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ORIGINAL ARTICLE

Seismites in Calizas Peñas of Campanian-Maastrichtian Age in Sierra de los Órganos, Western Cuba

Sismitas en las Calizas Peñas del Campaniano – Maastrichtiano en Sierra de los Órganos, Cuba occidental

Sujai Banzo-Morales[1*], Reinaldo Rojas-Consuegra[1], Esther María Cruz-Gámez[2], Wilmer Pérez-Gil[2], Isabel Beatriz Griñán-Ferrer[1], Mercedes Torres-de la Rosa[1]

[1]Oil Research Center, Habana, Cuba.

[2]University of Pinar del Río, Pinar del Río, Cuba.

*Corresponding Author: sujai.banzo@ceinpet.cupet.cu

Abstract

The informal unit Calizas Peñas of Campanian-Maastrichtian age outcrops to the SW of the town of Pons, Sierra de los Órganos, in western Cuba. It is composed of dark gray to black limestone, well stratified with black chert intercalations. This unit underlies the laminated limestone of the Ancón Formation of Early Paleocene-Middle Eocene age. The objective was to determine the petrographic and micropaleontological characteristics of the Peñas Limestones and their relationship with the Chicxulub catastrophic event. It is a Cretaceous micrite with recrystallized mudstones-wackestones texture, partly wackestones-mudstones and brecciated wackestones, while the Paleogene laminated limestone is partially brecciated wackestones-packestones and wackestones with 30%-40% of fossils present. There are different types of fractures in the Cretaceous micrite, where the folded lamination, systems of straight, parallel and inclined microcracks, irregular cracks with variable thicknesses, among other elements, stand out. These features correspond to sismites, related to the Chicxulub impact. The ejecta material, shock quartz and spherules, although scarce, support the previous idea. In general, the results of the study of the Peñas river outcrop, endorse it as a new section of the K/Pg boundary in deep water environment, located in western Cuba and the Protocaribe, which opens new research perspectives.

Keywords: Calizas Peñas, seismites, ejecta, Chicxulub

Resumen

La unidad informal Calizas Peñas de edad Campaniano-Maastrichtiano aflora al SW del poblado de Pons, Sierra de los Órganos, en Cuba occidental. Está integrada por caliza de color gris oscuro a negro, bien estratificadas con intercalaciones de pedernal negro. Esta unidad subyace a la caliza laminada de la formación Ancón de edad Paleoceno temprano-Eoceno medio. El objetivo fue precisar las características petrográficas y micro-paleontológicas en las Calizas Peñas y su relación con el evento catastrófico de Chicxulub. Se trata de una micrita cretácica con textura de *mudstones-wackestones* recristalizado, en parte *wackestones mudstones* y *wackestones brechado*, en tanto la caliza laminada paleogénica es *wackestones-packestones* parcialmente brechado y *wackestones* con presencia de fósiles en un 30%-40%. Hay presencia de diferentes tipos de fracturas en la micrita cretácica, donde resaltan la laminación plegada, sistemas de microgrietas rectas, paralelas e inclinadas, grietas irregulares con espesores variables entre otros elementos. Estos rasgos corresponden a sismitas, relacionadas con el impacto de Chicxulub. El material eyéctico, de cuarzo de choque y esférulas, aunque escaso, apoya la idea anterior. En general, los resultados del estudio del afloramiento del río Peñas, le avalan como una nueva sección del límite K/Pg en ambiente de aguas profundas, situada en el occidente de Cuba y del Protocaribe, que abre nuevas perspectivas de investigación.

Palabras clave: Calizas Peñas, sismitas, eyecta, Chicxulub

1. INTRODUCTION

Studies of the Cretaceous-Paleogene (K-Pg) boundary in Cuba are now numerous (Rojas-Consuegra and Núñez-Cambra, 2017) and have been directed towards understanding sedimentary processes (Takayama et al., 2000; Tada *et al.,* 2002, 2003; Kiyokawa *et al.,* 2002; Goto *et al.,* 2008, and others), the microfossil record (Molina *et al.,* 2002; Alegret *et al.,* 2005; Arenillas *et al.,* 2016; Arz *et al.,* 2022, and others), as well as its mineralogical and geochemical composition, especially that associated with the impact ejecta. Furthermore, the relationship with the Proto-Caribbean paleogeography at the time of the Chicxulub meteorite impact on the Yucatán Peninsula, southeastern Mexico, has been of interest.

Manifestations of paleoseismicity, such as that associated with the Chicxulub impact, have been explained as sediment liquefaction, platform collapse, large-scale slope failure, and catastrophic sedimentation (Busby *et al.*, 2002; Arenillas *et al.,* 2006; Denne *et al.,* 2013; Bermúdez *et al.,* 2015, 2024).

In Cuba, detailed research has been conducted on the deposits originating from the catastrophic event at the end of the Cretaceous, but systematic observations regarding paleoseismicity have only recently begun (Banzo, 2024; Bermúdez *et al.*, 2024; Banzo *et al.*, 2025).

Numerous authors have examined the sedimentary record associated with this catastrophic event to obtain further physical evidence to clarify the consequences generated by the impact. This demonstrates that it is possible to identify seismic phenomena, such as faulting, fracturing, folding, and collapses, as well as in-situ liquefaction processes and soft-sediment deformation, occurring before, during, and after the impact. These findings can be associated with the Chicxulub megathrust earthquake, which persisted for months or even years after the bolide impact and are in many cases located thousands of kilometers from the crater (Busby *et al.,* 2002; Tada *et al.,* 2002; Arenillas *et al.,* 2006; Schulte *et al.,* 2009, 2010, 2012; Rojas-Consuegra, 2000; Rojas-Consuegra *et al.,* 2021; Bermúdez *et al.,* 2024). Thus, for the purpose of this work, "seismites" are understood as any deformation, such as those mentioned, that can be identified in the investigated geological record.

Pszczólkowski (1987, 1999) links the Peñas Limestones with the K-Pg boundary, explicitly stated in communication (Álvarez-Sánchez & Bernal, 2013). Therefore, the objective of this research was to explore the possible relationship between the Chicxulub impact and the geological features observed in the Peñas Limestones, at their contact with the Paleogene Ancón Formation, as a deep-water sequence encompassing the K-Pg boundary in western Cuba (Figures 1 and 2).

This work is a contribution of the R&D project "Complex Clastic Unit of the Cretaceous–Paleogene Boundary in Cuba and its Relationship with Geological Evolution" (IGP/SGC PS104LH002-025; Ceinpet 6520) within the program led by the Institute of Geology and Paleontology / Geological Survey of Cuba (IGP/SGC), under the Ministry of Energy and Mines.

2. MATERIALS AND METHODS

A multidisciplinary approach integrating geology, paleontology, and petrography was employed to elucidate a phenomenon that remains a subject of intense research and debate within the scientific community regarding the K-Pg boundary.

The studied outcrop is located in the bed of the Peñas River, situated approximately 850 m southwest of the junction of the road connecting the town of Pons with Viñales (Figure 1). Access is via a track parallel to this intermittent fluvial stream, following a west-northwest direction. The coordinates of the point are: 22° 32' 31'' N; 83° 54' 19'' W.

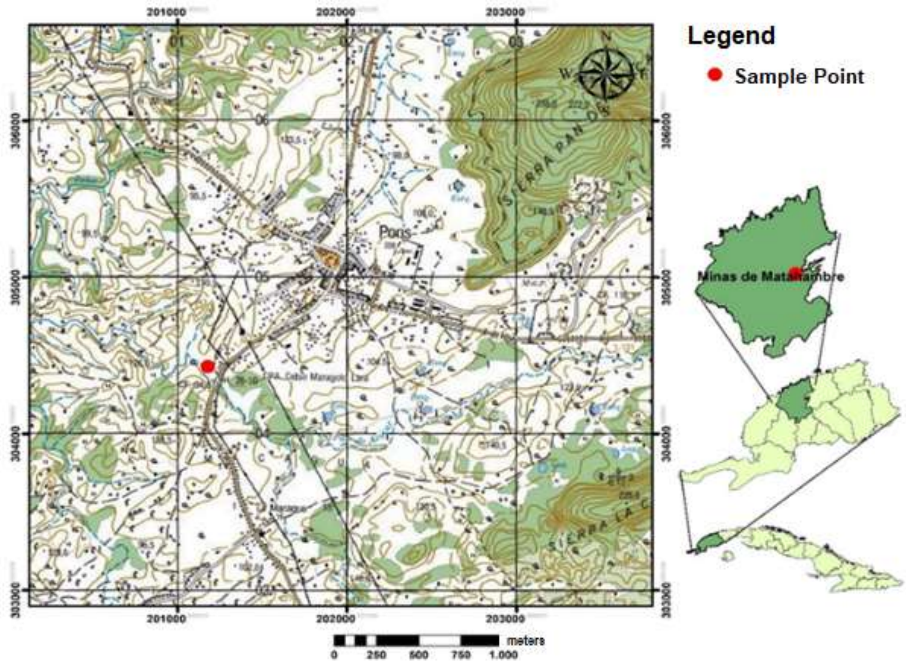

Figure 1. Geographic location map of the Peñas Limestones outcrop.

To conduct a comprehensive study of the deformations, present within the informal unit, a review of previous research literature was undertaken. Two field campaigns were carried out, resulting in the collection of 15 macroscopic samples. Subsequently, 29 thin sections were prepared at the Oil Research Center for petrographic and biostratigraphic analyses, with a specific emphasis on the observation and characterization of microdeformations.

3. RESULTS

At the base of the studied outcrop, massive, dark-colored limestone stratified into thick beds with intercalations of black siliceous layers is observed; this sequence belongs to the Peñas Limestones. Overlying this unit, a distinct contact with finely stratified, violet-colored limestone corresponding to the Ancón Formation is clearly distinguished (Figure 2).

Figure 2. Section of the K-Pg boundary at the Peñas River in the Pons Valley, Sierra de los Órganos.

3.1. Lithologies

The Peñas Limestones are exposed on the riverbed, specifically at the contact between the two lithostratigraphic units, and are notably recrystallized and altered. The presence of fracture systems suggesting shearing is observed, some of which are filled with white calcite. They exhibit a predominant dark gray coloration with rounded areas containing white calcite veins. Additionally, reddish iron oxide patinas and dark brown nodules of bituminous material are distinguished.

At some levels, brecciated-looking rocks are evident, containing clasts and showing changes in grain size from coarse to fine (Figure 3, A-D). The biogenic limestone of the Ancón Formation appears finely laminated, compact, and somewhat oxidized, with a color ranging from light gray to reddish or creamy purple (Figure 3, 3E and 3F).

Based on the field documentation of the section and the information from the samples collected in the Peñas River bed, a stratigraphic column was constructed. This column delineated the predominant lithologies: micritic limestone, Paleogene laminated limestone, and black silicite (Figure 4).

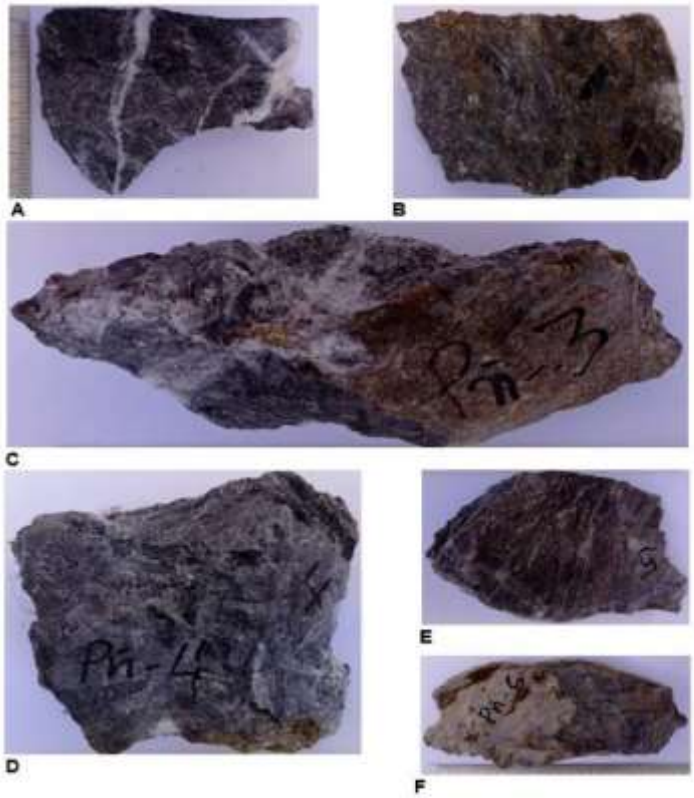

Figure 3. Macroscopic descriptions of the samples: **A** (sample Pñ-1) – Dark gray limestone with calcite veins (Peñas); **B** (Pñ-2) – Breccia of micrite and black silicite with oxidation; **C** (Pñ-3) – Fractured dark gray limestone with sparite-filled fractures; **D** (Pñ-4) – Cracked gray micrite with bitumen; **E** (Pñ-5) and **F** (Pñ-6) – Laminated limestone (Ancón).

3.2. Microfacies

The identified microfacies generally correspond to very fine-grained, sometimes crystalline, carbonates, which typically exhibit textures ranging from mudstone to packestone (Dunham, 1962).

Cretaceous Limestone

Under the microscope, the Cretaceous micrite was identified as recrystallized mudstone to wackestone, composed of micritic carbonate mud with 10%-20% microfossil molds, transitioning to wackestone. It is partially brecciated, contains organic matter mixed with calcareous mud and thin calcite veinlets, and features stylolites with iron oxides and hydroxides. The rock locally exhibits chemical structures such as microstylolites, cross-cutting veinlets, and tension gashes filled with calcite, along with anhydrite grains. This microfacies grades into wackestone-mudstone and brecciated wackestone, formed by carbonate mud, with an increase in fossil content up to approximately 30%; scarce quartz and metallic grains are dispersed throughout.

Paleogene Limestone

The Paleogene biodetrital limestone is very fine-grained, has a calcarenite-like appearance, is finely laminated, compact, and ranges in color from light gray to reddish or purple. Under the microscope, it was identified as wackestone to packestone, partially brecciated, formed by partially recrystallized carbonate mud with a variable bioclast content (increased compared to the Cretaceous facies); oriented microfossils, arranged in a subparallel manner, and thin calcite veinlets are observed. Also present is wackestone in lenses of carbonate mud, with 30%-40% oriented fossil molds, and short veinlets of calcite and iron oxides. Locally, the mud is interstitial to deformed calcite, displaying a set of twins characteristic of calcite tectonites (Groshong *et al.,* 1984; Ferrill, 1991; Burkhard, 1993).

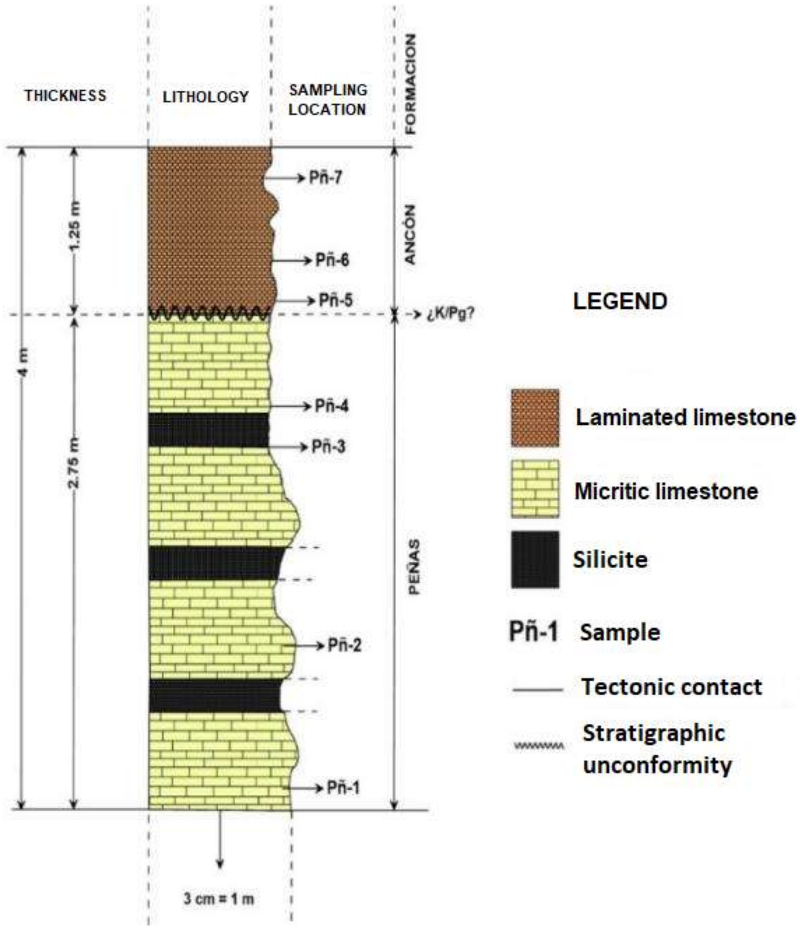

Figure 4. Lithostratigraphic column from the Peñas River bed, indicating the sampling locations.

The textural change observed in the analyzed samples clearly reveals the K-Pg boundary in the Peñas River section (Table 1). In thin section Pñ-4.5, both lithologies are present, where rare shocked quartz grains with the typical planar deformation features (PDFs) are detected within a macrosparite matrix.

Table 1. Distribution of the identified textures in the samples. Green – Cretaceous, reddish ochre – Paleogene, red – K-Pg boundary

Samples / Textures	Pñ-1	Pñ-2	Pñ-2a	Pñ-3	Pñ-4	Pñ-4a	Pñ-4.5	Pñ-5	Pñ-5.1	Pñ-5.2	Pñ-5.3	Pñ-5a	Pñ-5.5	Pñ-6	P-7
Mw-stn	Green	Green	Green	Green			Red								
Wm-stn		Green	Green		Green	Green	Red								
W-stn							Red	Reddish ochre	Reddish ochre	Reddish ochre	Reddish ochre	Reddish ochre	Reddish ochre		Reddish ochre
Wp-stn							Red							Reddish ochre	

3.3. Microfossil Assemblages

In the micrite, a microfossil assemblage rich in planktonic foraminifera (PF) and some radiolarians was identified. Among the former, the following species and genera are listed: *Contusotruncana fornicata*, *Contusotruncana walfishensis*, *Globotruncana rosetta*, *Globotruncana ventricosa*, *Globotruncanella havanensis*, *Globotruncana linneiana*, *Globotruncanita conica*, *Laeviheterohelix glabrans*, *Muricohedbergella homdelensis*, *Planohedbergella ultramicra*, *Planoheterohelix* sp., *Pseudotextularia* sp., and *Rugoglobigerina* sp. The *Radotruncana calcarata* Biozone was identified. The indicated age is Campanian–Maastrichtian.

The laminated limestone (fossiliferous mudstone) possesses a high abundance of PF individuals, among which the following assemblage of species and genera was identified: *Acarinina* sp., *Alicantina lozanoi*, *Globanomalina pseudomenardii*, *Guembelitroides nutalli*, *Morozovella aequa*, *Morozovella velascoensis*, *Morozovella* cf. *M. gracilis*, *Morozovella* spp., *Planorotalites* spp., *Subbotina* spp., and radiolarians. The determined age is Paleocene-Eocene.

3.4. Seismites

The study of microdeformations in the rocks comprising the Campanian-Maastrichtian sequence in the Peñas River section has been particularly challenging due to the high deformation intensity exhibited by the micrite (Figures 5, 6, 7, and 8). Nevertheless, among the principal manifestations suggesting the possible presence of seismites, the following have been identified in the selected oriented samples (S/D):

- Folded lamination (microfolds) and subparallel stylolites.
- Folded lamination and microbreccia, with oriented microfossils, suggesting possible liquefaction.

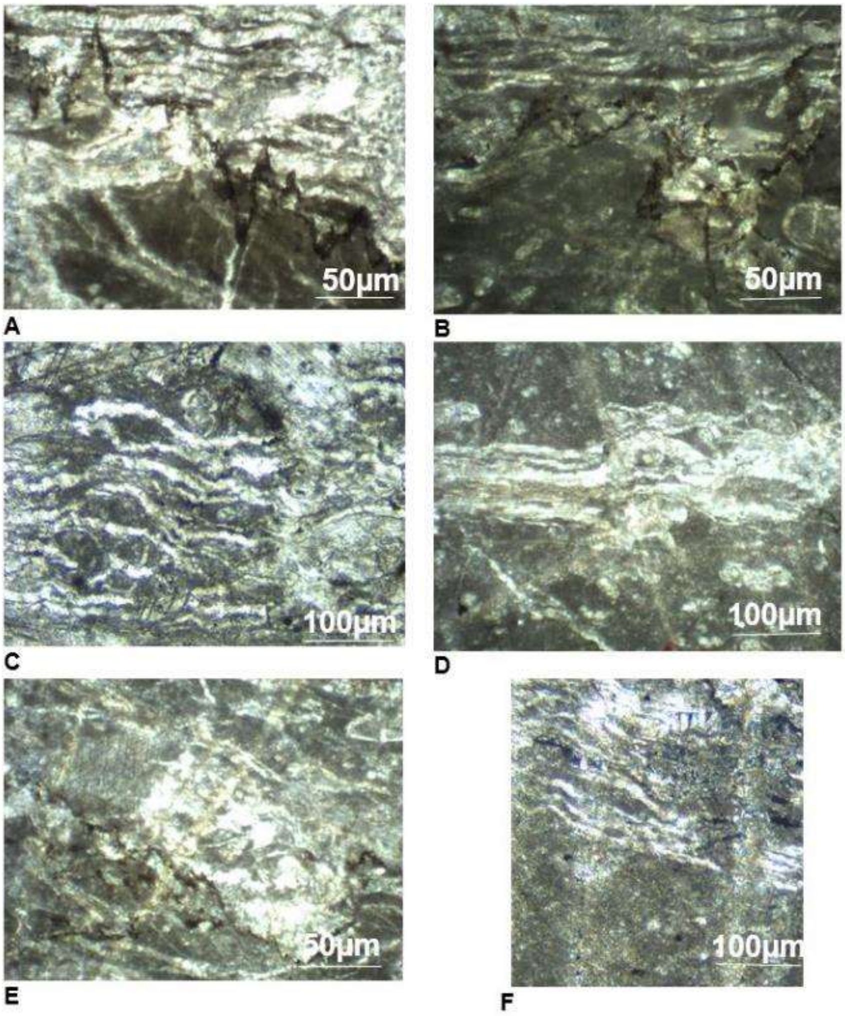

Figure 5. Microdeformations in the Peñas micrite: **A** (sample 2.1) – Folded lamination and subparallel stylolites; **B** (2.2) – Folded lamination and microbreccia, with reoriented foraminifera; **C** (3.1) – Folded lamination and a system of parallel and inclined, shearing micro-fractures, brecciation; **D** (3.1) – Folded lamination and approximately three systems of parallel and cross-cutting fractures, brecciation; **E** (3.1) – Sparitic infill parallel to the lamination and stylolites; **F** (3.1) – Folded and fractured lamination with microfossils.

- Folded lamination with a system of parallel and inclined micro-fractures that shear the lamination, associated with brecciation (approximately three systems of parallel and cross-cutting fractures).
- Folded parallel lamination, fractured and containing microfossils, with sparitic infill parallel to both the lamination and the stylolites.
- Complex system of cross-cutting fractures of varying magnitudes and timing within the micrite.
- Irregular fractures of two distinct thicknesses, quasi-parallel to each other, which are sheared and inclined relative to the lamination.
- Stylolites nearly parallel to the lamination, which cut across the fracture systems, showing displacements (subsequent).
- Very fine system of subparallel hairline fractures relative to the lamination, locally bifurcating and splaying into irregular fan-shaped arrays.
- Contact marked by stylolites between the underlying sparite and the overlying Paleocene laminated limestone; breccia at the contact, with an intense presence of stylolites highlighted by bitumen (possibly due to lithostatic loading).

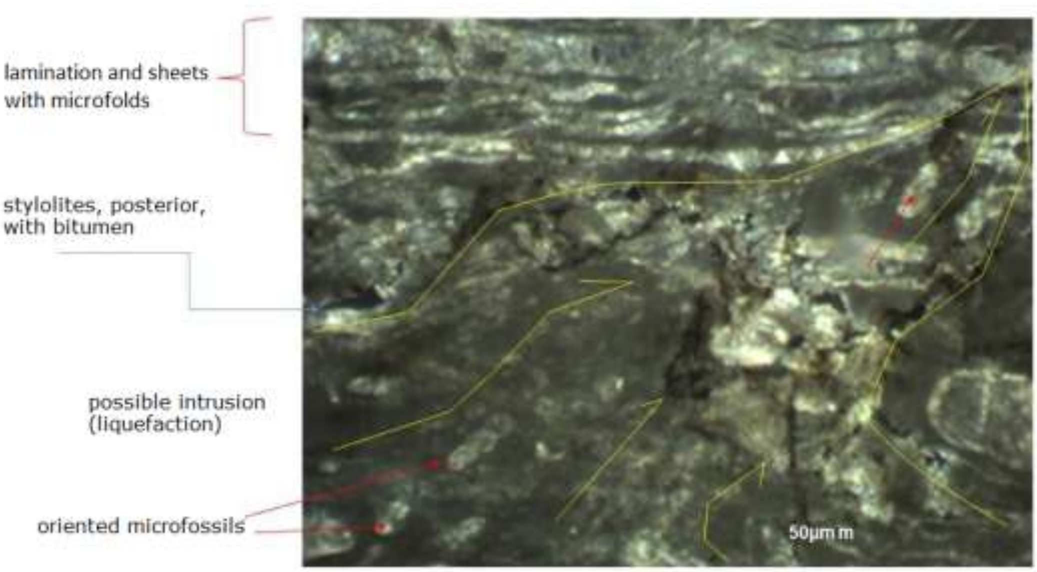

Figure 6. Microseismite in Cretaceous micrite. Observe the elements of microdeformations, ductile and fragile, among these the styloliths; the entire assembly inclined with respect to the lamination.

Cretaceous Sequence

The lithofacies identified in the Late Cretaceous sequence exhibit intense deformation, including brecciation, abundant fracturing, and recrystallization. Furthermore, they are cross-cut by multiple systems of fine fractures and stylolites containing oxides and bitumen. The fractures are generally filled with calcite, partially macrosparitic in nature (Figures 5 and 6).

The systems of parallel and inclined fractures, which shear the bedding and lamination with a similar dip angle, most likely reflect the seismic impact from a single direction, in this case, from west to east (Figure 7).

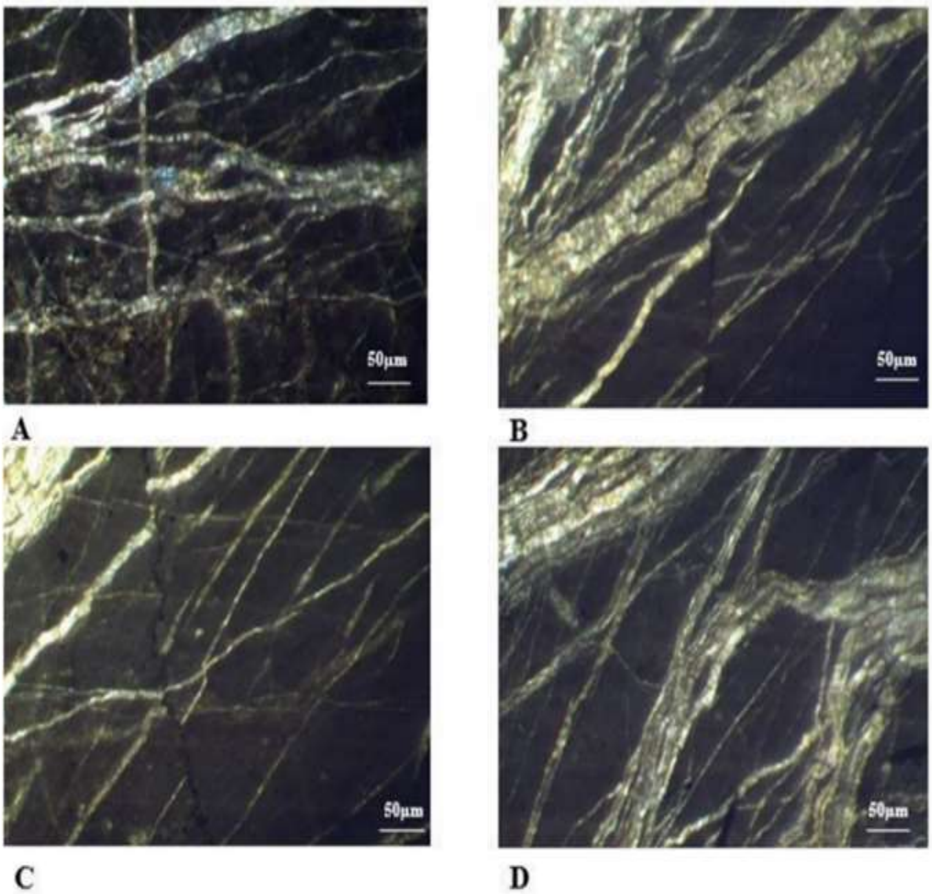

Figure 7. System of irregular and shearing fractures, some appearing as bundles or packets, displaced by subsequent stylolitic microstructures. Samples: **A** (Pñ-1-1, XPL), **B** (Pñ-2-a, XPL), **C** (Pñ-2-a, XPL), **D** (Pñ-2-a, XPL).

Subsequent fractures and offsets are observed cross-cutting the older ones and are filled with calcite or oxides (Figures 7A-C). Multiple fracture systems generally intersect with a high fracture density within the micrite (Figures 5, 6, and 7). A field study over a larger area with a more extensive microtectonic dataset is recommended here.

As confirmed, this Cretaceous sequence exhibits a high degree of diastrophism. It is deduced that sediment diagenetic processes played an influential role, but the effects of tectonic processes —and, in all probability, those seismically induced by the Chicxulub impact— are manifested with greater clarity.

Paleogene Sequence

The manifestation of deformation per unit area in this rock is lower, as is its morphological diversity, compared to those features exhibited by the Cretaceous micrite, as previously described. Several samples of the Paleogene rock were characterized, but the one taken directly at the lower boundary, at the K-Pg contact, is illustrated here, as all samples proved very similar.

The finely laminated or very fine biogenic limestone contains abundant planktonic foraminifera oriented parallel to the bedding, dated to the early Paleocene, Danian (Ancón Formation). Impact quartz grains have been identified in its upper part (Figure 8). This lithofacies contains:

- Systems of fine to very fine, irregular fractures, which predominate and are inclined relative to the orientation of the foraminiferal tests (lamination).
- Scarce fractures filled with calcite and stylolites parallel or subparallel to the lamination planes.

These deformations, like their counterparts in the older micrite, appear to be related to the effects of lithostatic load endured by the sequence during synorogenic thrusting and, in part, may also result from the effects of transpressional displacement stresses involved in the regional substrate.

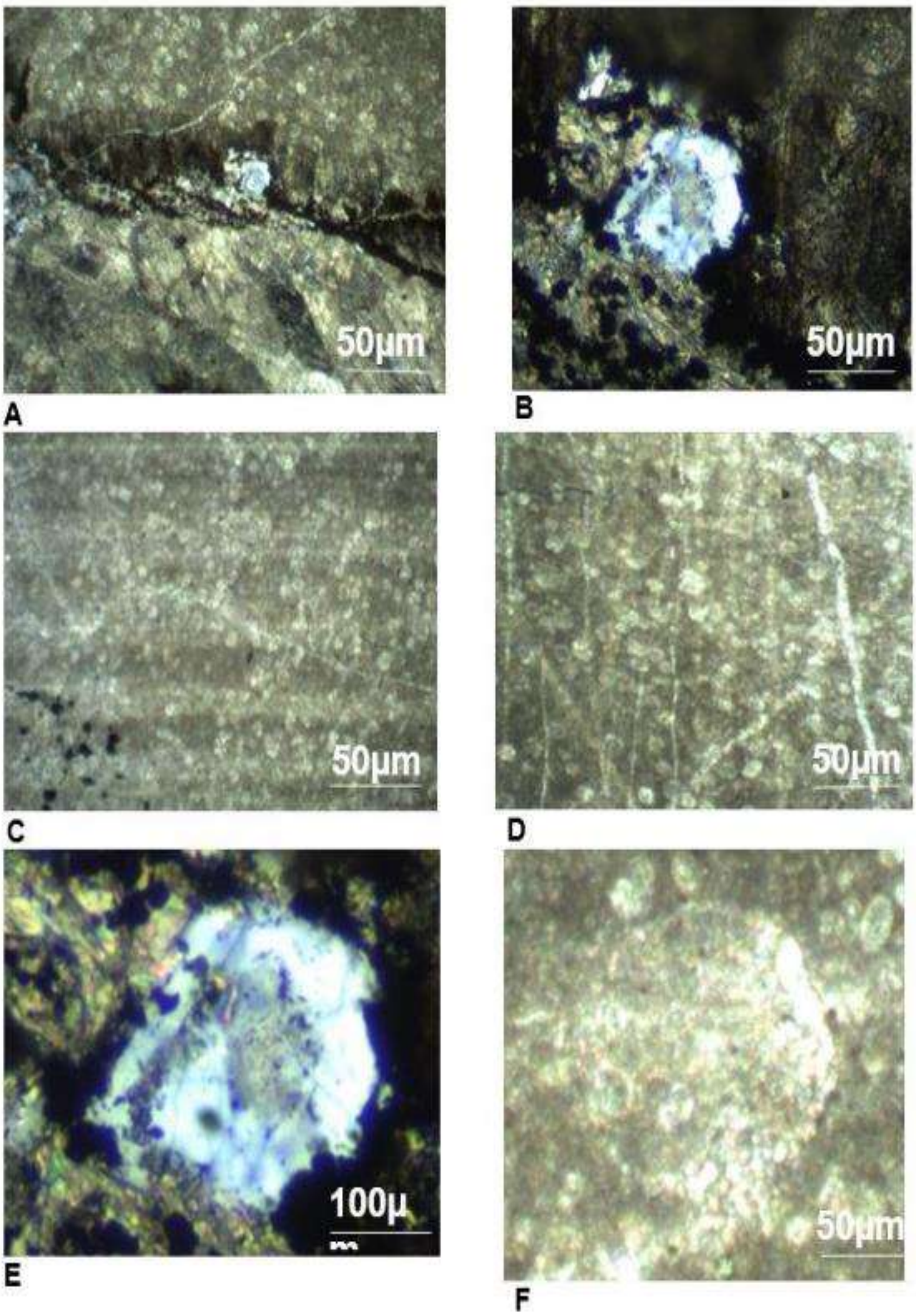

Figure 8. A (4.5 all) – Contact between sparite (Peñas) and laminated limestone with Danian Paleocene planktonic foraminifera (Ancón); **B** (4.5) – Quartz grain at the contact; **C** – Finely laminated limestone very rich in planktonic foraminifera (PF); **D** – Identical sample, with a system of very fine, irregular fractures inclined relative to the orientation of the tests (lamination); **E** (4.5) – Detail of B, fractured quartz; **F** – Agglomeratic spherule with microspherules.

The stylolite system post-dates the consolidation of both sequences, as it cuts across both in a similar manner, with identical clay, oxide, and bitumen content. Given their subparallel orientation to the lamination, which was originally subhorizontal, they are likely the result of intense lithostatic loading according to the regional geological structure of thrust sheets.

Furthermore, the formation of sparite and macrosparite in fractures is also generally observed, as well as at the contact, at the top of the Cretaceous micrite. This fact is related to the probable circulation of hydrocarbons during dysmigration; a process associated with the Cuban orogeny.

3.5. Ejecta

Within this stratigraphic section, albeit sparse, K-Pg impact ejecta material was found. In the boundary sample (4.5), located on the sparite (at the top of the micrite) and beneath the Paleogene laminated limestone, isolated fractured or shocked quartz grains were identified (Figures 8B and 8E). Although rare or scarce, they nonetheless indicate a direct relationship of this deposit with the Chicxulub impact. Additionally, a probable complex spherule was identified, exhibiting a circular or globular form with infill composed of microspherules, resembling the texture of an agglomeratic impact glass spherule (Figure 8F).

3.6. Twinning

Petrographic analysis of the thin sections described a set of carbonate twins of Type I, II, and III (Groshong *et al.*, 1984; Burkhard, 1993; Ferrill, 1991), indicative of deformation temperatures ranging between 200 and 300 degrees Celsius (Figure 9). This finding is significant due to its relationship with the generation and migration of hydrocarbons, to which the presence of bitumens in the stylolites observed in the section would be associated.

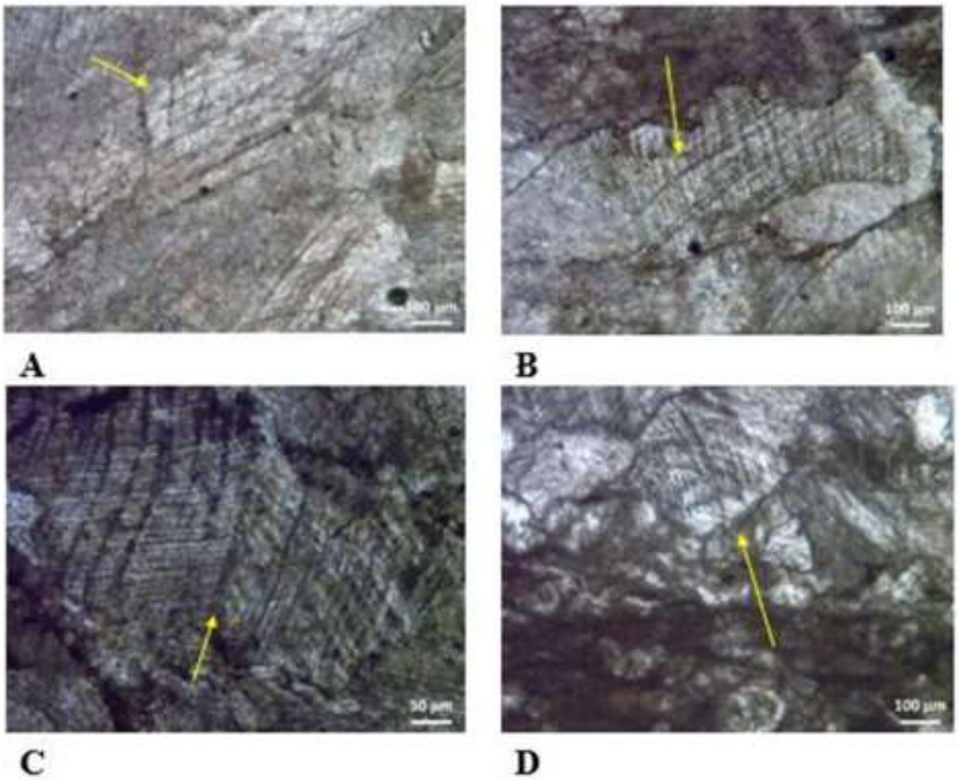

Figure 9. Calcite twinning observed in the Cretaceous micrite. **A** (Pñ-3-1, XPL) – Deformed calcite. **B** (Pñ-4-2, XPL) – Brecciated wackestone and a fracture with deformed calcite. **C** (Pñ-7-1, XPL) – Detail of calcite showing twin sets. **D** (Pñ-7-1, XPL) – Wackestone with deformed calcite exhibiting curved and wedge-shaped twins towards the grain boundary.

4. DISCUSSION

The combined presence of normal faulting, plastic deformation, liquefaction and injection structures, as well as the occurrence of oppositely verging folds and fault-graded beds located beneath undeformed levels, is considered a typical feature of paleoseismites (Seilacher, 1969; Obermeier, 1996; Montenat *et al.,* 2007). In a K/Pg scenario, these features are related to the intense seismic energy released by the Chicxulub impact, which triggered a destructive megathrust earthquake with an estimated magnitude between 10 and 13 (Shoemaker *et al.,* 1990), sufficient to cause deformation throughout North and South America (Klaus *et al.,* 2000).

The presence of in-situ deformed sediments in northern South America strengthens the evidence that the seismic shaking generated by the impact, and potential aftershocks, represents a major geological event that affected the upper Maastrichtian sediments across a vast region. The released seismic energy was sufficient to affect localities more than 3,000 km from the

Chicxulub impact site (Renne *et al.,* 2018). It is estimated that the Proto-Caribbean seafloor, where the Maastrichtian sequences forming the Cuban geological substrate accumulated, was located between 200 km and 1,500 km from the impact crater. This premise supports the notion that paleoseismic deformations in Cuban territory should be diverse and clearly expressed.

The relationship of the Peñas Formation limestones (Pszczółkowski, 1999) with the K-Pg boundary was explicitly stated by this author in a personal communication to Álvarez-Sánchez and Bernal (2013); in a footnote (number 2, p. 12): "The almost black limestones evidently show traces of a rare event (possibly K/T or K/P), as the silicites are deformed in a very specific (non-tectonic) way and these rocks pass laterally into breccia. Of course, these limestones originally belonged to the 'Infierno Member' (= Pons Formation), but were later 'disturbed' and partially included in the younger breccia (Pszczółkowski, 1987)."

He also describes the basal Paleocene breccia, similar to the Cacarajícara Formation in Sierra del Rosario, which has already been studied in detail (Kiyokawa *et al.,* 2002; Tada *et al.,* 2003; Goto *et al.,* 2008a): "Most, if not all, layers included in an earthy matrix belong to the Infierno Member itself. The matrix also contains large amounts of broken chert layers, but from the unit itself" (Pszczółkowski, 1987). According to Álvarez-Sánchez and Bernal (2013), these features are also known in other locations within this region (Figure 10).

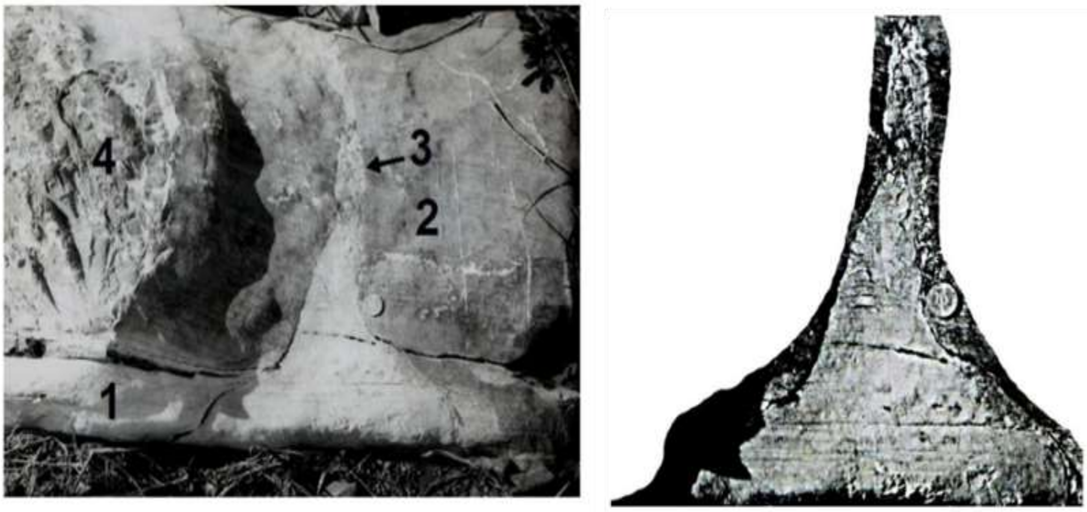

Figure 10. Seismites in the form of a calcilutite dike intruding a layer of Peñas micrite (left), and details of the injection chimney of liquefied material from the underlying layer, showing brecciation at the contact (right). From Álvarez-Sánchez and Bernal (2013).

4.1. Importance of the Geosite

Based on the results of the present study, the Peñas River section stands as a new K-Pg boundary section in western Cuba. Its stratigraphic importance for regional geology and its heritage value can now be assessed.

The presence of the transition from the late Maastrichtian to the Danian Paleocene (Mesozoic/Cenozoic), possibly continuous, eventually without a hiatus, or with a diastem, within a deep-water succession near the CCD (Carbonate Compensation Depth), originated paleogeographically in the western part of the Proto-Caribbean, only about 200 km–300 km west-northwest of the Chicxulub impact crater on the Yucatán Peninsula (Mexico). It is further distinguished by its paleoseismic manifestations.

All the aforementioned characteristics establish it as a geosite of exceptional value, which should be formally designated in the future and become an object of heritage conservation for scientific and educational purposes.

5. CONCLUSIONS

- The stratigraphic section of the Peñas River exhibits evidence of intense deformation processes and ejecta related to the K-Pg boundary seismic impact in a deep-water environment, a unique case in the Caribbean region.
- In particular, the Cretaceous Peñas micrite displays a wide variety of microfractures, microfolds, and brecciation, with multiple systems of calcite-filled fractures, interpreted as manifestations of seismites that occurred in the western Proto-Caribbean, induced by the seismic shock generated by the Chicxulub impact, located just a few hundred kilometers to the west on the Yucatán platform in southeastern Mexico.

6. ACKNOWLEDGMENTS

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Additional Information

Conflict of Interest

None declared.

Author´s Contributions

SBM: Section documentation. Fieldwork, sampling, sample description and preparation. Data interpretation and integration. Stratigraphic column elaboration, writing, review, and editing of the article. **RRC:** Section documentation, fieldwork, sampling, sample description and preparation. Stratigraphic column analysis. Data interpretation and integration, writing, editing, and review of the scientific article. **EMCG:** Section documentation. Fieldwork, sampling, sample description. Data interpretation and integration, and article review. **WPG:** Section documentation. Fieldwork, sampling, sample description. Data interpretation and integration, stratigraphic column elaboration, and article review. **IBGF:** Sample description, data acquisition. Data interpretation and integration, and article review. **MTR:** Sample description, data acquisition. Data interpretation and integration, and article review.

ORCID

SBM: https://orcid.org/0009-0008-1709-2390
RRC: https://orcid.org/0000-0003-1572-2527
EMCG: https://orcid.org/0000-0001-8887-7277
WPG: https://orcid.org/0000-0001-9667-3258
IBGF: https://orcid.org/0000-0003-4225-8467
MTR: https://orcid.org/0000-0001-5299-6098

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