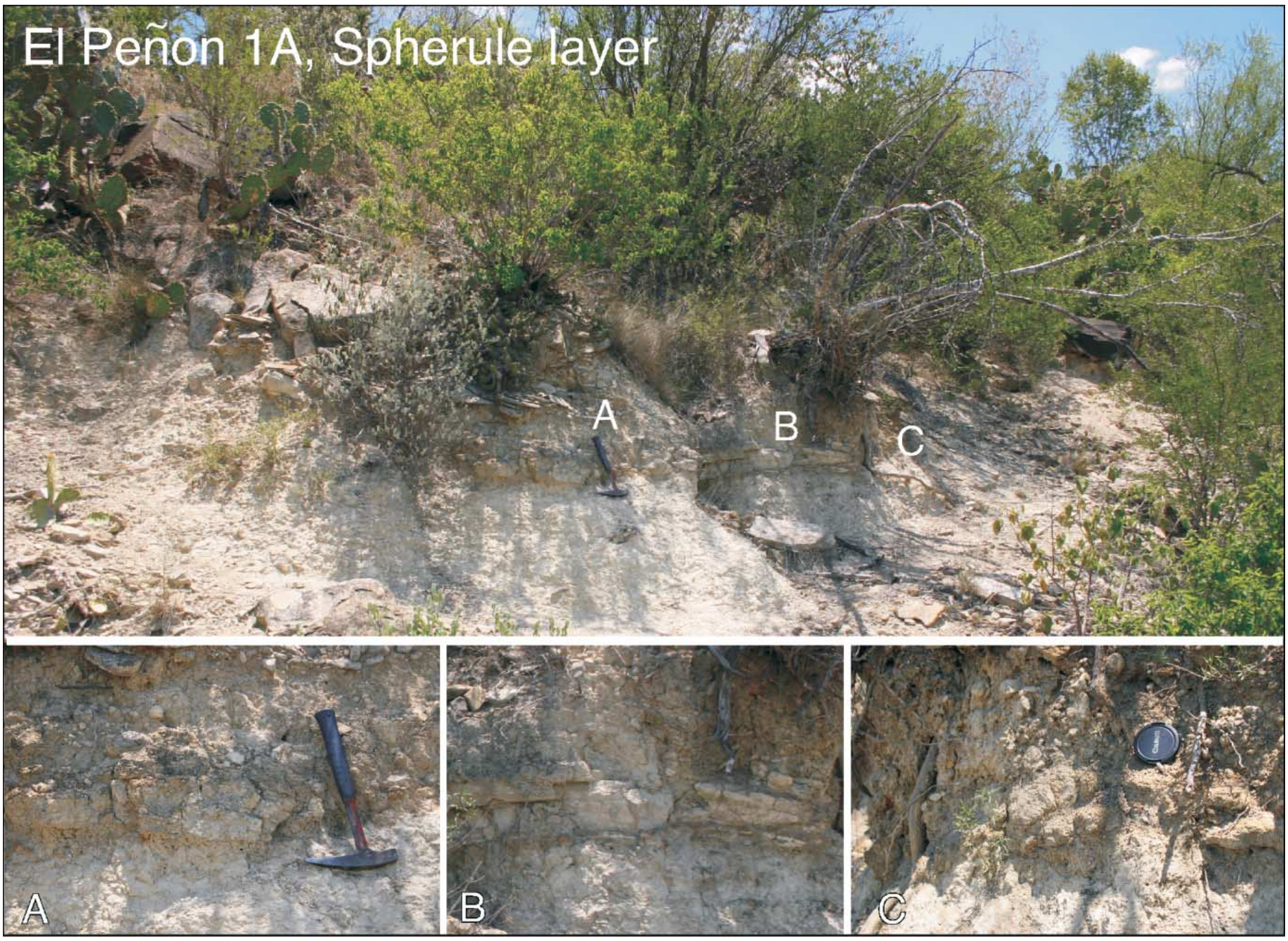

Fig. 5. El Peñon 1A spherule layer exposed over 5 m (locations A–C) about 10 m from the upper Maastrichtian marl and marly limestone sequence shown in Figure 4. The spherule layer is interbedded in the horizontally bedded marls and parallel to the sandstone complex 4–5 m above.

fore excavated below spherule unit 1 at El Peñon 1 (Fig. 3) and a composite sequence is shown in Figure 6. The trench exposed 4 m of horizontally bedded marls with two marly limestone layers marked by more resistant beds and higher calcite content (*c*. 60%), similar to El Peñon 1A. *Chondrites* burrows are common throughout the sequence. Spherule clasts are present about 1.1 m above the spherule layer. Bulk-rock composition of marls and marly limestones is in the range of 40–60% calcite, 15–20% quartz, *c*. 5% plagioclase and 20–35% phyllosilicates (Fig. 6).

A 2 m thick Chicxulub impact spherule unit was discovered between 4 and 6 m below the sandstone complex (Fig. 6, layer C). The spherule unit overlies an erosional surface with angular and rounded (2–5 cm, occasionally 10 cm) rip-up clasts from the underlying marls. The rip-up clasts decrease in abundance and size upsection. Four layers with upward decreasing spherule abundance make up the spherule unit. More densely packed impact glass at the base of each layer forms more resistant beds in outcrops (Fig. 6, layer B). Thin sections of these 5–10 cm thick resistant layers reveal impact melt glass and compressed or welded spherules with convex–concave contacts in a calcite matrix of 80–90% (Fig. 7). Foraminifers are absent, though rare foraminiferal shells can be seen encased in melt rock glass, as also observed in the late Maastrichtian spherule layer at Loma Cerca (Keller *et al*. 2002). In the upper parts of each layer spherules are generally isolated in a marly matrix (Fig. 8e and f) and decrease in abundance and size towards the top (Fig. 8c and d). Above the spherule unit, the contact to the overlying marls is gradational and diverse foraminiferal assemblages are present within bioturbated sediments (Fig. 8a and b). Marls below the spherule unit are similar to those above it, except for slightly higher quartz (25–30%), plagioclase (7%) and feldspar contents and lower calcite (Fig. 6). Platinum group element analysis (Ir, Pb, Pt, Ru, Rh) revealed no anomalous concentrations in the spherule layers or marls (Stüben *et al*. 2005).

Mineralogical values of the marls and abundant burrows thus reflect normal pelagic sedimentation above and below the 2 m thick impact spherule unit. The impact spherule unit differs from the reworked spherules at the base of the sandstone complex by distinct layers of welded glass, calcite cement, absence of detritus and, in the upper part, gradational contact with spherules in a marl matrix. These characteristics indicate marine sedimentation rather than slumps or chaotic deposition. The welded glass (Fig. 6, layer B and Fig. 7) suggests rapid deposition while still hot, possibly by accumulation as rafts on the sea surface before sinking rapidly. Absence of shallow-water debris and exotic lithologies indicate locally derived sediments, which strongly contrasts with the two reworked spherule layers at the base of the

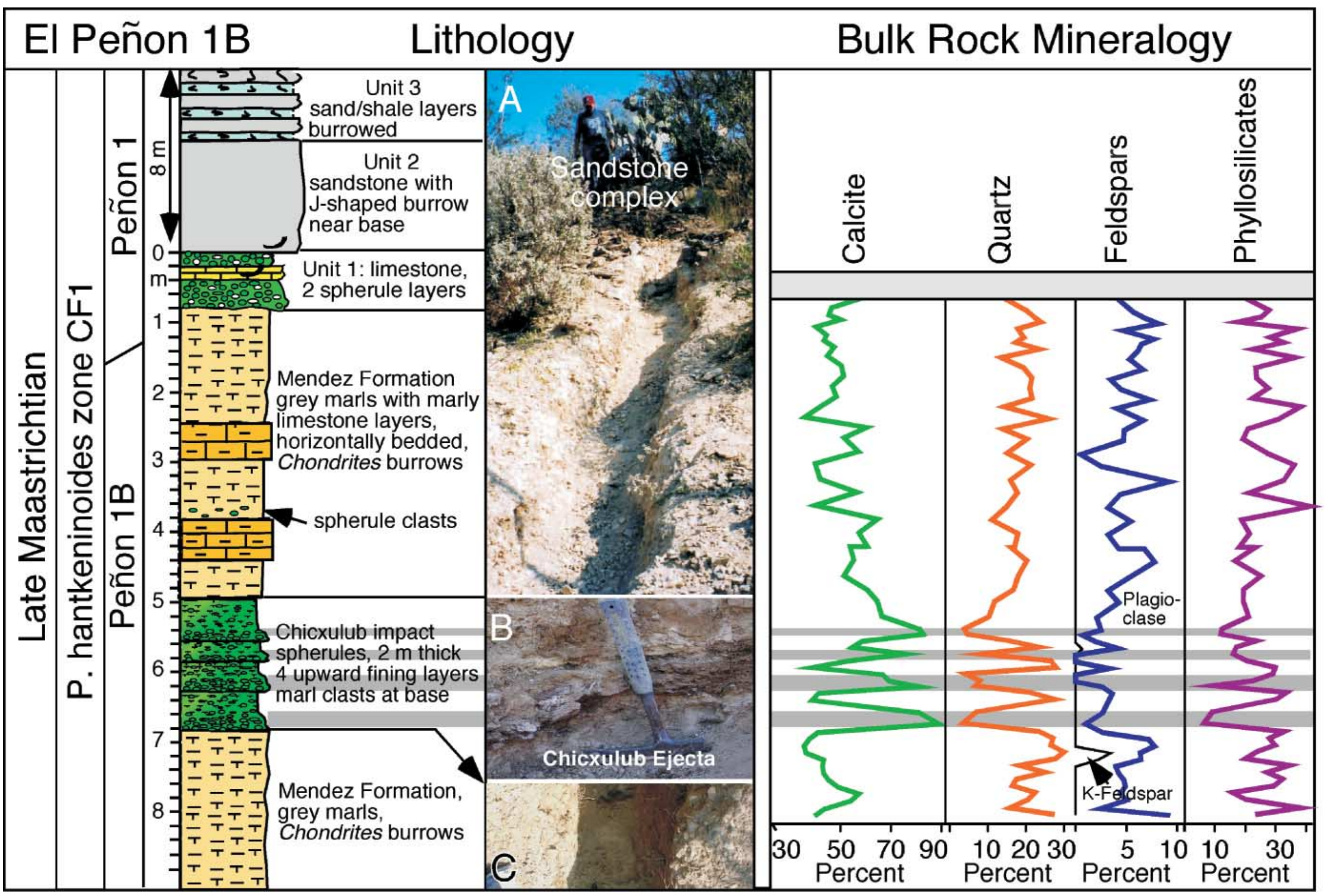

Fig. 6. Composite section of the sandstone complex at El Peñon 1 and underlying trenched sequence (layers A–C) at El Penon 1B about 80 m SW. El Peñon 1B consists of horizontally bedded marls and two marly limestone layers with a 2 m thick Chicxulub impact spherule unit (B) about 4 m below the reworked spherule layers at the base of the sandstone complex. The 2 m thick spherule unit consists of four upward fining layers with more resistant bases (B). Mineralogical composition reveals normal pelagic marl deposition with high calcite at the base of each layer and increasing marls and quartz in the upper parts.

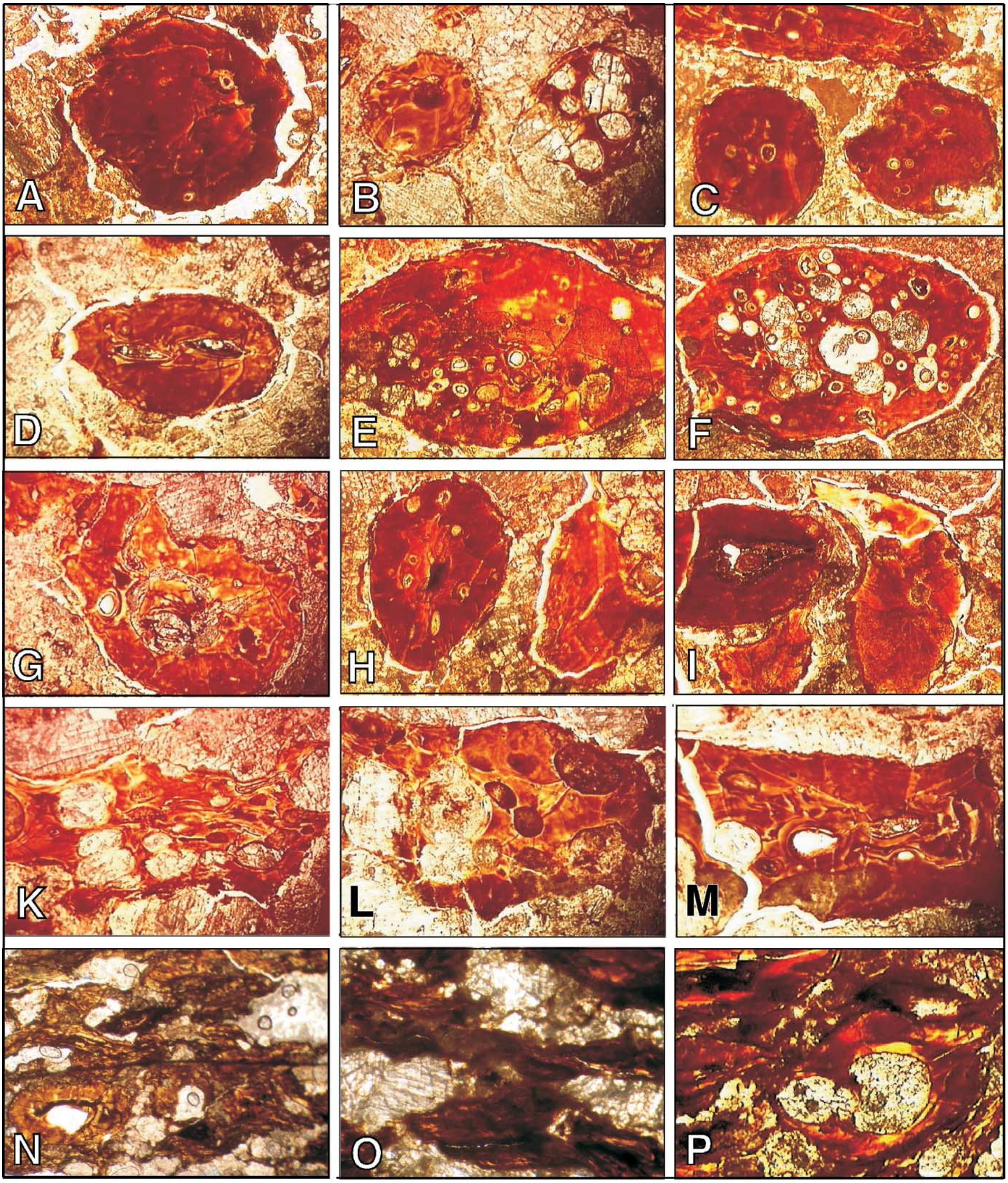

Fig. 7. Chicxulub impact spherules, glass shards and melt rock in a calcite matrix from the primary spherule deposit near the base of uppermost Maastrichtian zone CF1 at El Peñon 1B. Spherules range from 2 mm to 5 mm in size. (**a**–**c**) vesicular spherules; (**d**–**f**) compressed vesicular spherules; (**g**–**i**) dumbbell (**g**) and compressed vesicular spherules with concave–convex contact (**i**); (**k**–**m**) vesicular glass shards; (**n**, **o**) melt rock glass of welded, amalgamated spherules; original spherules can rarely be recognized (**n**). (**p**) foraminifer in melt rock. Deposition of the Chicxulub impact spherule layer occurred rapidly, possibly by raft-like accumulation of hot spherules at the sea surface and rapid sinking. This is suggested by the calcite matrix, compressed spherules, melt rock, and the absence of clastic grains, clasts or other reworked components.

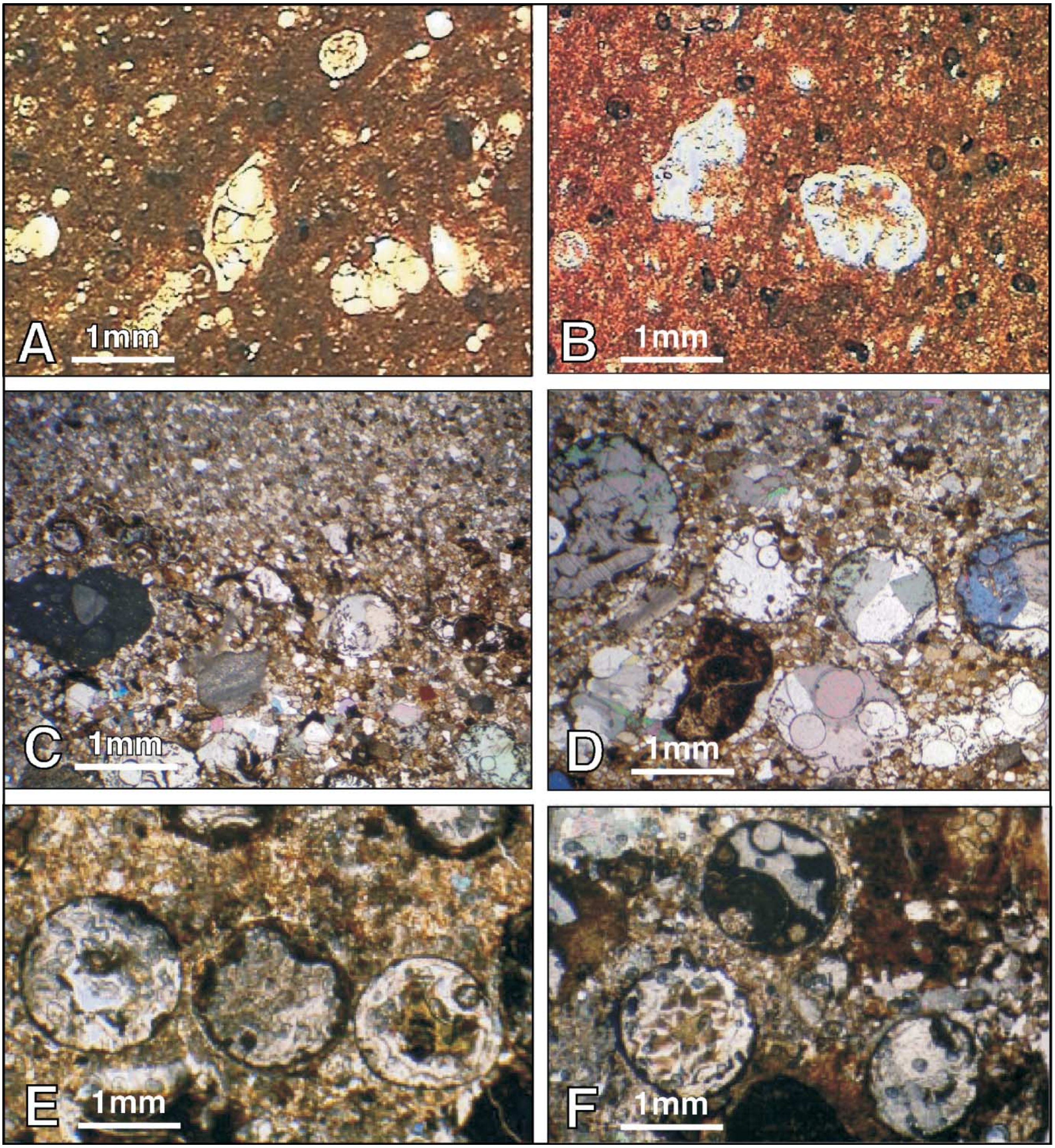

Fig. 8. Chicxulub impact spherules in marly matrix from the upper part of the primary impact spherule layer near the base of zone CF1 at El Peñon 1B. From bottom to top: (**e**, **f**) spherules in marly matrix; (**c**, **d**) gradational contact between spherules and overlying upper Maastrichtian marls; (**a**, **b**) upper Maastrichtian planktic foraminifers in marls above spherule layer; marls show the same mineralogical composition as in the marly matrix of the spherule unit.

sandstone complex (Keller *et al*. 1994*b*, 2003; Alegret *et al*. 2001). These characteristics suggest that the late Maastrichtian spherule unit represents the original Chicxulub impact ejecta layer. If this is correct, then the stratigraphic position near the base of zone CF1 records the time of the Chicxulub impact about 300 ka before the K–T mass extinction, as earlier documented from NE Mexico, the Chicxulub impact crater and Texas (Keller *et al*. 2003, 2004*a*,*b*, 2007).

The maximum lateral extent of the late Maastrichtian spherule layer at El Peñon is still unknown because of rockslides and vegetation cover. However, within about 10 m to the right of the trench, the spherule unit thins to about 25–40 cm and occasional large (10–15 cm) rounded marl clasts are surrounded by spherules (Fig. 2, outcrops E and F). At 20 m from the trench the spherule layer disappears, although occasional clasts are present (Fig. 2, outcrop G). To the left of the trench, the spherule unit remains >1 m thick for at least 10–20 m, as visible among the vegetation (Fig. 2, outcrop C).

Correlation of spherule layers

El Peñon 1

El Peñon 1 outcrops (A–G) reveal intermittent exposure of the late Maastrichtian spherule layer over a distance of about 80 m parallel to the sandstone complex that marks the top of the hill. The maximum lateral extent of this spherule layer is still unknown because of rockslides and vegetation cover. However, within about 10 m to the right of the trench (Fig. 2, outcrop D), the spherule unit thins to about 25–40 cm and occasional large (10–15 cm) rounded marl clasts are surrounded by spherules (Fig. 2, outcrops E and F). At 20 m from the trench the spherule layer disappears, though occasional clasts are present (Fig. 2, outcrop G). To the left of the trench, the spherule unit remains >1 m thick for at least 10–20 m, as visible among the vegetation (Fig. 2, outcrop C).

The stratigraphic sections at El Peñon 1A and 1B illustrate the similarity in marine sedimentation between the late Maastrichtian spherule layer and sandstone complex (Fig. 9). Above and below this spherule layer both sections consist of horizontally bedded light grey marls with abundant burrows (*Chondrites*). Two marly limestone layers (*c*. 20% higher calcite contents) are present, with the lower one 40–50 cm above the spherule layer and the second layer 1 m and 1.5 m above the first layer at El Peñon 1A and 1B, respectively. The two 1 cm thick rust-coloured layers of El Peñon 1A were not observed in El Peñon 1B. The lower rust-coloured layer is a hardground and may correspond to the spherule clasts in El Peñon 1B above the lower marly limestone. The shorter interval between the two marly limestone layers in El Peñon 1B and the spherule clasts suggests erosion. Above the upper marly limestone approximately the same marl intervals are exposed, with the uppermost part covered by large broken sandstone blocks and vegetation. In places where *in situ* sandstone could be accessed, rare spherules were observed. The massive sandstone unit is continuously present.

The major difference between El Peñon 1A and 1B is the thickness of the spherule layer, which is 2 m thick at El Peñon 1B and narrows to 1 m thick within 10–20 m and to 40 cm within 50 m (El Peñon 1A). Rapid narrowing is also observed within 20 m to the right (outcrops E, F and G, Fig. 2). This lenticular shape of the spherule layer is commonly observed throughout NE Mexico and marks deposition in submarine channels (Adatte *et al*. 1996; Keller *et al*. 2003; Schulte *et al*. 2003).

El Peñon 1 has excellent exposure of the sandstone complex with two spherule layers at the base, but only 1 m of the underlying marls is accessible near the ground level (Fig. 3). El Peñon 1 differs from 1A and 1B mainly by the two reworked spherule layers separated by a sandy limestone below the sandstone (Fig. 9). The reworked spherule layers narrow laterally

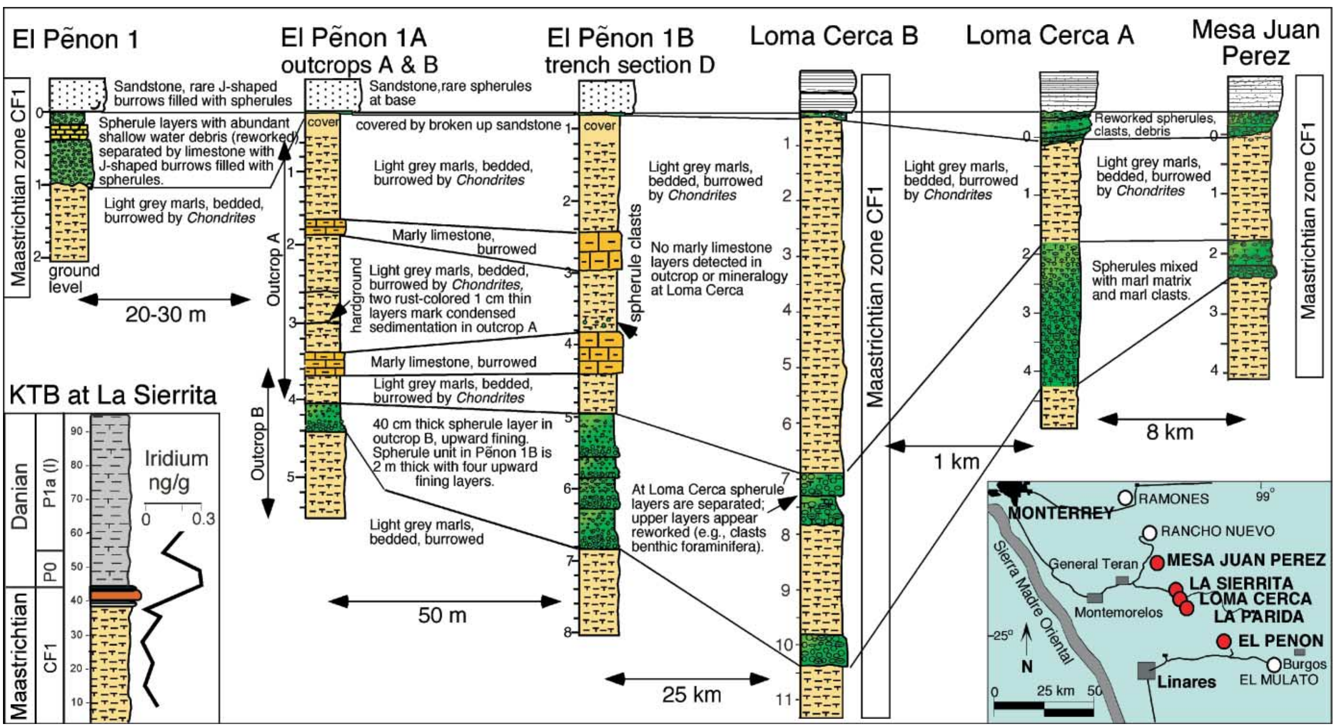

Fig. 9. Correlation of El Peñon 1 outcrops showing similar horizontal deposition of marls, marly limestone and primary impact spherule layer, which was deposited in a submarine channel centred at El Peñon 1B. El Peñon can be correlated to Loma Cerca and Mesa Juan Perez sections at 25 km and 35 km to the north, respectively. Variable erosion in submarine channels below the reworked spherule unit at the top accounts for the reduced marl layer at Loma Cerca A and Mesa Juan Perez. The K–T boundary is exposed at La Sierrita and contains no evidence of Chicxulub impact spherules.

and mark a channel deposit, similar to the lower spherule layer in El Peñon 1B *c*. 80 m distant.

Loma Cerca–Mesa Juan Perez

The spherule layer embedded in Maastrichtian marls at El Peñon is not an isolated occurrence; similar deposits have been documented in many outcrops through northeastern Mexico (Affolter 2000; Schilli 2000; Keller *et al*. 2002, 2003; Schulte *et al*. 2003). Here we show the correlation with Loma Cerca and Mesa Juan Perez sections between 25 and 35 km to the NW (Fig. 9). At Loma Cerca B, only a thin spherule layer is present at the base of the sandstone complex, whereas at Loma Cerca A and Mesa Juan Perez this spherule layer is 50 cm thick. Interbedded in late Maastrichtian marls at Loma Cerca B are two spherule layers at 6.5 and 10 m below the sandstone complex (Keller *et al*. 2002). We correlate these spherule layers to El Peñon 1B, but note that the upper layer (7.0–7.8 m) is probably reworked as suggested by peak abundance of benthic foraminifers (Keller *et al*. 2002). Another difference is the absence of marly limestone layers at this location, which is probably due to regional variations in calcite deposition. Loma Cerca A has a nearly 2.4 m thick deposit of spherules mixed with marl about 1.9 m below the reworked spherules at the base of the sandstone complex. At Mesa Juan Perez about 8 km to the north the late Maastrichtian spherule layer is about 70 cm thick and separated from the reworked spherule layer by about 1.8 m (Fig. 9). The reduced marl thickness, as compared with Loma Cerca B, is probably due to greater erosion and downcutting of the submarine channel at these locations.

Schulte *et al*. (2003) described five additional outcrops in the Mesa Juan Perez area over a lateral distance of about 250 m. At these locations, spherules are present in variable abundances ranging from a few centimetres to 1 m at the base of the sandstone complex and occasionally contain a sandy limestone layer, similar to El Peñon 1. Additional spherule deposits are observed in late Maastrichtian marls 2–3 m below. These spherule deposits are described as devoid of marl clasts, with sharp upper and lower contacts, but discontinuously exposed or ‘lens-like’. A small overturned fold (60 cm) with large marl clasts at the centre was observed in one section (see also Soria *et al*. 2001). Other outcrops reveal spherules distributions over 2 m dispersed within marls, similar to Loma Cerca A (Fig. 9; Schulte *et al*. 2003, p. 121, fig. 4).

Although Schulte’s analysis concentrated on the reworked spherule deposits at the base of the sandstone complex and did not differentiate between the two stratigraphically separated spherule layers, there are some similarities to our observations at El Peñon. For example, Schulte *et al*. (2003) noted that the spherule layer embedded in Maastrichtian marls contains no detritus, in contrast to the abundant shallow-water detritus in the spherule deposits at the base of the sandstone complex. This is consistent with our observations. Schulte *et al*. observed clusters of welded and amalgamated melt rock and clasts of spherules in a marl matrix in the reworked spherule layer. These clasts and clusters probably originated from erosion of the primary spherule layer interbedded in Maastrichtian marls where we observed distinct sublayers with welded, amalgamated melt rock (Fig. 7) and upward grading of spherules in marly matrix (Fig. 8).

Schulte *et al*. (2003) interpreted the spherule deposits at the base of the sandstone complex as the result of reworking, redeposition, slumps and turbidity currents with deposition in submarine channels. This is consistent with previous interpretations. In contrast, the spherule deposits in late Maastrichtian marls are explained as derived from these deposits via a complex interplay of slumps, folding and liquefaction that redistributed and embedded the spherules into the marls up to 6 m below. In view of the regional distribution and new data from El Peñon, including the strong differences in the composition of the spherule layers, this interpretation is very unlikely. More consistent with the data is the interpretation that the lower spherule layer is the original ejecta fallout and was subsequently reworked, with particularly strong reworking and redeposition from nearshore areas, at the base of the sandstone complex.

Biotic effects of the Chicxulub impact

El Peñon

Biostratigraphy places the spherule layers interbedded in marls at El Peñon, Loma Cerca and Mesa Juan Perez near the base of zone CF1, the range of *Plummerita hantkeninoides*, a species that evolved in magnetochron C29r about 300 ka earlier than the K–T boundary (Pardo *et al*. 1996; Keller *et al*. 2002, 2003). The same age for the Chicxulub impact spherules was determined from spherule deposits in Texas and from the Chicxulub crater on Yucatan (Keller *et al*. 2004*a*,*b*, 2007). The biotic effects of this impact can be evaluated based on species richness and the relative abundances of single species populations, two commonly used proxies to assess environmental changes. Both proxies were analysed at El Peñon in two size fractions to evaluate the response of small (63–150 μm) and larger (>150 μm) species. Larger species comprise a very diverse group of generally complex, ornamented and highly specialized *K*-strategists (Abramovich & Keller 2003; Abramovich *et al*. 2003) that thrived in tropical and subtropical environments, but were intolerant of environmental changes and hence prone to extinction (Begon *et al*. 1998; Keller & Pardo 2004; Keller & Abramovich 2009). All of these species (two-thirds of the species assemblage) went extinct at the K–T boundary. Small species are less diverse, ecologic generalists, or *r*-strategists, and generally more tolerant of environmental perturbations, including variations in temperature, salinity, oxygen and nutrients (Koutsoukos 1996; Keller 2001; Keller & Abramovich 2009). Some of these species responded to environmental catastrophes by opportunistic blooms, such as observed for *Heterohelix* and *Guembelitria* species (Pardo & Keller 2008).

A total of 52 species are present in the >150 μm size fraction at El Peñon during the late Maastrichtian. Of these 75% (39 species) are *K*-strategists and 25% (13 species) are *r*-strategists (Fig. 10). Across the Chicxulub impact spherule layer species richness remained unchanged: none of the 52 species extant below this level went extinct. About 2 m above the spherule layer is a gradual decrease to 42–44 species, rising slightly at the unconformity at the base of the sandstone complex as a result of reworking. The variability in species richness is due to the rare and sporadic occurrences of nine (*K*-strategy) species, or 17% of the total assemblage. Their increasingly rare and sporadic occurrences may be due to increasing biotic stress (no change was observed in preservation). Most species (83%) are continuously present. These data indicate that the species richness decrease cannot be assigned to the biotic effects of the Chicxulub impact because (1) it occurs much later, (2) the rare species are already endangered prior to deposition of the impact spherule layer, and (3) all rare species are known to have survived to the K–T boundary at the stratotype section in Tunisia and elsewhere (e.g. Keller *et al*. 2002; Luciani 2002; Molina *et al*. 2006; Keller *et al*. 2008*b*).

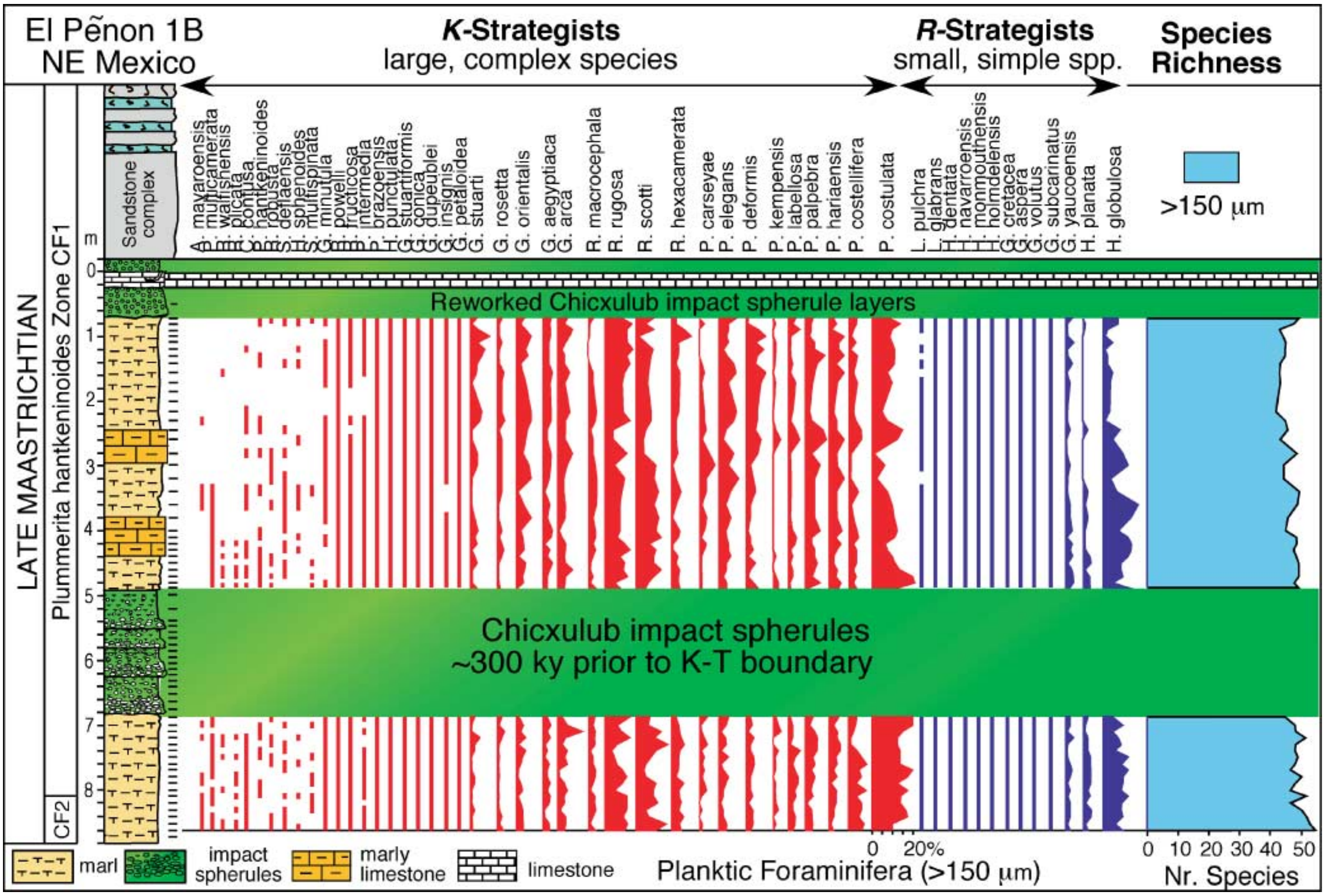

Fig. 10. Relative species abundances of planktic foraminifers (>150 μm) across the 2 m thick Chicxulub spherule unit near the base of the upper Maastrichtian zone CF1 at El Peñon 1B. No species went extinct and there are no significant species population changes as a result of this impact. Two spherule layers, separated by a burrowed limestone at the base of the sandstone complex, are reworked from shallow nearshore areas.

Relative abundance changes in single species populations are more sensitive indicators of environmental change than the presence or absence of species. During the late Maastrichtian, *K*-strategy species (>150 μm) show normal diversity and abundances. Nearly half of the *K*-strategists are common, with the assemblages dominated (10–20%) by *Pseudoguembelina costulata*, *Rugoglobigerina rugosa* and *R. scotti* (Fig. 10). Also common are pseudotextularids, other rugoglobigerinids and globotruncanids (e.g. *arca*, *aegyptiaca*, *rosetta*, *orientalis*, *stuarti*). Among *r*-strategists, the larger morphotype of *Heterohelix globulosa* is common in this assemblage. Relative species abundance variations above and below the spherule unit are within normal fluctuations of the section with no significant changes, except for a decrease in *H. globulosa* and increase in *Pseudotextularia deformis* and *Globotruncana stuarti* in the upper 2 m of the section. No specific biotic effects in *K*-strategists can be attributed to the Chicxulub impact.

Species richness in the smaller (63–150 μm) size fraction totals 39 species, of which 64% (25 species) are *K*-strategists and 36% (14 species) are *r*-strategists (Fig. 11). Similar to larger species, diversity remained unchanged across the spherule layer and throughout the section, with variability between 34 and 36 species, rising to 38 species at the unconformity at the base of the reworked spherule layers. Variability is due to five *K*-strategy species, which are rare and sporadically present.

Species abundances in the smaller size fraction (63–150 μm) are dominated by the small biserial *r*-strategist *Heterohelix navarroensis*, which varies between 40 and 50% across the spherule layer and decreases in the upper part to an average of 40% (Fig. 11). Other *r*-strategists vary between 5 and 15% and consist of small heterohelicids, globigerinellids, and hedbergellids. The disaster opportunist *Guembelitria* is a minor component (<5%). In the same size fraction, *K*-strategists are dominated by *Pseudoguembelina costulata* and *P. costellifera*. All other *K*-species are rare (<1%). There are no significant abundance variations across the spherule unit, except for *P. costellifera*, which decreases 8% concurrent with an increase in *H. navarroensis*. This may reflect a change in the watermass stratification, although whether this was related to the Chicxulub impact cannot be determined.

Mesa Juan Perez

Quantitative analysis of planktic foraminifers is generally carried out on the >63 μm size fraction, which consists mainly of the most common smaller and larger species (Fig. 12). This size fraction was earlier analysed at Loma Cerca (Keller *et al*. 2002) and now also at Mesa Juan Perez. Both sections show similar results, with a total of 41 species and species richness per sample varying between 30 and 39 species (Fig. 12). As at El Peñon the

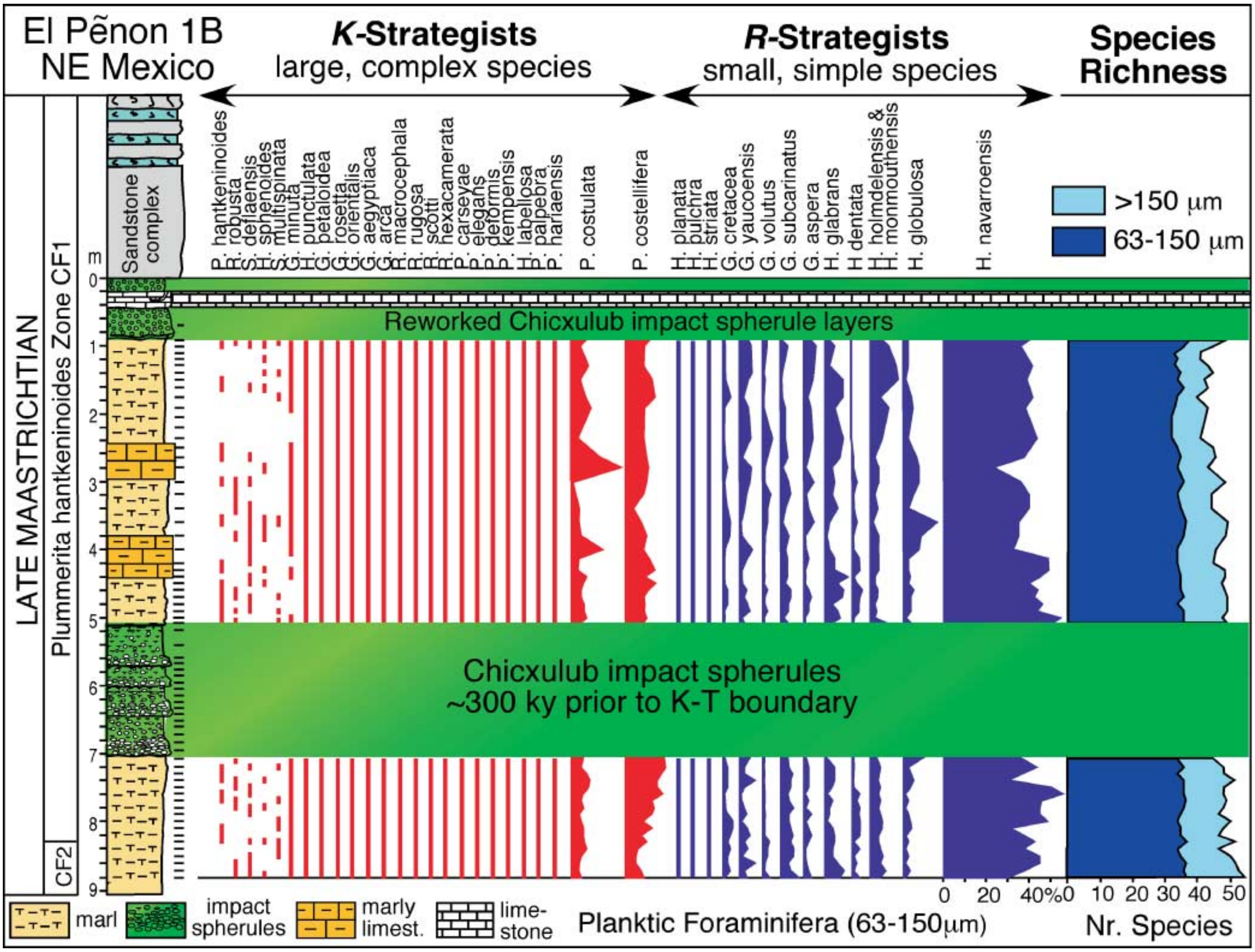

Fig. 11. Relative species abundances of planktic foraminifers (63–150 μm) across the 2 m thick Chicxulub spherule unit at El Peñon 1B. No species went extinct and there are no significant species population changes as a result of this impact. (See Fig. 10 for complete caption.)

variability is due to 17% rare and sporadically occurring species. Among small species heterohelicids (*r*-strategists) are common. Among larger species (*k*-strategists) rugoglobigerinids and pseudoguembelinids (*P. costulata*, *P. costellifera*) dominate (Fig. 12). No species extinctions occurred across the late Maastrichtian Chicxulub impact spherule layer and no significant variations are observed in species abundances at Mesa Juan Perez (Fig. 12). The same observations were earlier reported at Loma Cerca B (Keller *et al*. 2002, fig. 6, p. 151). The results from three sections are thus consistent and show no significant environmental changes or species extinctions at the time of the Chicxulub impact about 300 ka before the K–T mass extinction.

Biotic effects of the K–T boundary event

The K–T interval and younger sediments are eroded at El Peñon, as well as many other localities throughout NE Mexico where the sandstone complex forms flat-topped hills. However, the K–T boundary transition and Ir anomaly are present at several localities outside the submarine channels (e.g. El Mimbral, La Sierrita (Fig. 9), La Parida, El Mulato, La Lajilla, Lopez-Oliva & Keller 1996; Rocchia *et al*. 1996; Keller *et al*. 2003; Stüben *et al*. 2005). Several of these sections show a 5–10 cm thick Maastrichtian marl layer between the K–T boundary and remnant sandstone complex (Lopez-Oliva & Keller 1996). This suggests that the sandstone complex predates the K–T boundary, as recently observed along the Brazos River, Texas, where there is at least 0.8 m of Maastrichtian claystone between the top of the sandstone complex and the K–T boundary (Gale 2006; Keller *et al*. 2007). Schulte *et al*. (2006, 2008) reported this interval as 1.6 m thick in an old core, but argued that the reworked spherule layer at the base of the sandstone complex should define the K–T boundary (however, see Keller *et al*. 2009).

For this study we review the La Parida and La Sierrita sections, which show relatively complete K–T transitions (Fig. 1). At La Parida the sandstone complex is 80 cm thick and thins out to the west to a 5–10 cm thick sand layer over a distance of 50 m (Stinnesbeck *et al*. 1996). The section was sampled at the point where the sandstone layer is only 5 cm thick (Fig. 13). A 5–10 cm thick marl layer overlies the sandstone layer (Lopez-Oliva & Keller 1996). Marls below and above it contain uppermost Maastrichtian planktic foraminiferal assemblages indicative of zone CF1. The overlying grey shale contains early Danian assemblages characteristic of the lowermost Danian zone P1a (Subzone P1a(1), Fig. 14). The very thin zone P0 that marks the K–T clay or red layer was not observed at La Parida. Except for the boundary red clay, the K–T section appears continuous, as

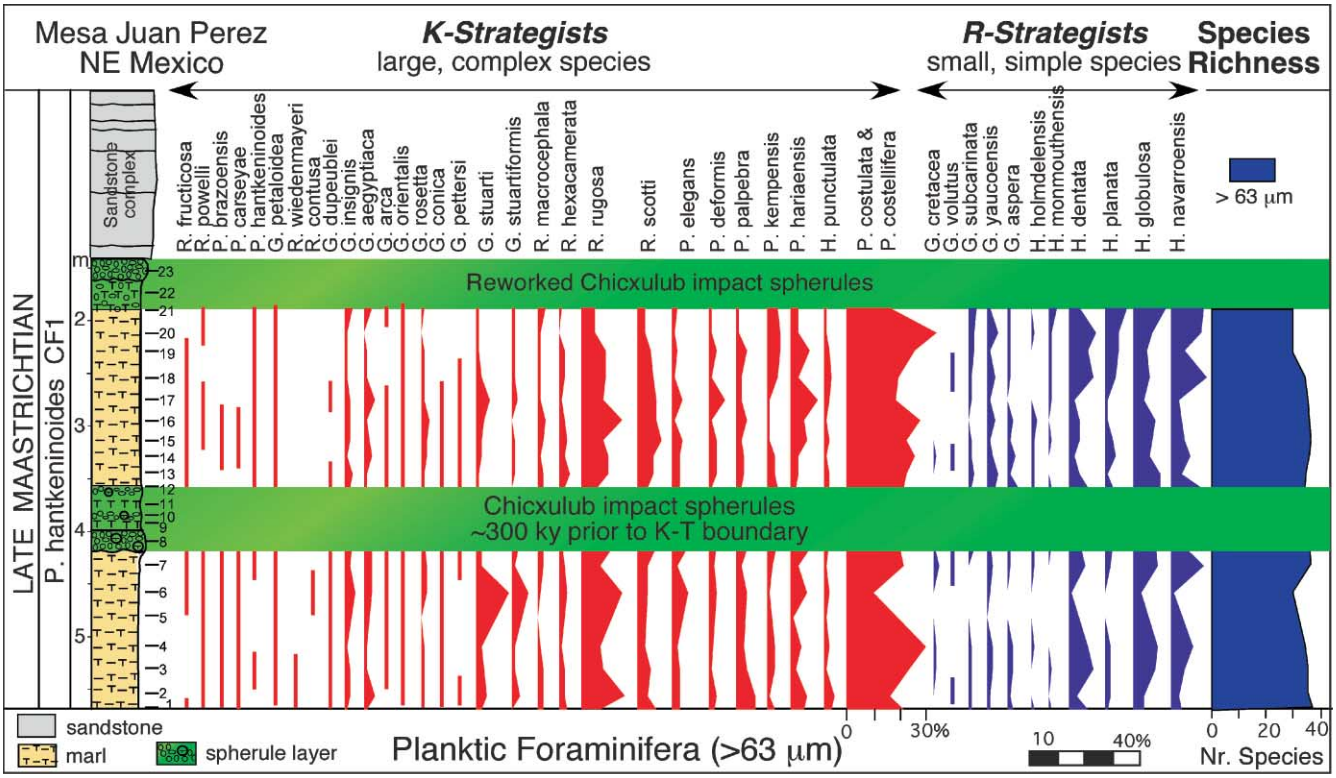

Fig. 12. Relative species abundances of planktic foraminifers (>63 μm) across the primary impact spherule layer at Mesa Juan Perez. No species went extinct and there are no significant species population changes as a result of this impact. Differences in the relative abundances of some species as compared with El Peñon 1B are due to the fact that the >63 μm size fraction analysed includes both large and small species, which were separately analysed for El Peñon 1B.

Fig. 13. La Parida outcrop showing the thin sandstone layer that underlies a 10 cm thick marl followed by Danian shale.

indicated by the abrupt dominance of the disaster opportunist *Guembelitria cretacea*, followed by abundant *Parvularugoglobigerina eugubina*. The biotic effects across the K–T event can thus be evaluated.

A total of 44 Cretaceous species were identified at La Parida and 31 (69%) went extinct at the K–T boundary, all of them specialized *K*-strategists (Fig. 14). The presence of most of these species in early Danian sediments is probably due to reworking. Ten of the species (22%), all *r*-strategists, are known to have survived the catastrophe for at least some time. One species, the disaster opportunist *Guembelitria cretacea*, thrived in the immediate aftermath of the catastrophe globally. The evolution of new species (*r*-strategists) began almost immediately after the mass extinction in zones P0 and P1a, although zone P0 is missing at La Parida. These mass extinction and evolution patterns are characteristic in planktic foraminifers throughout the Tethys, although species abundances may vary depending on regional conditions (Koutsoukos 1996; Luciani 2002; Keller & Pardo 2004; Molina *et al*. 2006; Fornaciari *et al*. 2007).

In the La Sierrita area sediments above the thick sandstone complex on the hills are eroded, but the K–T boundary can be recovered in the valleys between the hills. One such locality is La Sierrita A (also called Los dos Plebes, Stüben *et al*. 2005), located between Loma Cerca and Mesa Juan Perez (Fig. 9). Similar to La Parida, the sandstone complex thins out laterally over a distance of 20 m and disappears. This is where the K–T boundary can be recovered, including the thin brown–red clay layer, small Ir anomaly (0.3 ppb) and δ^{13}C shift (Stüben *et al*. 2005) that marks the K–T boundary along with the mass extinction of Cretaceous species and evolution of early Danian

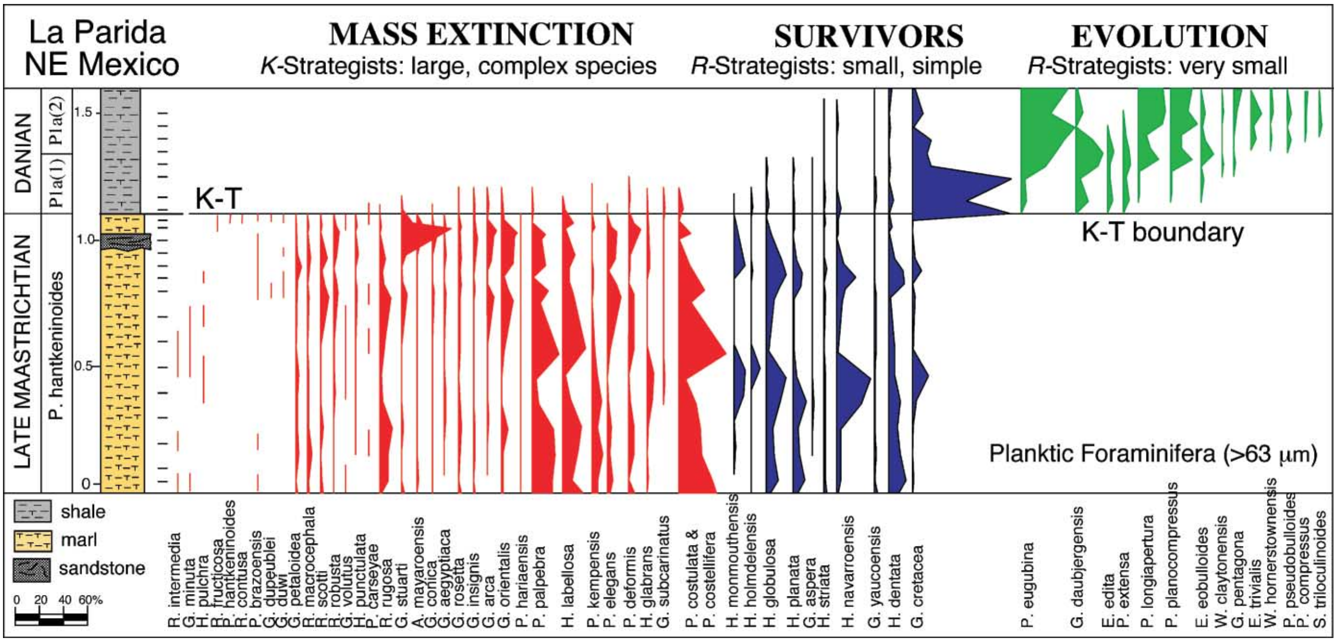

Fig. 14. The K–T mass extinction at La Parida shows two-thirds of the species extinct, all of them *K*-strategists, similar to the mass extinction pattern globally. A 10 cm thick Maastrichtian marl above the sandstone layer indicates that the top of the sandstone is not synchronous with the K–T boundary. The absence of the boundary clay suggests a short hiatus or condensed interval. The presence of many Cretaceous species above the K–T boundary is probably due to reworking.

species (Figs 15 and 16). There is no evidence of Chicxulub impact spherules. The first *Parvularugoglobigerina eugubina*, index species of zone P1a, were found 10 cm above the K–T boundary. Marls below the sandstone contain zone CF1 assemblages.

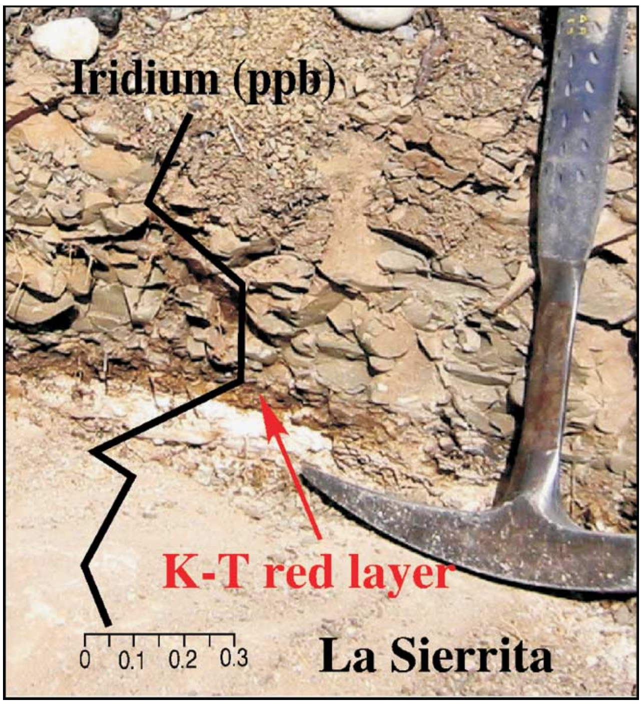

Fig. 15. K–T boundary at La Sierrita shows the characteristic K–T clay and red–brown layer with an Ir anomaly that marks the most continuous sections worldwide.

Discussion

Dating two closely spaced events, such as the Chicxulub impact and the K–T mass extinction, requires high sediment accumulation rates that physically separate the events in space and time. Continental shelves and upper slopes provide such environments because of their high biological productivity coupled with high terrigenous influx. The K–T sections in NE Mexico are excellent. Located on the outer continental shelf to upper slope of the Gulf of Mexico they provide expanded sedimentation records, including the sandstone complex of the submarine channels and thick Chicxulub spherule units at 4–5 m below in undisturbed sediments at El Peñon 1A and 1B, as well as at Loma Cerca and Mesa Juan Perez (Fig. 1). Such temporal and spatial separation between the K–T and Chicxulub events is difficult to observe in deep-sea environments because of the highly reduced sedimentation rate coupled with periods of intensified bottom current activity leading to erosion of older sediments and redeposition. As a result, Chicxulub spherules in deep-sea sites (e.g. Blake Nose, Demarara Rise) tend to be in disturbed sediments, but close to the K–T boundary, which has been interpreted as evidence in support of the K–T age for this impact and tsunami disturbance (Norris *et al*. 1999, 2000; MacLeod *et al*. 2006; but see Keller 2008*a*,*b*). Previous studies of NE Mexico localities concentrated exclusively on the sandstone complex and interpreted the reworked spherule layers as evidence of K–T age and Chicxulub tsunami disturbance (Smit *et al*. 1992, 1996; Smit 1999; Soria *et al*. 2001; Schulte *et al*. 2003; Arenillas *et al*. 2006).

The new data presented here for El Peñon and Mesa Juan Perez, and earlier observed at Loma Cerca, the Chicxulub crater core Yaxcopoil-1 and in Texas (Keller *et al*. 2002, 2003, 2004*a*,*b*, 2007) demonstrate the pre-K–T age of the Chicxulub impact. A depositional scenario for NE Mexico consistent with current evidence is shown in Figure 17 along with the climate curve for the South Atlantic deep-sea Site 525 (Li & Keller

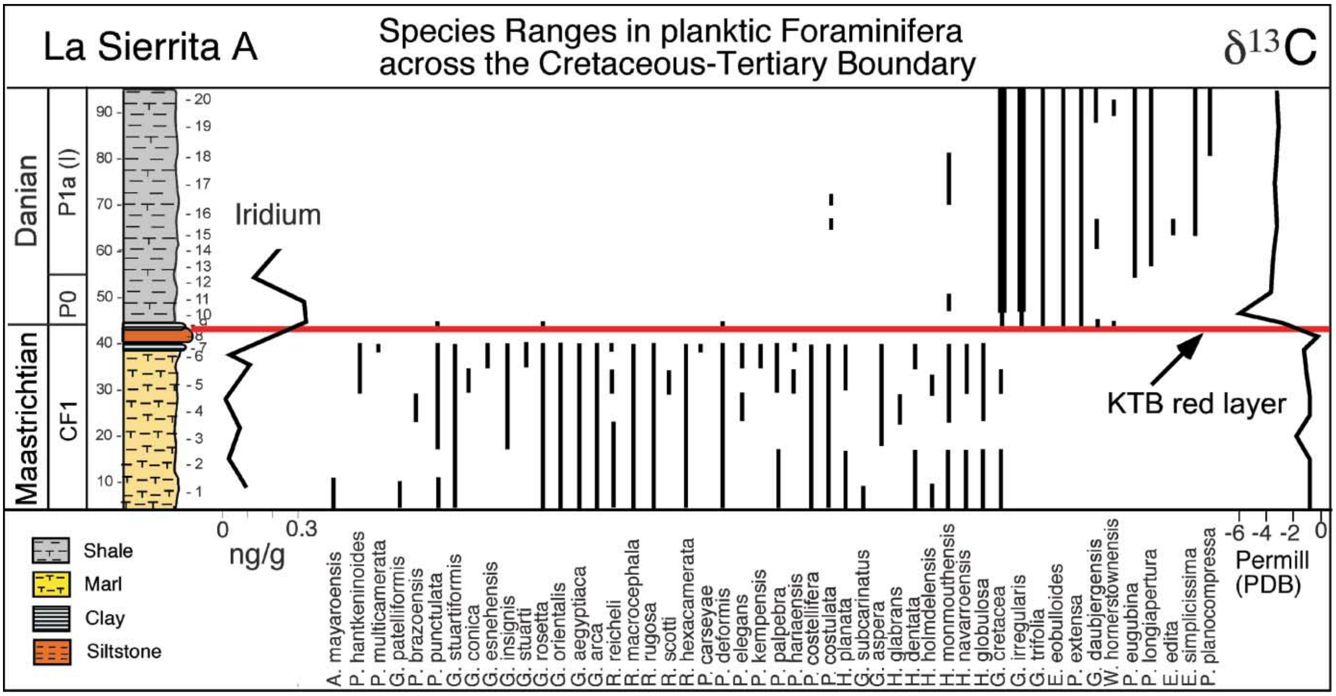

Fig. 16. Planktic foraminiferal species ranges, along with Ir anomaly and $\delta^{13}C$ shift (from Stüben *et al*. 2005) across the K–T boundary at La Sierrita. In contrast to La Parida, few Cretaceous species are present above the K–T boundary, which suggests absence of reworking.

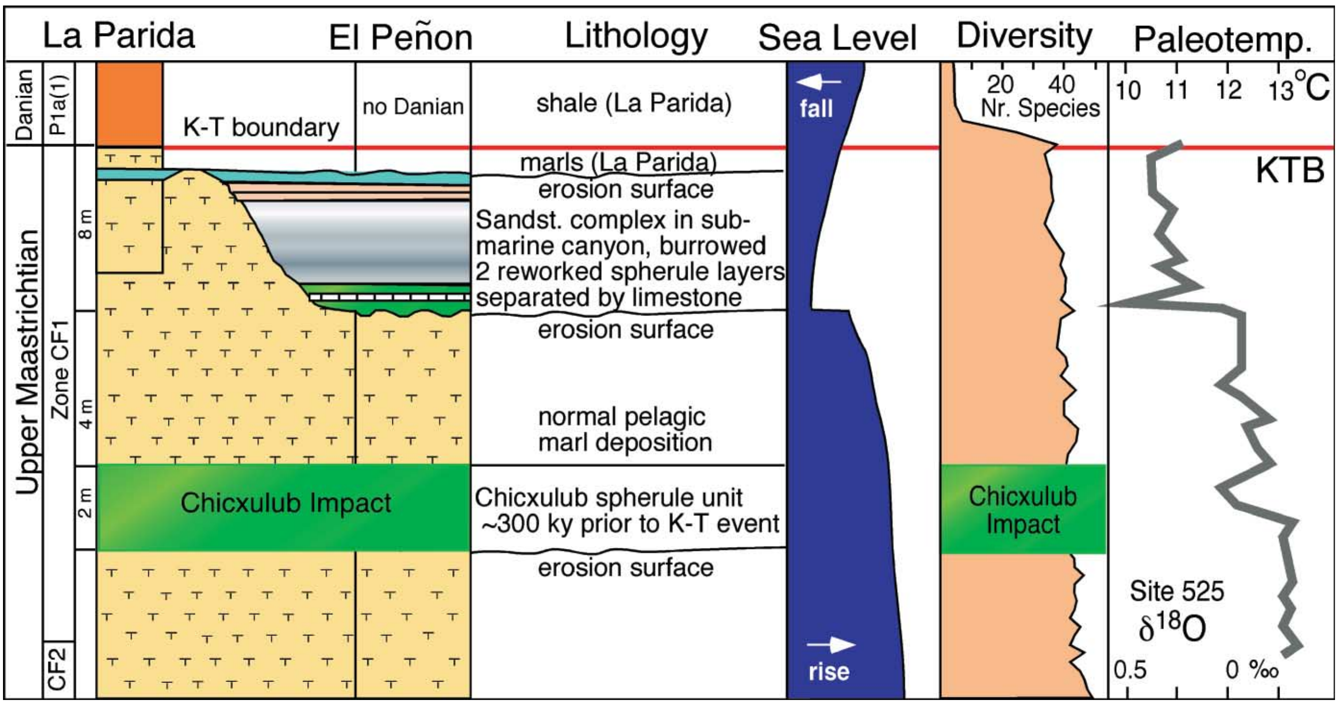

Fig. 17. Summary diagram of La Parida and El Peñon shows the temporal and spatial sequence of the Chicxulub impact, sandstone complex and the K–T boundary. A sea-level fall coincides with deposition of the sandstone complex and correlates with the global cooling following the short warm event in zone CF1. The K–T mass extinction is unrelated to the Chicxulub impact and may have been caused by massive volcanic eruptions.

1998). The Chicxulub impact occurred during the late Maastrichtian warm event, about 300 ka before the K–T boundary, and probably caused catastrophic destruction as a result of impact-induced earthquakes and giant tsunamis, and probably altered climate and environmental conditions for decades. However, in the geological time scale the record of this immediate destruction is not preserved and no credible evidence of tsunami deposits or massive slumps have been found to date.

What has been preserved are the impact melt rock spherules that rained down throughout the region and settled rapidly while still hot to form mats of agglutinated and compressed glass spherules. At El Peñon the presence of spherules in four upward fining layers followed by gradual return to normal marl deposition suggests current activity. Despite the probably immediate massive environmental destruction caused by the Chicxulub impact, marine biota show no long-term effects. Of the 52 planktic foraminiferal species extant prior to the impact, none went extinct and none underwent major changes in species populations. Over the next *c*. 150–200 ka normal marine sedimentation prevailed during warm climatic conditions.

The sandstone complex formed in submarine channels during the latest Maastrichtian cooling and sea-level fall estimated around 100–150 ka before the K–T boundary. This global cooling may have been caused by the massive Deccan volcanic eruptions and SO_2 release (Ravizza & Peucker-Ehrenbrink 2003; Chenet *et al*. 2007; Self *et al*. 2008). The sea-level fall exposed the spherule deposits in nearshore areas and transported them and shallow-water debris seaward, infilling submarine channels and forming the sandstone complex (Fig. 17). During the low sea level erosion and redeposition occurred intermittently, alternating between rapid influx (e.g. clastic debris, sand, shallow-water foraminifers, plant fragments) and periods of normal sedimentation, which permitted colonization by invertebrates (e.g. limestone, marl, shale). As sea level rose, normal marine sedimentation resumed during the last 100 ka before the K–T mass extinction, as suggested by the Late Maastrichtian marl layer at La Parida, La Lajilla, El Mulatto and other NE Mexico localities, limestone in the Chicxulub crater, and clay and mudstones in Texas (Keller *et al*. 2003, 2004*a*,*b*, 2007). The K–T mass extinction, which occurred well after the Chicxulub impact and sandstone deposition, resulted in the rapid extinction of two-thirds of the planktic foraminiferal species; this extinction rate is comparable with the mass extinction globally.

The absence of any recognizable biotic effects as a result of the Chicxulub impact comes as a surprise mainly because we have assumed that this impact caused the K–T mass extinction. A survey of impact craters and mass extinctions over the past 500 Ma reveals that apart from the K–T boundary none of the five major mass extinctions are associated with an impact (Courtillot 1999; Wignall 2001; Keller 2005). The Chicxulub crater with a maximum diameter of 180 km is the largest known impact. Other well-studied impacts that show no extinctions or significant other biotic effects include the 90–100 km diameter late Eocene Chesapeake Bay and Popigai craters, and the 100–120 km diameter late Triassic Manicouagan and late Devonian Alamo and Woodleigh craters (Montanari & Koeberl 2000; Wignall 2001; Poag *et al*. 2002; Keller 2005).

If not the Chicxulub impact, what caused the K–T mass extinction? We have previously suggested another larger impact based on the prevailing view that the K–T Ir anomaly is of cosmic origin (Keller *et al*. 2003; Stüben *et al*. 2005). However, the absence of any biotic effects attributable to the Chicxulub impact suggests that even a larger impact alone would probably not have been sufficient to cause the K–T mass extinction. In addition, there is currently no credible evidence of a second larger impact at K–T time. Another problem is that the K–T Ir anomaly is frequently not just a single anomaly as commonly reported, but multiple anomalies of diverse origins (e.g. impact, volcanic, redox conditions, Graup & Spettel 1989; Grachev *et al*. 2005, 2007; Stüben *et al*. 2005; Keller 2008*a*) that have yet to be fully understood. The Ir anomaly can thus no longer be considered sufficient credible evidence for a large impact at the K–T boundary.

A likely although often overlooked cause for the K–T catastrophe is the Deccan Trap volcanic eruptions, as has long been advocated by McLean (1985) and Courtillot *et al*. (1986, 1988). Deccan Trap eruptions were long thought to have occurred over several million years, but recent studies suggest that the main phase (80%) of eruptions may have been very rapid, over a period of <100 ka (Chenet *et al*. 2007), and ended at the K–T mass extinction (Keller *et al*. 2008*b*). These new results suggest that Deccan volcanism and associated climate and environmental effects may have triggered the K–T catastrophe and that the Chicxulub impact was an early contributor, but not the main cause.

Conclusions

The Chicxulub impact, long thought to be the cause for the K–T mass extinction, is revealed as both being pre-K–T age and having caused no species extinctions. This is indicated by evidence from the Brazos River area of Texas (Keller *et al*. 2007, 2009), the La Sierrita area (Mesa Juan Perez and Loma Cerca) and the classic El Peñon area of NE Mexico.

(1) The original Chixculub impact spherule layer at El Peñon is about 4–5 m below two reworked spherule layers that are separated by a 20 cm thick sandy limestone at the base of the sandstone complex, which was originally interpreted as an impact-generated mega-tsunami deposit.

(2) The original impact spherule layer at El Peñon is 2 m thick, thins out laterally to *c*. 40 cm over about 50 m, and is parallel to the sandstone complex above. There is no significant tectonic disturbance or slumps, although fallen blocks of the sandstone complex sometimes obscure the original spherule layer in the outcrops.

(3) Spherules were deposited rapidly, as evident by agglutinated spherules with convex–concave contacts and a layer of melt rock that indicates rapid settling. No transported shallow-water debris is present.

(4) Sediments between the sandstone complex and the Chicxulub impact spherule layer consist of horizontally bedded and bioturbated marls and marly limestones with two thin rust-coloured layers representing condensed sedimentation. Volcanic influx is prevalent in one rust-coloured layer. This indicates that normal sedimentation resumed after the Chicxulub impact.

(5) The age of the original Chixulub spherule layer is late Maastrichtian near the beginning of zone CF1, or about 300 ka prior to the K–T boundary, consistent with earlier observations in the Chicxulub crater core and Texas (Keller *et al*. 2003, 2004*a*,*b*, 2007).

(6) Planktic foraminifers, which underwent extinction of two-thirds of all species at the K–T boundary, reveal no significant biotic effects across the Chicxulub impact ejecta layer at El Peñon, Mesa Juan Perez and Loma Cerca (Keller *et al*. 2002) or in Texas (Keller *et al*. 2009). Not a single species went extinct and there are no significant changes in species abundances.

(7) The K–T boundary interval is eroded at El Peñon, but the biotic effects of the K–T event can be assessed in the nearby La Parida and La Sierrita sections. The K–T mass extinction at these two localities is marked by the global K–T defining criteria, which include extinction of about two-thirds of the species, the evolution of the first Danian species immediately after the K–T boundary, the $\delta^{13}C$ shift, clay layer and Ir anomaly.

(8) These observations indicate that the Chicxulub impact can

no longer be considered of K–T age and the primary cause for the K–T mass extinction. Deccan volcanism and associated climate and environmental effects may have triggered the K–T catastrophe with the Chicxulub impact an early contributor.

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