Volume 3

Chapter 1

The Cretaceous/Paleogene Boundary Deposits on Gorgonilla Island

https://doi.org/10.32685/pub.esp.37.2019.01

Hermann Darío BERMÚDEZ[1]*, Ignacio ARENILLAS[2], José Antonio ARZ[3], Vivi VAJDA[4], Paul R. RENNE[5], Vicente GILABERT[6], and José Vicente RODRÍGUEZ[7]

1 hdbermudez@yahoo.com
Grupo de Investigación Paleoexplorer
4690 W. Eldorado parkway, apt 1016, McKinney, Texas
75070 USA

2 ias@unizar.es
Universidad de Zaragoza
Instituto Universitario de Ciencias Ambientales de Aragón
Departamento de Ciencias de la Tierra
E–50009 Zaragoza, Spain

3 josearz@unizar.es
Universidad de Zaragoza
Instituto Universitario de Ciencias Ambientales de Aragón
Departamento de Ciencias de la Tierra
E–50009 Zaragoza, Spain

4 vivi.vajda@nrm.se
Swedish Museum of Natural History
Departament of Palaeobiology
Stockholm, Sweden

5 prenne@bgc.org
Berkeley Geochronology Center (BGC)
2455 Ridge Road, Berkeley, CA 94709, USA
University of California, Berkeley
Department of Earth and Planetary Science
Berkeley, CA, 94720, USA

6 vgilabert@unizar.es
Universidad de Zaragoza
Departamento de Ciencias de la Tierra
E–50009 Zaragoza, Spain

7 jovicrodri@yahoo.com
4690 W. Eldorado parkway, apt 1016, McKinney, TX, 75070

* Corresponding author

Abstract A ca. 20 mm thick spherule bed representing Chicxulub impact ejecta deposits and marking the Cretaceous/Paleogene (K/Pg) boundary was recently discovered on Gorgonilla Island (Gorgona National Natural Park, Pacific of Colombia). This discovery represents the first confirmed record of the K/Pg event in Colombia, South America, and the eastern Pacific Ocean. The deposit consists of extraordinarily well–preserved glass spherules (microtektites and microkrystites) reaching 1.1 mm in diameter. Importantly, the Gorgonilla spherule bed is unique relative to other K/Pg boundary sites in that up to 90% of the spherules are intact and not devitrified, and the bed is virtually devoid of lithic fragments and microfossils. The spherules were deposited in a deep marine environment, possibly below the calcite compensation depth. The preservation, normal size–gradation, presence of fine textures within the spherules, and absence of bioturbation or traction transport indicate that the Gorgonilla spherules settled within a water column with minimal disturbance. The spherule bed may represent one of the first parautochthonous primary deposits of the Chicxulub impact known to date. ^{40}Ar/^{39}Ar dating and micropaleontological analysis reveal that the Gorgonilla spherule bed resulted from the Chicxulub impact. Intense soft–sediment deformation and bed disruption in Maastrichtian sediments of the Gorgonilla Island K/Pg section provide evidence for seismic activity triggered by the Chicxulub bolide impact, 66 million years ago. It is also notable that the basal deposits of the Danian in the Colombian locality present the first evidence of a recovery vegetation, characterized by ferns from a tropical habitat, shortly following the end–Cretaceous event.

Keywords: *K/Pg boundary, Chicxulub, microtektites, seismites, Gorgonilla Island, Colombia.*

Resumen Una capa de aproximadamente 20 mm de espesor con depósitos de eyecta del impacto de Chicxulub, que marca el límite Cretácico–Paleógeno (K/Pg), fue recientemente descubierta en la isla Gorgonilla (Parque Nacional Natural Gorgona, Pacífico colombiano). Este es el primer registro confirmado del evento K/Pg en Colombia, Suramérica y el Pacífico oriental. El depósito consiste en una acumulación de esferulitas de vidrio (microtectitas y microcristitas) de hasta 1,1 mm de diámetro extraordinariamente bien preservadas. La capa de esferulitas de Gorgonilla es única entre los depósitos conocidos de eyecta de Chicxulub; hasta un 90 % de las esférulas está aún completamente vitrificadas y la capa está prácticamente desprovista de líticos o microfósiles. Las esferulitas fueron depositadas en un paleoambiente marino de aguas profundas, posiblemente por debajo

---

Citation: Bermúdez, H.D., Arenillas, I., Arz, J.A., Vajda, V., Renne, P.R., Gilabert, V. & Rodríguez, J.V. 2019. The Cretaceous/Paleogene boundary deposits on Gorgonilla Island. In: Gómez, J. & Mateus–Zabala, D. (editors), The Geology of Colombia, Volume 3 Paleogene – Neogene. Servicio Geológico Colombiano, Publicaciones Geológicas Especiales 37, 19 p. Bogotá. https://doi.org/10.32685/pub.esp.37.2019.01

del nivel de compensación de la calcita. La preservación, gradación normal, presencia de estructuras delicadas dentro de las esférulas y ausencia de evidencias de bioturbación o de transporte indican que la capa de esferulitas de Gorgonilla se asentó a través de la columna de agua con mínima perturbación subsecuente. Esta capa puede representar uno de los primeros depósitos paraautóctonos primarios del impacto de Chicxulub conocidos hasta el momento. Dataciones $^{40}Ar/^{39}Ar$ y resultados de análisis micropaleontológicos muestran que la capa de esférulas de Gorgonilla fue producida por el impacto del asteroide que formó el cráter de Chicxulub. Adicionalmente, la intensa deformación sinsedimentaria y la perturbación de las capas del Maastrichtiano en la sección K/Pg de la isla Gorgonilla proporcionan evidencia de la actividad sísmica producida por el impacto de Chicxulub hace 66 millones de años. Es también notable que las capas basales del Daniano en la localidad colombiana muestran las primeras evidencias de la recuperación de la vegetación, representada por helechos de un hábitat tropical, justo después del evento del fin del Cretácico.

Palabras clave: *límite K/Pg, Chicxulub, microtectitas, sismitas, isla Gorgonilla, Colombia.*

1. Introduction

The Cretaceous/Paleogene (K/Pg) boundary marks one of the five major mass extinctions in Earth's history and has long been associated with the Chicxulub impact in the Yucatán Peninsula, 66 million years ago (Alvarez et al., 1980; Hildebrand et al., 1991; Pope et al., 1991; Schulte et al., 2010). However, some authors question this vast evidence, suggesting that the Chicxulub impact predated the K/Pg boundary by several hundred thousand years and that it was not responsible for the K/Pg mass extinction (Keller, 2011; Keller et al., 2001, 2003a, 2003b; Stinnesbeck et al., 1997, 2002).

Ejecta deposits containing melt droplets in the form of tiny glass spherules, with a similar chemical composition as the glass from the Yucatán impact breccia, have been documented throughout Central and North America and the Caribbean (Keller et al., 2013; Norris et al., 1999; Ocampo et al., 1996; Olsson et al., 1997; Schulte et al., 2010; Smit et al., 1992; Wigforss–Lange et al., 2007). However, in South America, K/Pg boundary sections are exceedingly rare, and only two sections have been formally associated with the Chicxulub impact event. In the Neuquén Basin, Argentina, Scasso et al. (2005) described a coarse–grained sandstone bed, which occurs in a homogeneous shallow shelf mudstone sequence. The authors suggested that this siliciclastic unit represents a tsunami deposit, triggered by the Chicxulub impact. In a subsequent analysis from the same section, however, Keller et al. (2007) suggested that the deposition of the sandstone occurred 500 ky after the K/Pg hiatus and is unrelated to the Chicxulub impact. At Poty quarry, Pernambuco, Northeast Brazil, Albertão & Martins (1996) described a shallow–marine marl and limestone succession with impact–derived exotic products (microtektite–like microspherules and shock–metamorphosed quartz), associated with a possible impact–generated tsunamite. However, subsequent work by Albertão et al. (2004), Morgan et al. (2006), and Gertsch et al. (2013) concluded that there is no evidence supporting the impact origin of those spherules. The breccia unit, interpreted as a tsunamite, is composed of intraformational lime– and marlstone clasts but also contains bones, phosphatic lumps, phosphatized foraminifera, glauconite, and small pyrite concretions, which indicate reworking and erosion from near–shore areas (Stinnesbeck & Keller, 1996). Gertsch et al. (2013) suggested that this unit represented a gravity flow formed during the latest Maastrichtian lowstand.

A new pristine K/Pg section has been discovered on Gorgonilla Island, in the Pacific of Colombia (Bermúdez et al., 2016). Although most of the glass spherules formed during the Chicxulub impact are now devitrified and have been altered to secondary clay minerals, such as smectite, the spherules from Gorgonilla Island are virtually unaltered and represent the most pristine K/Pg boundary spherules known to date. This unique boundary section is the first confirmed record of this event in Colombia, South America, and the eastern Pacific Ocean and it has been studied with respect to stratigraphy, sedimentology, mineralogy, chemistry, micropaleontology, palynology, and $^{40}Ar/^{39}Ar$ geochronology (Renne et al., 2018). The present paper is a summary of an international interdisciplinary research project, still in progress, and condenses the information available to date.

1.1. Location and Geological Setting

The Gorgonilla Island K/Pg section (2° 56' N, 78° 12' W) is located in Gorgona National Natural Park, south of the Playa del Amor, SW coast of Gorgonilla Island, approximately 35 kilometers off the Colombian Pacific coast (Figure 1a). The island is 0.5 to 1 km in diameter and is located approximately 500 m SW of the larger Gorgona Island. Rock units only crop out along the coast at both islands, and as a result, outcrops are generally only accessible during low tide. Gorgona and Gor-

Figure 1. (a) Map of the Gorgonilla K/Pg section's location, Pacific of Colombia. **(b)** Global distribution of key K/Pg boundary sections (outcrops and deep sea drill sites). Modified from Schulte et al. (2009, 2010).

gonilla are among the less deformed and last accreted portions of the Caribbean Plateau and expose a mafic and ultramafic magmatic sequence of Late Cretaceous to early Paleocene age, which includes basalts, gabbros, peridotites, basaltic komatiites, microgabbroic intrusions, and pyroclastic sediments (Dietrich et al., 1981; Echeverria & Aitken, 1986; Gansser, 1950; Gansser et al., 1979; Kerr, 2005; Serrano et al., 2011). The sedimentary rock sequence at Gorgona and Gorgonilla Islands consists of Paleogene litharenite, mudstone, tuffaceous shale, radiolarite, limestone, and minor conglomerate, and Neogene mudstone, fossiliferous shale, and sandstone (Gansser, 1950).

Gorgonilla is interpreted to form the southernmost part of the Caribbean Oceanic Plateau or part of Gorgona Plateau that was accreted to northern South America in the middle Eocene (Kennan & Pindell, 2009; Kerr & Tarney, 2005). At the time of the Chicxulub impact, the Gorgonilla site was thus located approximately 2000–3000 km southwest of the impact site in northern Yucatán (Figure 1b).

2. Materials and Methods

Field work was performed during geological campaigns in 2014 and 2015. The exposure hosting the K/Pg boundary deposits was measured and examined for lithological changes, composition, sedimentologic structures, trace fossils, erosion surfaces, and deformation, and documented through drawings and high–resolution photographs. Sediments were sampled at close intervals for microfossils, and petrographic, mineralogical, and geochemical analyses; a total of 140 rock samples were collected. For petrographic and electron microprobe analysis, polished thin sections were generated from cuts normal and parallel to the bedding in the spherule deposit, as well as from Maastrichtian and Danian sediments enclosing the event bed.

To investigate their shapes and surface structures, spherules were hand–picked from gently disintegrated samples at the Paleoexplorer SAS laboratory, Bogotá, Colombia. Polished cut slabs and disaggregated spherules were coated with graphite, under prevacuum conditions (<10–1 torr), in an Emscope TB500 SEM Carbon Coater, at the Departamento de Geociencias of the Universidad Nacional de Colombia, Bogotá. The typical thickness of coating was +/–60 nm. Imaging and microanalysis of the spherules were executed in a scanning electron microscope (FEI QUANTA 200), equipped with an Everhart–Thorney detector (ETD) and a solid–state detector (SSD). Additional imaging, chemical analysis, and mapping of spherules were performed at the Institut für Geowissenschaften of Ruprecht–Karls–Universität, Heidelberg, Germany, with an LEO 440 scanning electron microscope equipped with an Oxford Inca EDX system. Electron microprobe analyses were performed using a CAMECA SX51 instrument equipped with five wavelength–dispersive spectrometers (methods described in Bermúdez et al., 2016).

For the $^{40}Ar/^{39}Ar$ geochronology study (Renne et al., 2017, 2018), spherules were irradiated in the Cd–lined CLICIT of the Oregon State University TRIGA reactor, along with the Fish Canyon sanidine (FCs–EK) standard; they were analyzed individually by stepwise degassing in 9–15 steps, with a defocused CO_2 laser, and Ar ion beams were measured using peak hopping with an MAP 215C mass spectrometer, following procedures essentially identical to those of Renne et al. (2013). Decay and interference corrections were those of Renne et al. (2013). Ages were calculated using the optimization calibration of Renne et al. (2011).

For the planktic foraminiferan study, samples were disaggregated using a solution of 80% acetic acid and 20% H_2O_2 or a 2M NaOH solution, and subsequently washed through a 63 µm sieve; all foraminiferan specimens were identified, sorted, and fixed on standard 60–square micropaleontological slides; some of these were examined under the scanning electron microscope (Zeiss MERLIN FE–SEM), at the Electron Microscopy Service of the Universidad de Zaragoza, Spain.

Ten samples spanning the K/Pg boundary succession were processed for palynological analysis at the palynological laboratory at the Department of Paleobiology, in the Swedish Museum of Natural History, following standard methods. Two strew slides per sample, one kerogen sample (not sieved, nor oxidized), and one where the residue was sieved and oxidated, were analyzed for organic particles, including pollen and spores.

3. Results

The sedimentary record of the Cretaceous – Paleogene transition in Gorgonilla Island (Figure 2) is composed of thin to medium–bedded light olive–gray tuffaceous litharenite (locally conglomeratic), with calcitic cement rhythmically alternating with massive gray–yellow tuffaceous marl, siltstone, and claystone (Figure 2a–d). Sandstone components are lithic and include feldspar, olivine, quartz, pyroxene, and mica, as well as abundant volcanic lithics, and floating clasts of siliciclastic sedimentary rocks. Diverse microfossils are present in the intercalated mudstone, including abundant radiolarians, coccoliths, rare poorly preserved foraminifers, and sponge spicules (Bermúdez et al., 2016).

Slump and other soft–sediment deformation features are abundant at the Gorgonilla K/Pg boundary section in the beds underlying the spherule bed (Figure 2g), leading to uneven surfaces and disrupted bedding. Upsection from the spherule bed, soft sediment deformation is also occasionally present, but markedly rarer and restricted to small–scale slumps and the contortion of individual thin sediment units, while other units appear to be unaffected (Figure 2f). Soft–sediment deformation structures include syndepositional faulting and fault–grading, hydroplastic mixed layers, pillar and flame structures, small and medium–scale slumps with internal folding and associated

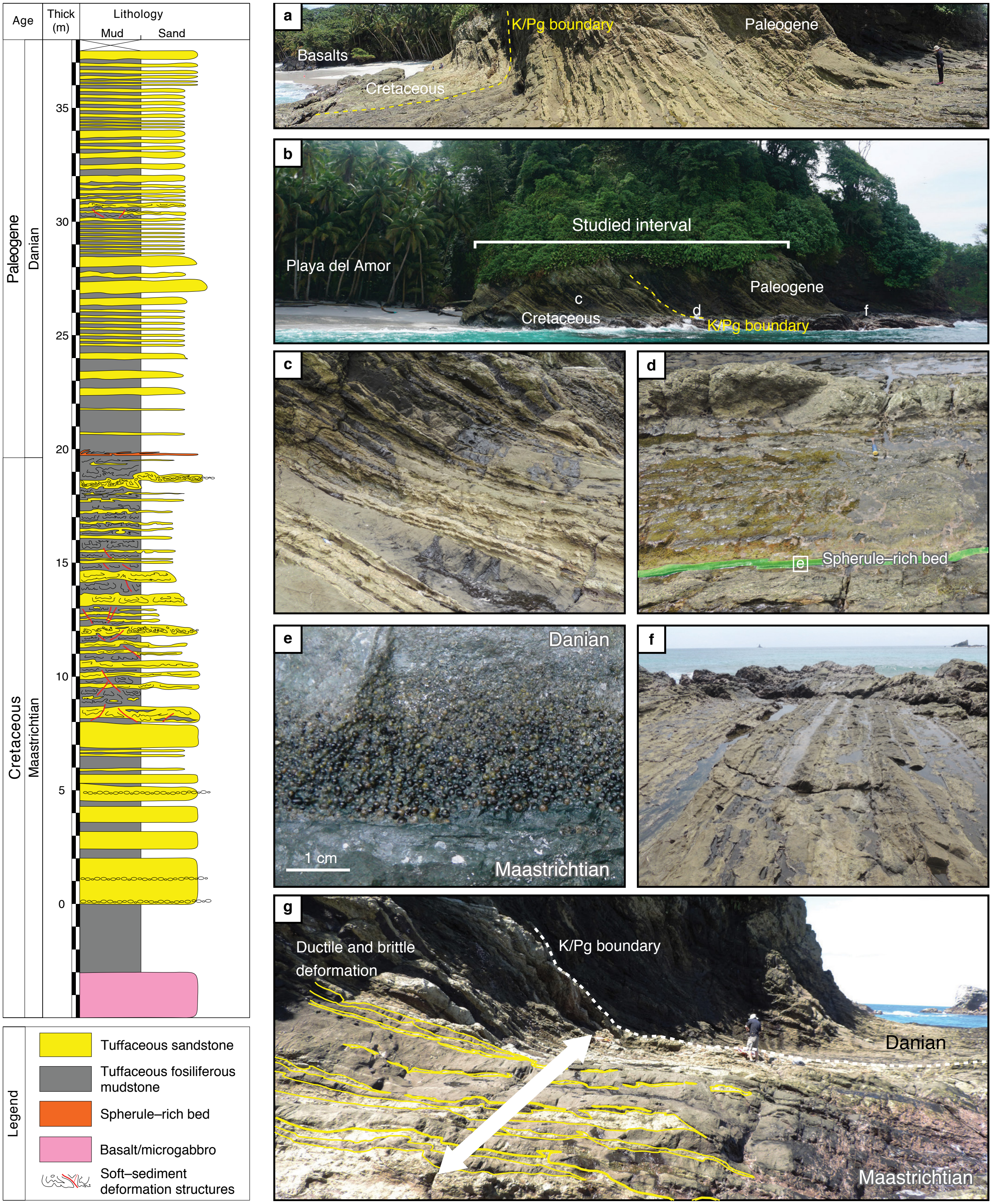


Figure 2. Stratigraphic section at Gorgonilla Island. **(a)** Panoramic view of the studied outcrop during low tide. **(b)** Outcrop overview of the Gorgonilla K/Pg section (c, d, and f indicate location of Figure 2c, 2b, and 2f). **(c)** Maastrichtian rocks below the spherule–rich bed. **(d)** Aspect of the K/Pg boundary showing the interval from the uppermost Maastrichtian to the lowermost Danian. **(e)** Spherule deposit showing the normally graded sequence. **(f)** Danian rocks above the K/Pg boundary. **(g)** Upper Maastrichtian deposits with soft–sediment deformation structures and microfaults.

thrusting, contorted laminae, small–scale convolution, abundant sand injections, and convolute structures (Bermúdez et al., 2015; Renne et al., 2018).

The K/Pg boundary sequence includes a ca. 20 mm thick pristine grayish green to dark green spherule–rich bed (Figure 2e). The deposit is traceable over approximately 20 meters laterally, without significant changes in thickness or lithology; it is normally graded and composed of rounded and compressed 0.1–1.1 mm sized spherules in a matrix composed of calcitic cement, with an absence of clastic grains or microfossils (Figure 3a). The spherule deposit lacks sedimentary structures suggestive of traction or mass flow transport (such as cross bedding, basal or internal scours, reversals, or interruptions in grading).

Spherules are black to olive or translucent–honey colored. The majority are round, but oval, teardrop and dumbbell morphologies are also frequent (Figure 3b), in addition to irregular grape–like clusters of two, three, four, or even more spherules; when broken apart, convex–concave contacts are observed (Bermúdez et al., 2016). Approximately 70% of the spherules are massive glass (microtektites); the other 30% contain single, or more rarely two or more vesicles. Up to 90% of the glass spherules are unaltered or only partly altered. In thin section, the glass is usually colorless; some spherules are faintly green or yellow. Schlieren textures are frequent. Backscattered electron images occasionally reveal the presence of tiny dendritic and/or fibrous crystals of mafic primary microlites, which suggests that some Gorgonilla spherules are microkrystites (Figure 3c–f).

The chemical composition of unaltered or minimally altered glass spherules at Gorgonilla is variable (Figure 4), especially in spherules with schlieren textures. SiO_2 ranges from 48 to 69 wt %, Al_2O_3 from 8 to 15 wt %, FeO from 4.0 to 6.6 wt %, MgO from 1.8 to 4.6 wt %, CaO from 5 to 29 wt %, Na_2O from 0.9 to 5 wt %, and K_2O from 0.1 to 1.9 wt %. In contrast, totals from the microprobe analyses are close to 100 wt %, indicating a rather low volatiles (Bermúdez et al., 2016).

Planktic foraminiferans are absent in the Cretaceous deposits at Gorgonilla, except for scarce specimens identified in G–11.20 and G–15.30 samples (the numbers represent the stratigraphic position in the sequence), which includes the Maastrichtian index–species *Pseudoguembelina palpebra* (Figure 5). No planktic foraminifera were identified in samples from the deformed microtektite bed, nor in washed residues or thin sections, contrary to previous claims by Gerta KELLER in Bermúdez et al. (2016). Foraminiferans are absent in the 50 mm thick stratigraphic interval between the top of the spherule bed and the first sample (G–19.98), with preserved planktic foraminifera, whose assemblages belong to the Zone Pα, in the basal Danian (Renne et al., 2018). These assemblages include index–species such as *Parvularugoglobigerina longiapertura*, *Parvularugoglobigerina eugubina,* and *Eoglobigerina simplicissima*.

All samples, without exception, were poor in organic matter. Green algae are present through the succession, which possibly reflect an influx of fresh–water from tropical wetland environments. Importantly, relatively abundant assemblages of the water fern *Azolla*, represented by microspores and the megaspore *massulae*, appear above the spherule bed together with fern spores, including *Cyathidites minor*, *Gleicheniidites senonicus*, and *Deltoidospora toralis* (Figure 5). These cooccur with sparse fungal spores and clusters of fungal hyphae.

To test whether the Gorgonilla spherules are Chicxulub–derived tektites, Renne et al. (2018) used $^{40}Ar/^{39}Ar$ methods to date them. Incremental heating of 25 individual spherules, in 9 to 15 steps, yielded plateau ages for all spherules, with 19/25 yielding 100% concordant plateau and the remainder comprising >85% of the ^{39}Ar released. The weighted mean of all plateau ages is 66.051 ± 0.031 Ma (1 sd, analytical uncertainties only). This age is indistinguishable from the $^{40}Ar/^{39}Ar$ ages (66.038 ± 0.025 Ma) of the Haitian tektites, and from the age (66.043 ± 0.010 Ma) of the K/Pg boundary (Renne et al., 2013).

4. Discussion

The external geometry, faint normal grain size gradation and sorting, and micropaleontological assemblages at the Gorgonilla Island K/Pg section suggest that this rhythmic bedding sequence was deposited as turbidites in pelagic bathyal environments. The evidence suggests that the Gorgonilla site was close enough (2000–3000 km) to the impact site to receive 20 mm of ejecta, yet also located far enough away from the shelf edge so as not to be affected by the destabilization and collapse of the continental margin. Its pelagic position in deep water in the tropical western Pacific likely protected the Gorgonilla spherule bed from reworking by impact–induced tsunami waves (Bermúdez et al., 2016). The absence of siliciclastic debris, bioturbation, or microfossils indicates rapid deposition and an absence of reworking. This is also supported by the excellent preservation of delicate details of the texture, such as the convex–concave contacts and agglutination of spherules. This suggests parautochthonous deposition and indicates that Gorgonilla's spherules settled within a water column with minimal disturbance.

The stratigraphic position of the Gorgonilla spherule bed, coupled with preliminary biostratigraphic and geochemical data (Bermúdez et al., 2016), suggests that these spherules are correlative with those found in many circum–Caribbean locations closely associated with the K/Pg boundary and ascribed to impact melt produced by the Chicxulub impact. The range of the main elemental compositions and the oxide variation of the Gorgonilla glasses are compatible with those from Beloc, Haiti and Mimbral, and Mexico. The average chemical compositions are similar to those of yellow and black glasses from

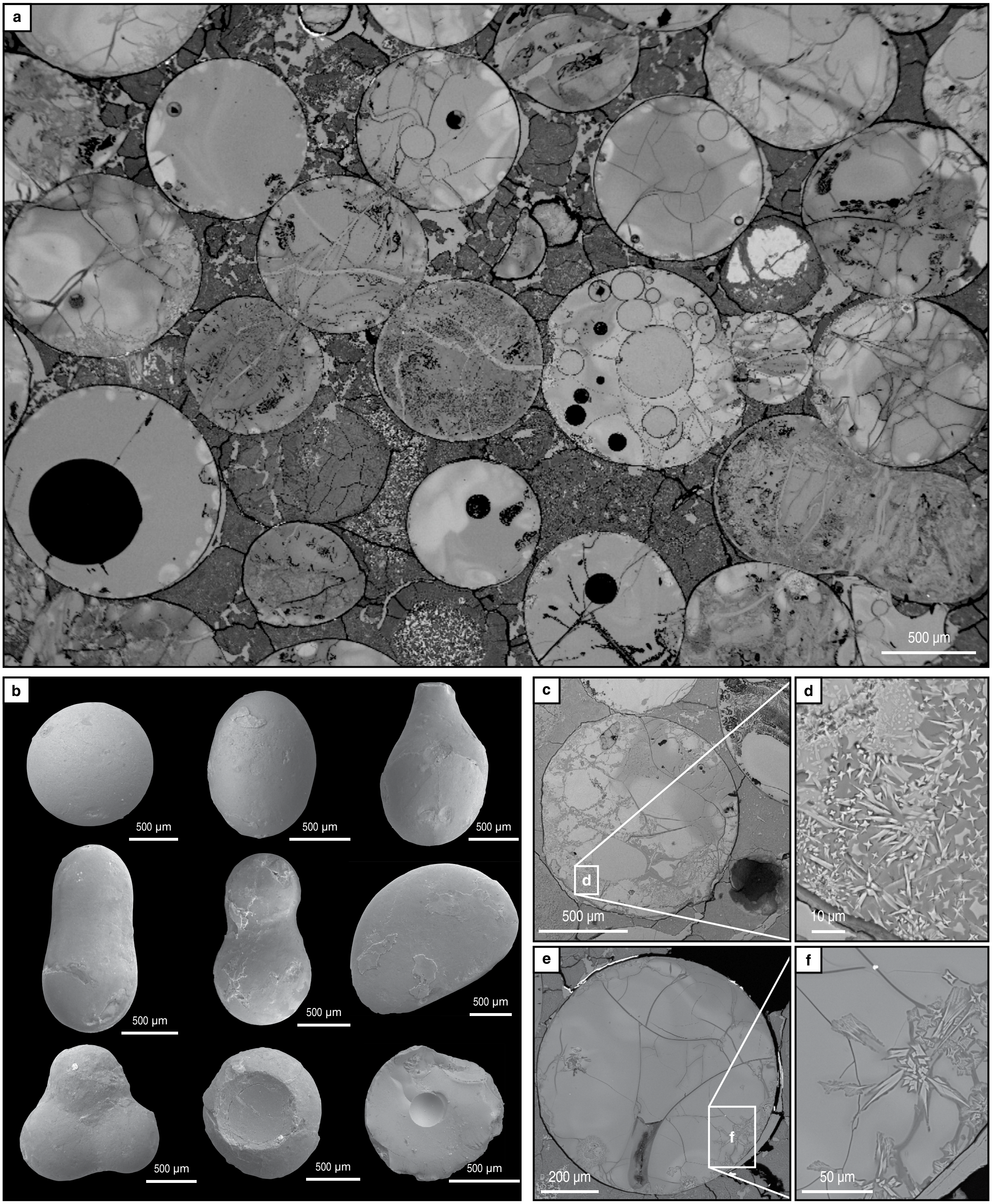


Figure 3. Spherules from the Gorgonilla Island K/Pg section. **(a)** SEM microphotograph of the bottom of the spherule–rich bed, showing a matrix composed by calcitic cement, absence of clastic grains or reworked microfossils, and round, oval, and compressed spherules with concave/convex contacts. **(b)** Backscattered electron microscope images of selected glass spherules illustrating round, oval, tear–drop, and dumbbell morphologies (scale bar = 500 µm). **(c–f)** Backscattered electron microscope images of microkrystites of the Gorgonilla Island. **(d, f)** Details, illustrating primary microlites.

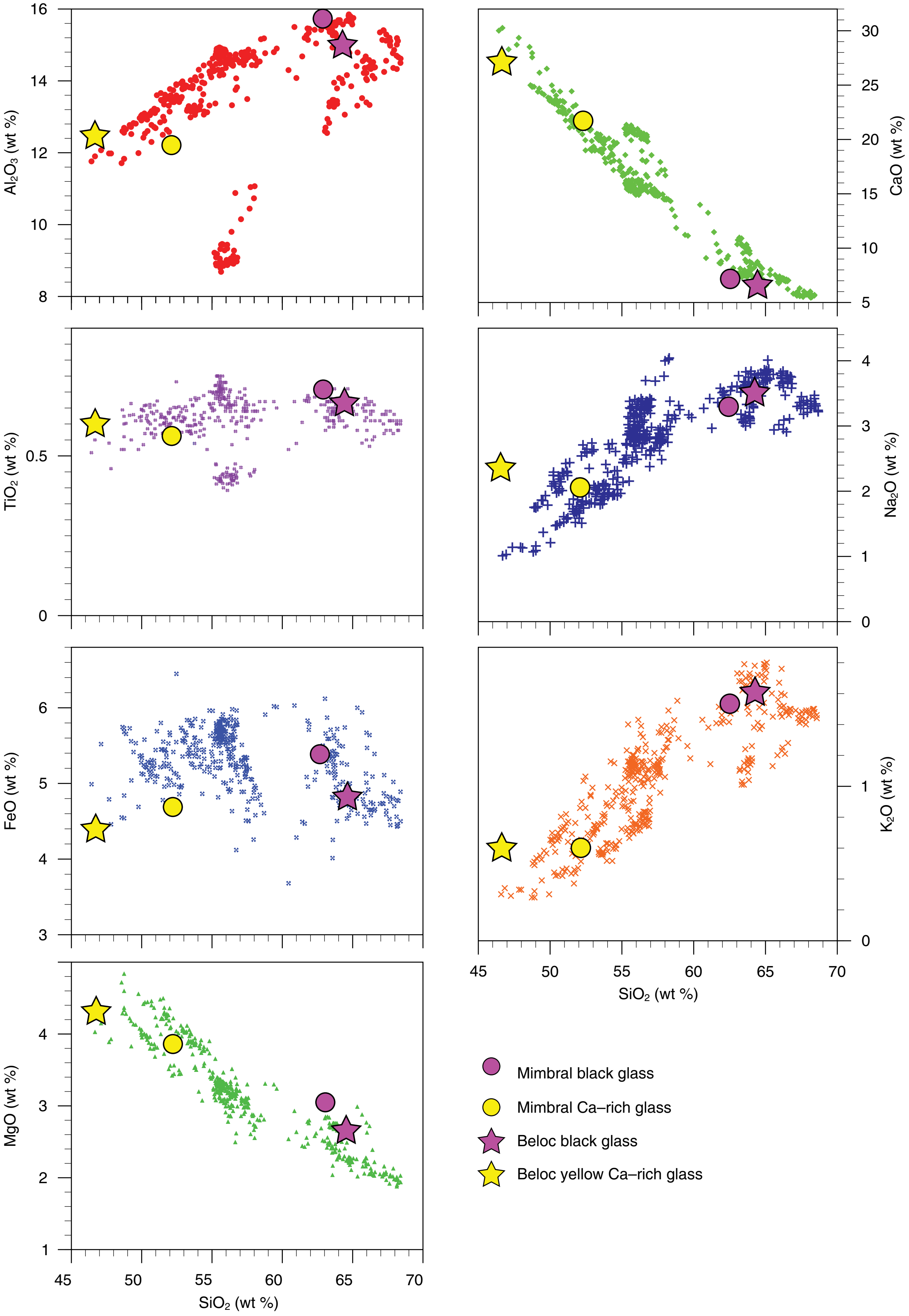


Figure 4. Harker diagrams of selected major and minor elements of the Gorgonilla Island glass spherules. For comparison, average compositions of glasses are shown from the Mimbral (Mexico) and Beloc (Haiti) sites, according to Glass & Simonson (2013). Data from Bermúdez et al. (2016).

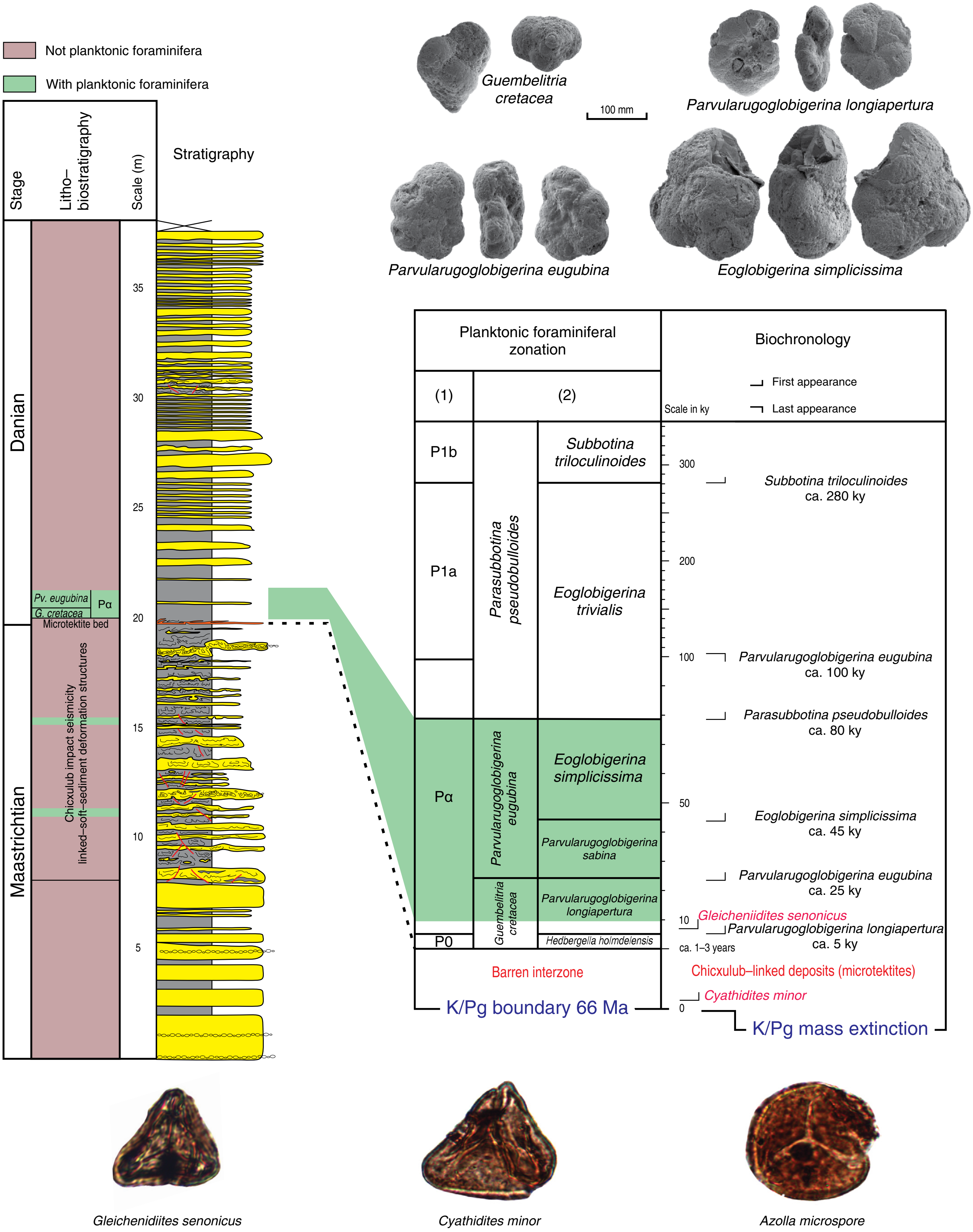


Figure 5. Planktic foraminiferal and palynological record in the Gorgonilla section. The green shading indicates stratigraphic intervals with preserved planktic foraminifera. **(1)** Zonation of Berggren & Pearson (2005). **(2)** Zonation of Arenillas et al. (2004).

Beloc (Glass & Simonson, 2013; Izett et al., 1991; Koeberl & Sigurdsson, 1992).

New micropaleontological and geochemical data confirm a K/Pg age for the spherule bed (Renne et al., 2018). The first Danian biozone (Zone P0) within planktic foraminiferan scales has not been recognized in Gorgonilla. If it were absent, we should infer that there is a small hiatus of no more than 10 ka, according to the biochronological scale of Arenillas et al. (2004). However, this short hiatus would not preclude the conclusion that the spherule bed is chronostratigraphically correlatable to the K/Pg boundary. Moreover, this hiatus could be a local taphonomic artifact in the planktic foraminiferal record. The absence of preserved calcareous microfossils (foraminifera) and the abundance of siliceous microfossils (radiolarians) suggest that the substrate was below the carbonate compensation depth (CCD) for much of the time interval recorded in the Gorgonilla section. Foraminiferans are absent in the 50 mm thick stratigraphic interval between the top of the spherule bed and the first sample with preserved planktic foraminifera, suggesting these sediments were still deposited below the CCD. The dissolution of the foraminiferan tests in this thin stratigraphic interval prevents the verification of whether Zone P0 is present or absent in Gorgonilla.

The fern spores, which only occur above the K/Pg boundary at Gorgonilla, are represented by ground fern taxa such as Gleicheniaceae and *Dictyophyllum*, together with the abundant occurrence of the aquatic fern *Azolla* (Renne et al., 2018). Interestingly, these cooccur with fungal spores and hyphae. A posited fungal spike has previously been described from a New Zealand K/Pg boundary clay coincident with the iridium–enriched layer and was interpreted as a response to short–term darkness (Vajda & McLoughlin, 2004; Vajda et al., 2015). The genus *Azolla* consistently characterizes warm–climate lacustrine environments and first appears in the geological record in Lower Cretaceous successions (Vajda, 1999; Vajda & McLoughlin, 2005). The ranges of many *Azolla* species span the K/Pg boundary and the identification of *Azolla* microspores and massulae in Colombia, directly following the K/Pg boundary event, which at the Gorgonilla locality is marked by the spherule bed (Bermúdez et al., 2016), shows their potential to endure altered environmental conditions. Aquatic ferns such as *Azolla* can reproduce asexually through vegetative regeneration in association with nitrogen–fixing cyanobacterial symbionts, which are shown to be abundant in the same samples. These characteristics provided an advantage in the aftermath of the Chicxulub impact and our results show that not only high–latitudinal settings but also low–latitudinal tropical environments were indeed affected by cooling and darkness.

The global pattern of recovery in the vegetation following the K/Pg mass extinction event is typified in North America (Schulte et al., 2010), Japan (Saito et al., 1986), and New Zealand (Vajda et al., 2001), by a posited fern–spike, an interval of short duration represented by a pioneering succession of ferns (Vajda & Bercovici, 2014). Although end–Cretaceous successions in Europe mainly represent marine depositional settings, the ecological collapse on land following the Chicxulub impact is also traceable in marine strata. In the Netherlands, for example, an anomalous abundance of bryophyte (moss) spores characterize the recovery community preserved within the basal part of the boundary clay (Brinkhuis & Schiøler, 1996; Herngreen et al., 1998). Here, we show the first evidence of post-impact recovery vegetation expressed by a fern–spike from the paleo–tropics.

The $^{40}Ar/^{39}Ar$ dating suggests the spherule age is 66.051 ± 0.031 Ma (Renne et al., 2018). This age is indistinguishable from the $^{40}Ar/^{39}Ar$ ages (66.038 ± 0.025 Ma) of the Haitian tektites and from the age (66.043 ± 0.010 Ma) of the K/Pg boundary (Renne et al., 2013). Thus, we conclude that the Gorgonilla spherules are tektites produced by the Chicxulub impact at the K/Pg boundary.

The uppermost Maastrichtian and the K/Pg boundary deposits at Gorgonilla were affected by intense soft–sediment deformation and bed disruption, and provide evidence for syndepositional microfaulting and faulting, injectites, hydroplastic mixed layers, small–scale slumping, fault–graded beds, and pillar and flame structures. These features are found between undisturbed Maastrichtian and Danian sediments, including the spherule–rich bed (Bermúdez et al., 2015, 2017; Renne et al., 2018). They show the development of three different zones (soupy zone, rubble zone, and segmented zone) and make evident gradational contacts between these zones and the bottom, but with a sharp boundary at the top (Figure 6). These features are typical of seismites (Montenat et al., 2007; Obermeier, 1996; Seilacher, 1969).

The evidence indicates that the bed–disruption processes began slightly before but continued during the emplacement of the ejecta deposit. The ubiquitous and obvious deformation of the Maastrichtian sediments cannot be explained by differences in lithology between the Maastrichtian and Paleogene strata, local tectonism, or the paleogeographic setting, but must result from seismic activity produced by the single very–high–energy Chicxulub impact. Large–scale seismicity, including magnitude 10+ earthquakes, are a predicted consequence of this impact (e.g., Boslough et al., 1996; Pierazzo & Artemieva, 2012; Schulte et al., 2010, 2012; Shoemaker et al., 1990). Accordingly, soft–sediment deformation structures, chaotic sediments mixtures and disturbed beds, "shale diapirs", injection structures, steeply to vertically inclined sedimentary beds, slumps, folds, microfaults and faults, steeply and chaotic seismic reflectors, etc. were reported from a variety of sections in Mexico, USA, the NW Atlantic Ocean, Caribbean, and the Gulf of Mexico (Figure 7); they have been explained as sediment liquefaction, platform collapse, large–scale slope failures, and

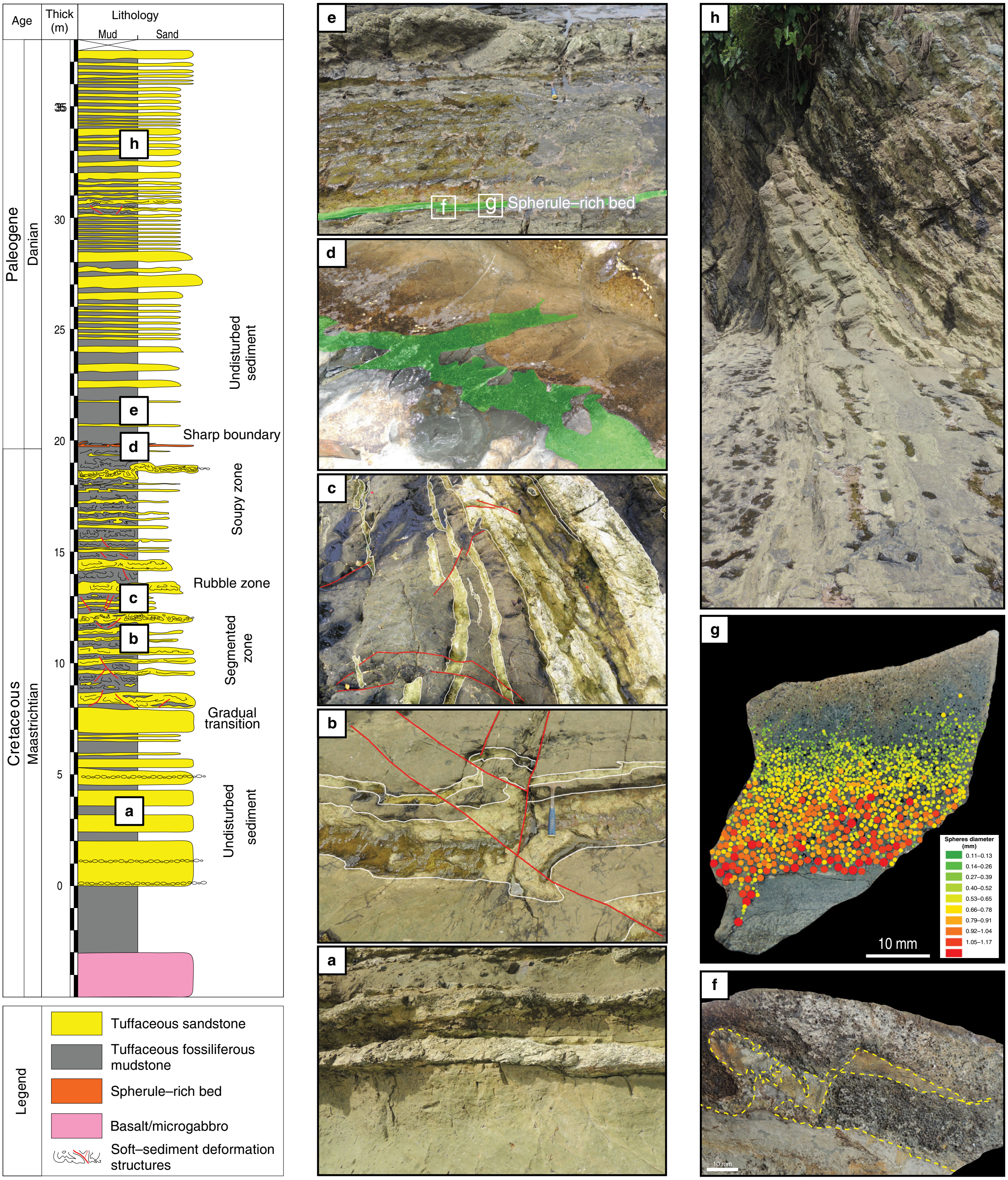


Figure 6. Stratigraphic section, illustrating the position of deformed zones and representative examples. **(a)** Maastrichtian undisturbed sediments, approximately 15 m below the K/Pg boundary. **(b)** Opposite vergent structures in the segmented zone, 10 m below the K/Pg boundary. **(c)** Rubble zone, 8 m below the K/Pg boundary, with predominance of plastic deformation in opposite directions, but with no major lateral transport. **(d)** Plastic deformation at the top of the soupy zone, involving the K/Pg spherule–rich bed. **(e)** Undisturbed sediments of the lowermost Danian, just above the K/Pg boundary. **(f–g)** Detail of the soft–sediment deformation in the K/Pg spherule bed (f and g in Figure 6e). **(h)** Undisturbed sediments of the Danian, 12 m above the K/Pg boundary.

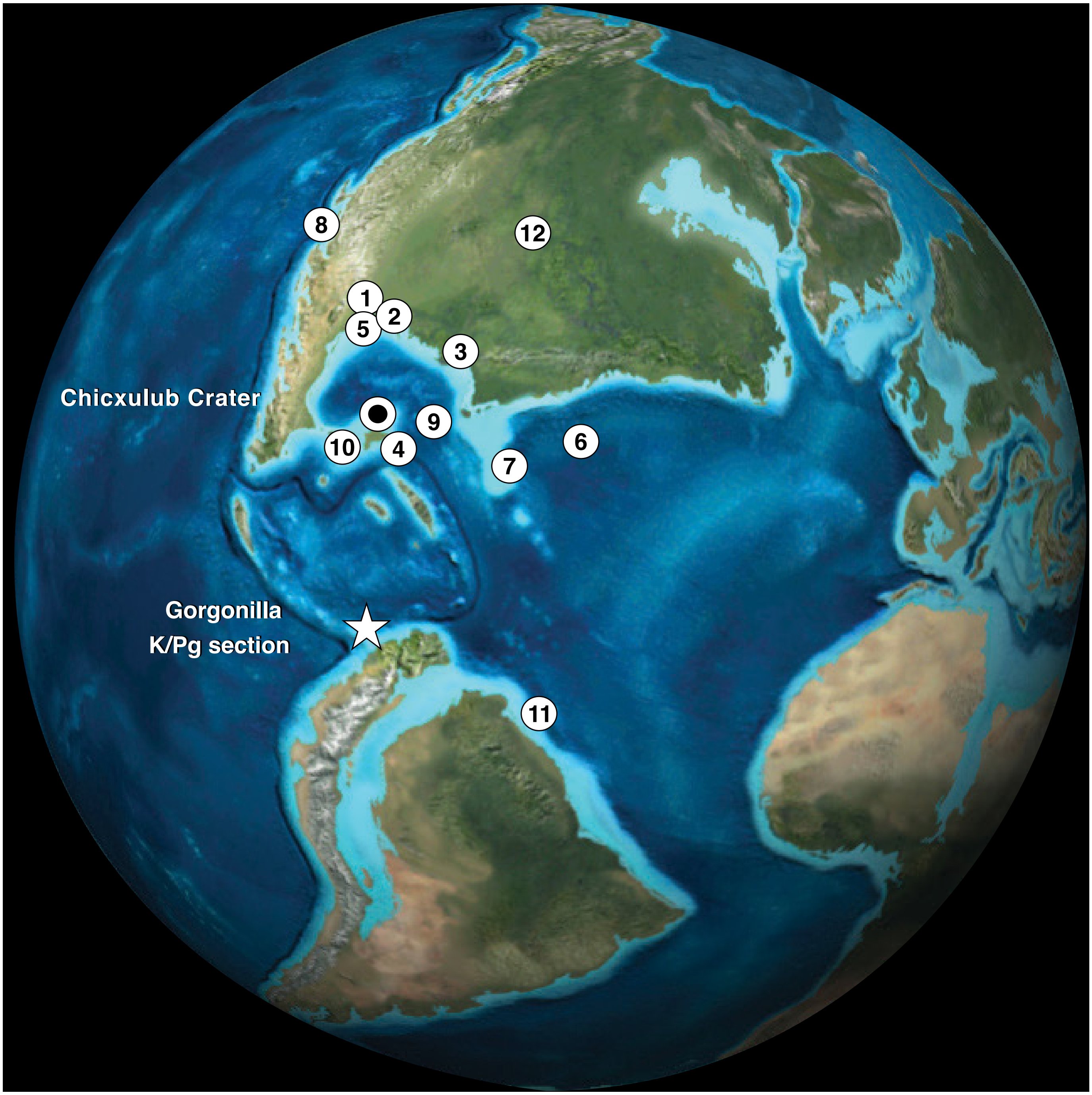


Figure 7. Paleogeographic map of key areas exhibiting evidence of Chicxulub impact–induced seismicity. **(1)** La Popa Basin, NE Mexico. **(2)** Brazos Texas, USA; NE Mexico (La Sierrita, Mimbral, El Toro sections). **(3)** Alabama, USA. **(4)** DSDP Sites 536 & 540, Gulf of Mexico. **(5)** El Tecolote, NE Mexico. **(6)** Bermuda Rise. **(7)** Black Nose. **(8)** Baja California, Mexico. **(9)** Gulf of Mexico. **(10)** SE Mexico. **(11)** Demerara Rise, South Atlantic. **(12)** South Dakota, USA. Source: Bermúdez et al. (2015).

catastrophic sedimentation by bolide impact–related seismic shocking (e.g., Arenillas et al., 2006; Arz et al., 2001, 2004; Bralower et al., 1998; Busby et al., 2002; Denne et al., 2013; Grajales–Nishimura et al., 2000; Klaus et al., 2000; MacLeod et al., 2007; Norris & Firth, 2002; Norris et al., 2000; Schulte et al., 2009, 2010, 2012; Smit et al., 1996; Soria et al., 2001; Stoffer et al., 2001).

Different from the situation in these proximal sections, the seismic energy did not cause erosion, slope failure, and severe reworking of fossils and lithologies of different ages at this study site (frequently known as the K/T (now K/Pg) "impact cocktail"; Bralower et al., 1998). Slope failure debris deposits or evident traction transport of sediments are not seen in the deformed Maastrichtian sequence at Gorgonilla (Bermúdez et al., 2017). Even though intense ductile and brittle deformation reaches to 12 m below the ejecta bed, these sediments are still placed in their correct stratigraphic order, and the sequence appears structurally intact. The spherule bed, for instance, is continuous over a distance of more than 15 meters and does not show changes in thickness or texture. Soft sediment deformation at this deep ocean site, at approximately 2000–3000 km distance from Chicxulub impact site, thus resulted in in situ liquefaction and microfaulting of soft and semilithified sediments.

The presence of in situ deformed sediments in northern South America strengthens the evidence that seismic shaking generated by the impact, and possible aftershocks, represents a major geological event that affected the uppermost Maastrichtian sediments in a vast region; the seismic energy released was sufficient to affect localities more than 2000 km from the Chicxulub impact site (Renne et al., 2018). The interpretation of the K/Pg boundary deposits in areas proximal to the impact site should be revised with caution, since the effects of seismic deformation would affect the position and distribution of ejecta in the Chicxulub–linked clastic units (e.g., deposits of eventual collapse of continental shelves and/or associated tsunamites).

5. Conclusions

This study confirms the first evidence of Chicxulub ejecta deposits (K/Pg boundary) in Colombia, South America, and the eastern Pacific Ocean.

The Gorgonilla Island spherule bed is approximately 20 mm thick and consists of extraordinarily well–preserved glass spherules (microtektites and microkrystites) up to 1.1 mm in diameter.

The size, morphology, and chemical composition of these spherules are similar to Chicxulub spherule ejecta from North and Central America, and the Caribbean, but differ in their unrivaled excellent preservation (up to 90% of the spherules are still completely vitrified). The Gorgonilla spherule bed thus represents a deposit of the most pristine K/Pg boundary spherules known to date.

The ejecta deposit is normally graded, with no evidence for traction transport, subsequent reworking or bioturbation, and thus, indicates that the Gorgonilla spherules settled within a water column with minimal disturbance.

^{40}Ar/^{39}Ar dating, geochemical, and micropaleontological analyses reveal that the Gorgonilla spherule bed resulted from the Chicxulub impact.

The basal deposits of the Danian in Gorgonilla Island demonstrate the first evidence of a recovery vegetation represented by ferns from a tropical habitat closely following the end–Cretaceous event.

The presence of intense soft–sediment deformation and bed disruption in Maastrichtian sediments of the Gorgonilla Island K/Pg section, provide proof for seismic activity triggered by the Chicxulub bolide impact, and strengthens the evidence that seismic shaking generated by the meteorite collision, and possible aftershocks, represents a major geological event that affected the uppermost Maastrichtian sediments in a vast region.

Acknowledgments

We thank Francisco J. VEGA, and Wolfgang STINNESBECK for corrections and suggestions that significantly improved this manuscript. This research was supported by Grupo de Investigación Paleoexplorer (Paleoexplorer SAS, Colombia). Victoria Elena CORREDOR, Luz Stella BOLÍVAR, and Alejandro NUMPAQUE are acknowledged for their assistance in the 2014 geological campaign. We acknowledge Parques Nacionales Naturales de Colombia, particularly María Ximena ZORRILLA and Luis Fernando PAYÁN, for their support during the fieldwork and for granting access to Gorgona National Natural Park. We thank Liliana BOLÍVAR (CEO Paleoexplorer SAS), Wolfgang STINNESBECK, Mario TRIELOFF, Michael HANEL, Jens HOPP, and Winfried H. SCHWARZ (Heidelberg University), and Francisco J. VEGA (Universidad Nacional Autónoma de México) for their invaluable contribution to the 2016 report. For José ARZ, Ignacio ARENILLAS, and Vicente GILABERT this study is a contribution to project CGL2015–64422–P (MINECO/FEDER–UE) and is also partially supported by the Departamento de Educación y Ciencia of the Aragonian Government, co–financed by the European Social Fund (grant number DGA group E05). Vicente GILABERT acknowledges support from the Spanish Ministerio de Economía, Industria y Competitividad (FPI grant BES–2016–077800). P.R, was supported by the Ann and Gordon Getty Foundation. V.V. was supported by the Swedish Research Council (VR grant 2015–4264, and LUCCI, Lund University Carbon Cycle Centre).

References

Albertão, G.A. & Martins, P.P. 1996. A possible tsunami deposit at the Cretaceous – Tertiary boundary in Pernambuco, Northeastern Brazil. Sedimentary Geology, 104(1–4): 189–201. https://doi.org/10.1016/0037-0738(95)00128-X

Albertão, G.A., De Azevedo–Grassi, A., Marini, F., Martins, P.P. & De Ross, L.F. 2004. The K–T boundary in Brazilian marginal sedimentary basins and related spherules. Geochemical Journal, 38(2): 121–128. https://doi.org/10.2343/geochemj.38.121

Alvarez, L.W., Alvarez, W., Asaro, F. & Michel, H.V. 1980. Extraterrestrial cause for the Cretaceous – Tertiary extinction. Science, 208(4448): 1095–1108. https://doi.org/10.1126/science.208.4448.1095

Arenillas, I., Arz, J.A. & Molina, E. 2004. A new high–resolution planktic foraminiferal zonation and subzonation for the lower Danian. Lethaia, 37(1): 79–95. https://doi.org/10.1080/00241160310005097

Arenillas, I., Arz, J.A., Grajales–Nishimura, J.M., Murillo–Muñetón, G., Alvarez, W., Camargo–Zanoguera, A., Molina, E. & Rosales–Domínguez, C. 2006. Chicxulub impact event is Cretaceous/Paleogene boundary in age: New micropaleontological evidence. Earth and Planetary Science Letters, 249(3–4): 241–257. https://doi.org/10.1016/j.epsl.2006.07.020

Arz, J.A., Alegret, L., Arenillas, I., Liesa, C., Molina, E. & Soria, A.R. 2001. Extinción de foraminíferos en el límite Cretácico/terciario en Coxquihui (México) y su relación con las evidencias de impacto. Revista Española de Micropaleontología, 33(2): 221–236.

Arz, J.A., Alegret, L. & Arenillas, I. 2004. Foraminiferal biostratigraphy and paleoenvironmental reconstruction at the Yaxcopoil–1 drill hole, Chicxulub Crater, Yucatán Peninsula. Meteoritics & Planetary Science, 39(7): 1099–1111. https://doi.org/10.1111/j.1945-5100.2004.tb01131.x

Berggren, W.A. & Pearson, P.N. 2005. A revised tropical to subtropical Paleogene planktonic foraminiferal zonation. Journal of Foraminiferal Research, 35(4): 279–298. https://doi.org/10.2113/35.4.279

Bermúdez, H.D., Stinnesbeck, W., Bolívar, L., Rodríguez, J.V., García, J. & Vega, F.J. 2015. Paleosismitas asociadas al límite K/Pg en la isla de Gorgonilla, Pacífico colombiano. XV Congreso Colombiano de Geología. Abstracts CD ROM, p. 1080.

Bermúdez, H.D., García, J., Stinnesbeck, W., Keller, G., Rodríguez, J.V., Hanel, M., Hopp, J., Schwarz, W., Trieloff, M., Bolívar, L. & Vega, F.J. 2016. The Cretaceous – Paleogene boundary at Gorgonilla Island, Colombia, South America. Terra Nova, 28(1): 83–90. https://doi.org/10.1111/ter.12196

Bermúdez, H.D., Arz, J.A., Renne, P.R., Arenillas, I., Gilabert, V., Rodríguez, J.V., Bolívar, L. & Bolívar, L.S. 2017. Evidence for Chicxulub impact seismicity at Gorgonilla Island K/Pg section, Pacific of Colombia. Geological Society of America Abstracts with Programs, 49(6). https://doi.org/10.1130/abs/2017AM-299005

Boslough, M.B., Chael, E.P., Trucano, T.G., Crawford, D.A. & Campbell, D.L. 1996. Axial focusing of impact energy in the Earth's interior: A possible link to flood basalts and hotspots. In: Ryder, G., Fastovsky, D. & Gartner, S. (editors), The Cretaceous – Tertiary event and other catastrophes in Earth history. Geological Society of America, Special Paper 307, p. 541–550. https://doi.org/10.1130/0-8137-2307-8.541

Bralower, T.J., Paull, C.K. & Leckie, R.M. 1998. The Cretaceous – Tertiary boundary cocktail: Chicxulub impact triggers margin collapse and extensive sediment gravity flows. Geology, 26(4): 331–334. https://doi.org/10.1130/0091-7613(1998)026<0331:TCTBCC>2.3.CO;2

Brinkhuis, H. & Schiøler, P. 1996. Palynology of the Geulhemmerberg Cretaceous/Tertiary boundary section (Limburg, SE Netherlands). Geologie en Mijnbouw, 75(2): 193–213.

Busby, C.J., Yip, G., Blikra, L. & Renne, P. 2002. Coastal landsliding and catastrophic sedimentation triggered by Cretaceous – Tertiary bolide impact: A Pacific margin example? Geology, 30(8): 687–690. https://doi.org/10.1130/0091-7613(2002)030<0687:CLACST>2.0.CO;2

Denne, R.A, Scott, E.D., Eickhoff, D.P., Kaiser, J.S., Hill, R.J. & Spaw, J.M. 2013. Massive Cretaceous – Paleogene boundary deposit, deep–water Gulf of Mexico: New evidence for widespread Chicxulub–induced slope failure. Geology, 41(9): 983–986. https://doi.org/10.1130/G34503.1

Dietrich, V.J., Gansser, A., Sommerauer, J. & Cameron, W.E. 1981. Palaeogene komatiites from Gorgona Island, East Pacific—A primary magma for ocean floor basalts? Geochemical Journal, 15(3): 141–161. https://doi.org/10.2343/geochemj.15.141

Echeverria, L.M. & Aitken, B.G. 1986. Pyroclastic rocks: Another manifestation of ultramafic volcanism on Gorgona Island, Colombia. Contributions to Mineralogy and Petrology, 92(4): 428–436. https://doi.org/10.1007/BF00374425

Gansser, A. 1950. Geological and petrographical notes on Gorgona Island in relation to north–western South America. Schweizerische Mineralogische und Petrographische Mitteilungen, 30: 219–237.

Gansser, A., Dietrich, V.J. & Cameron, W.E. 1979. Palaeogene komatiites from Gorgona Island. Nature, 278: 545–546. https://doi.org/10.1038/278545a0

Gertsch, B., Keller, G., Adatte, T. & Berner, Z. 2013. The Cretaceous – Tertiary boundary (KTB) transition in NE Brazil. Journal of the Geological Society, 170(2): 249 –262. https://doi.org/10.1144/jgs2012-029

Glass, B.P. & Simonson, B.M. 2013. Distal impact ejecta layers: A record of large impacts in sedimentary deposits. Springer, 716 p. Berlin. https://doi.org/10.1007/978-3-540-88262-6

Grajales–Nishimura, J.M., Cedillo–Pardo, E., Rosales–Domínguez, M.C., Morán–Zenteno, D.J., Alvarez, W., Claeys, P., Ruiz–Morales, J., García–Hernández, J., Padilla–Avila, P. & Sánchez–Ríos, A. 2000. Chicxulub impact: The origin of reservoir and seal facies in the southeastern Mexico oil fields. Geology, 28(4): 307–310. https://doi.org/10.1130/0091-7613(2000)28<307:CITOOR>2.0.CO;2

Herngreen, G.F.W., Schuurman, H.A.H.M., Verbeek, J.W., Brinkhuis, H., Burnett, J.A., Felder, W.M. & Kedves, M. 1998. Biostratigraphy of Cretaceous/Tertiary boundary strata in the Curfs quarry, the Netherlands. Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen (61), 58 p. Haarlem, the Netherlands.

Hildebrand, A.R., Penfield, G.T., Kring, D.A., Pilkington, M., Camargo, A., Jacobsen, S.B. & Boynton, W.V. 1991. Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico. Geology, 19(9): 867–871. https://doi.org/10.1130/0091-7613(1991)019<0867:CCAPCT>2.3.CO;2

Izett, G.A., Dalrymple, G.B. & Snee, L.W. 1991. ^{40}Ar/^{39}Ar age of Cretaceous – Tertiary boundary tektites from Haiti. Science, 252(5012): 1539–1542. https://doi.org/10.1126/science.252.5012.1539

Keller, G. 2011. The Cretaceous – Tertiary mass extinction: Theories and controversies. In: Keller, G. & Adatte, T. (editors), End–Cretaceous mass extinction and the Chicxulub impact in Texas. Society for Sedimentary Geology, Special Publication 100, p. 7–22. Tulsa, USA. https://doi.org/10.2110/sepmsp.100.007

Keller, G., Adatte, T., Stinnesbeck, W., Stüben, D. & Berner, Z. 2001. Age, chemo– and biostratigraphy of Haiti spherule–rich deposits: A multi–event K–T scenario. Canadian Journal of Earth Sciences, 38(2): 197–227. https://doi.org/10.1139/e00-087

Keller, G., Stinnesbeck, W., Adatte, T. & Stüben, D. 2003a. Multiple impacts across the Cretaceous – Tertiary boundary. Earth–Science Reviews, 62(3–4): 327–363. https://doi.org/10.1016/S0012-8252(02)00162-9

Keller, G., Stinnesbeck, W., Adatte, T., Holland, B., Stüben, D., Harting, M., De León, C. & De la Cruz, J. 2003b. Spherule deposits in Cretaceous – Tertiary boundary sediments in Belize and Guatemala. Journal of the Geological Society, 160(5): 783–795. https://doi.org/10.1144/0016-764902-119

Keller, G., Adatte, T., Tantawy, A.A., Berner, Z., Stinnesbeck, W., Stüben, D. & Leanza, H.A. 2007. High stress late Maastrichtian – early Danian palaeoenvironment in the Neuquén Basin, Argentina. Cretaceous Research, 28(6): 939–960. https://doi.org/10.1016/j.cretres.2007.01.006

Keller, G., Khozyem, H., Adatte, T., Malarkodi, N., Spangenberg, J. & Stinnesbeck, W. 2013. Chicxulub impact spherules in the North Atlantic and Caribbean: Age constraints and Cretaceous – Tertiary boundary hiatus. Geological Magazine, 150(5): 885–907. https://doi.org/10.1017/S0016756812001069

Kennan, L. & Pindell, J.L. 2009. Dextral shear, terrane accretion and basin formation in the northern Andes: Best explained by interaction with a Pacific–derived Caribbean Plate? In: James, K.H., Lorente, M.A. & Pindell, J.L. (editors), The origin and evolution of the Caribbean Plate. Geological Society of London, Special Publication 328, p. 487–531. https://doi.org/10.1144/SP328.20

Kerr, A.C. 2005. La isla de Gorgona, Colombia: A petrological enigma? Lithos, 84(1–2): 77–101. https://doi.org/10.1016/j.lithos.2005.02.006

Kerr, A.C. & Tarney, J. 2005. Tectonic evolution of the Caribbean and northwestern South America: The case for accretion of two Late Cretaceous oceanic plateaus. Geology, 33(4): 269–272. https://doi.org/10.1130/G21109.1

Klaus, A., Norris, R.D., Kroon, D. & Smit, J. 2000. Impact–induced mass wasting at the K–T boundary: Blake Nose, western North Atlantic. Geology, 28(4): 319–322. https://doi.org/10.1130/0091-7613(2000)28<319:IMWATK>2.0.CO;2

Koeberl, C. & Sigurdsson, H. 1992. Geochemistry of impact glasses from the K/T boundary in Haiti: Relation to smectites and a new types of glass. Geochimica et Cosmochimica Acta, 56(5): 2113–2129. https://doi.org/10.1016/0016-7037(92)90333-E

MacLeod, K.G., Whitney, D.L., Huber, B.T. & Koeberl, C. 2007. Impact and extinction in remarkably complete Cretaceous – Tertiary boundary sections from Demerara Rise, tropical western North Atlantic. Geological Society of America Bulletin, 119(1–2): 101–115. https://doi.org/10.1130/B25955.1

Montenat, C., Barrier, P., Ott–d'Estevou, P. & Hibsch, C. 2007. Seismites: An attempt at critical analysis and classification. Sedimentary Geology, 196(1–4): 5–30. https://doi.org/10.1016/j.sedgeo.2006.08.004

Morgan, J., Lana, C., Kearsley, A., Coles, B., Belcher, C., Montanari, S., Díaz–Martínez, E., Barbosa, A. & Neumann, V. 2006. Analyses of shocked quartz at the global K–P boundary indicate an origin from a single, high–angle, oblique impact at Chicxulub. Earth and Planetary Science Letters, 251(3–4): 264–279. https://doi.org/10.1016/j.epsl.2006.09.009

Norris, R.D. & Firth. J.V. 2002. Mass wasting of Atlantic continental margins following the Chicxulub impact event. In: Koeberl, C. & MacLeod, K.G. (editors), Catastrophic events and mass extinctions: Impacts and beyond. Geological Society of America, Special Paper 356, p. 79–95. https://doi.org/10.1130/0-8137-2356-6.79

Norris, R.D., Huber, B.T. & Self–Trail, J. 1999. Synchroneity of the K–T oceanic mass extinction and meteorite impact: Blake Nose, western North Atlantic. Geology, 27(5): 419–422. https://doi.org/10.1130/0091-7613(1999)027<0419:SOTKTO>2.3.CO;2

Norris, R.D., Firth, J., Blusztajn, J. & Ravizza, G. 2000. Mass failure of the North Atlantic margin triggered by the Cretaceous – Paleogene bolide impact. Geology, 28(12): 1119–1122. https://doi.org/10.1130/0091-7613(2000)28<1119:mfotna>2.0.co;2

Obermeier, S.F. 1996. Use of liquefaction–induced features for paleoseismic analysis—An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo–earthquakes. Engineering Geology, 44(1–4): 1–76. https://doi.org/10.1016/S0013-7952(96)00040-3

Ocampo, A.C., Pope, K.O. & Fischer, A.G. 1996. Ejecta blanket deposits of the Chicxulub Crater from Albion Island, Belize. In: Ryder, G., Fastovsky, D. & Gartner, S. (editors), The Cretaceous – Tertiary event and other catastrophes in Earth history. Geological Society of America, Special Paper 307, p. 75–88. Boulder, USA. https://doi.org/10.1130/0-8137-2307-8.75

Olsson, R.K., Miller, K.G., Browning, J.V., Habib, D. & Sugarman, P.J. 1997. Ejecta layer at the Cretaceous – Tertiary boundary, Bass River, New Jersey (Ocean Drilling Program Leg 174AX). Geology, 25(8): 759–762. https://doi.org/10.1130/0091-7613(1997)025<0759:ELATCT>2.3.CO;2

Pierazzo, E. & Artemieva, N. 2012. Local and global environmental effects of impacts on Earth. Elements, 8(1): 55–60. https://doi.org/10.2113/gselements.8.1.55

Pope, K.O., Ocampo, A.C. & Duller, C.E. 1991. Mexican site for K/T impact crater? Nature, 351: 105. https://doi.org/10.1038/351105a0

Renne, P.R., Balco, G., Ludwig, K.R., Mundil, R. & Min, K. 2011. Response to the comment by W.H. Schwarz et al. on "Joint determination of ^{40}K decay constants and ^{40}Ar*/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology" by P.R. Renne et al. (2010). Geochimica et Cosmochimica Acta, 75(17): 5097–5100. https://doi.org/10.1016/j.gca.2011.06.021

Renne, P.R., Deino, A.L., Hilgen, F.J., Kuiper, K.F., Mark, D.F., Mitchell, W.S., Morgan, L.E., Mundil, R. & Smit, J. 2013. Time scales of critical events around the Cretaceous – Paleogene boundary. Science, 339(6120): 684–687. https://doi.org/10.1126/science.1230492

Renne, P.R., Arenillas, I., Arz, J.A., Gilabert, V. & Bermúdez, H.D. 2017. New ^{40}Ar/^{39}Ar and planktonic foraminiferal data indicate a KPB age for the Chicxulub–linked spherule bed at Gorgonilla Island, Pacific of Colombia. Geological Society of America Abstracts with Programs, 49(6). https://doi.org/10.1130/abs/2017AM-299581

Renne, P.R., Arenillas, I., Arz, J.A., Vajda, V., Gilabert, V. & Bermúdez, H.D. 2018. Multi–proxy record of the Chicxulub impact at the Cretaceous – Paleogene boundary from Gorgonilla Island, Colombia. Geology, 46(6): 547–550. https://doi.org/10.1130/G40224.1

Saito, T., Yamanoi, K. & Kaiho, K. 1986. End–Cretaceous devastation of terrestrial flora in the boreal Far East. Nature, 323: 253–255. https://doi.org/10.1038/323253a0

Scasso, R.A., Concheyro, A., Kiessling, W., Aberhan, M., Hecht, L., Medina, F.A. & Tagle, R. 2005. A tsunami deposit at the Cretaceous/Paleogene boundary in the Neuquén Basin of Argentina. Cretaceous Research, 26(2): 283–297. https://doi.org/10.1016/j.cretres.2004.12.003

Schulte, P., Deutsch, A., Salge, T., Berndt, J., Kontny, A., MacLeod, K.G., Neuser, R.D. & Krumm, S. 2009. A dual–layer Chicxulub ejecta sequence with shocked carbonates from the Cretaceous – Paleogene (K–Pg) boundary, Demerara Rise, western Atlantic. Geochimica et Cosmochimica Acta, 73(4): 1180–1204. https://doi.org/10.1016/j.gca.2008.11.011

Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., Bralower, T.J., Christeson, G.L., Claeys, P., Cockell, C.S., Collins, G.S., Deutsch, A., Goldin, T.J., Goto, K., Grajales–Nishimura, J.M., Grieve, R.A.F., Gulick, S.P.S., Johnson, K.R., Kiessling, W., Koeberl, C., Kring, D.A., MacLeod, K.G., Matsui, T., Melosh, J., Montanari, A., Morgan, J.V., Neal, C.R., Nichols, D.J., Norris, R.D., Pierazzo, E., Ravizza, G., Rebolledo–Vieyra, M., Reimold, W.U., Robin, E., Salge, T., Speijer, R.P., Sweet, A.R., Urrutia–Fucugauchi, J., Vajda, V., Whalen, M.T. & Willumsen, P.S. 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous – Paleogene boundary. Science, 327(5970): 1214–1218. https://doi.org/10.1126/science.1177265

Schulte, P., Smit, J., Deutsch, A., Salge, T., Friese, A. & Beichel, K. 2012. Tsunami backwash deposits with Chicxulub impact ejecta and dinosaur remains from the Cretaceous – Palaeogene boundary in the La Popa Basin, Mexico. Sedimentology, 59(3): 737–765. https://doi.org/10.1111/j.1365-3091.2011.01274.x

Seilacher, A. 1969. Fault–graded beds interpreted as seismites. Sedimentology, 13(1–2): 155–159. https://doi.org/10.1111/j.1365-3091.1969.tb01125.x

Serrano, L., Ferrari, L., López–Martínez, M., Petrone, C.M. & Jaramillo, C. 2011. An integrative geologic, geochronologic and geochemical study of Gorgona Island, Colombia: Implications for the formation of the Caribbean Large Igneous Province. Earth and Planetary Science Letters, 309(3–4): 324–336. https://doi.org/10.1016/j.epsl.2011.07.011

Shoemaker, E.M., Wolfe, R.F. & Shoemaker, C.S. 1990. Asteroid and comet flux in the neighborhood of Earth. In: Sharpton, V.L. & Ward, P.D. (editors), Global catastrophes in Earth history: An interdisciplinary conference on impacts, volcanism, and mass mortality. Geological Society of America, Special Paper 247, p. 155–170. https://doi.org/10.1130/SPE247-p155

Smit, J., Montanari, A., Swinburne, N.H.M., Alvarez, W., Hildebrand, A., Margolis, S.V., Claeys, P., Lowrie, W. & Asaro, F. 1992. Tektite–bearing, deep–water clastic unit at the Cretaceous – Tertiary boundary in northeastern Mexico. Geology, 20(2): 99–103. https://doi.org/10.1130/0091-7613(1992)020<0099:TBDWCU>2.3.CO;2

Smit, J., Roep, T.B., Alvarez, W., Montanari, A., Claeys, P., Grajales–Nishimura, J.M. & Bermúdez, J. 1996. Coarse–grained, clastic sandstone complex at the K/T boundary around the Gulf of Mexico: Deposition by tsunami waves induced by the Chicxulub impact? In: Ryder, G., Fastovsky, D. & Gartner, S. (editors), The Cretaceous – Tertiary event and other catastrophes in Earth history. Geological Society of America, Special Paper 307, p. 151–182. https://doi.org/10.1130/0-8137-2307-8.151

Soria, A.R., Liesa, C.L., Mata, M.P., Arz, J.A., Alegret, L., Arenillas, I. & Meléndez, A. 2001. Slumping and a sandbar deposit at the Cretaceous – Tertiary boundary in the El Tecolote section (northeastern Mexico): An impact–induced sediment gravity flow. Geology, 29(3): 231–234. https://doi.org/10.1130/0091-7613(2001)029<0231:SAASDA>2.0.CO;2

Stinnesbeck, W. & Keller, G. 1996. K/T boundary coarse–grained siliciclastic deposits in northeastern Mexico and northeastern Brazil: Evidence for mega–tsunami or sea–level changes? In: Ryder, G., Fastovsky, D. & Gartner, S. (editors), The Cretaceous – Tertiary event and other catastrophes in Earth history. Geological Society of America, Special Paper 307, p. 197–209. https://doi.org/10.1130/0-8137-2307-8.197

Stinnesbeck, W., Keller, G., De la Cruz, J., De León, C., MacLeod, N. & Whittaker, J.E. 1997. The Cretaceous – Tertiary transition in Guatemala: Limestone breccia deposits from the South Petén Basin. Geologische Rundschau, 86(3): 686–709. https://doi.org/10.1007/s005310050171

Stinnesbeck, W., Keller, G., Schulte, P., Stüben, D., Berner, Z., Kramar, U. & López–Oliva, J.G. 2002. The Cretaceous – Tertiary (K/T) boundary transition at Coxquihui, state of Veracruz, Mexico: Evidence for an early Danian impact event? Journal of South American Earth Sciences, 15(5): 497–509. https://doi.org/10.1016/S0895-9811(02)00079-2

Stoffer, P.W., Messina, P., Chamberlain, J.A., Jr. & Terry, D.O., Jr. 2001. The Cretaceous – Tertiary boundary interval in Badlands National Park, South Dakota. U.S. Geological Survey, open–file report 01–56, 49 p. https://doi.org/10.3133/ofr0156

Vajda, V. 1999. Miospores from Upper Cretaceous – Paleocene strata in northwestern Bolivia. Palynology, 23(1): 181–196. https://doi.org/10.1080/01916122.1999.9989527

Vajda, V. & Bercovici, A. 2014. The global vegetation pattern across the Cretaceous – Paleogene mass extinction interval: A template for other extinction events. Global and Planetary Change, 122: 29–49. https://doi.org/10.1016/j.gloplacha.2014.07.014

Vajda, V. & McLoughlin, S. 2004. Fungal proliferation at the Cretaceous – Tertiary boundary. Science, 303(5663): 1489. https://doi.org/10.1126/science.1093807

Vajda, V. & McLoughlin, S. 2005. A new Maastrichtian – Paleocene *Azolla* species from of Bolivia, with a comparison of the global record of coeval *Azolla* microfossils. Alcheringa: An Australasian Journal of Palaeontology, 29(2): 305–329. https://doi.org/10.1080/03115510508619308

Vajda, V., Raine, J.I. & Hollis, C. 2001. Indication of global deforestation at the Cretaceous – Tertiary boundary by New Zealand fern spike. Science, 294(5547): 1700–1702. https://doi.org/10.1126/science.1064706

Vajda, V., Ocampo, A., Ferrow, E. & Bender–Koch, C. 2015. Nano particles as the primary cause for long–term sunlight suppression at high southern latitudes following the Chicxulub impact—Evidence from ejecta deposits in Belize and Mexico. Gondwana Research, 27(3): 1079–1088. https://doi.org/10.1016/j.gr.2014.05.009

Wigforss–Lange, J., Vajda, V. & Ocampo, A. 2007. Trace element concentrations in the Mexico–Belize ejecta layer: A link between the Chicxulub impact and the global Cretaceous – Paleogene boundary. Meteoritics & Planetary Science, 42(11): 1871–1882. https://doi.org/10.1111/j.1945-5100.2007.tb00546.x

Explanation of Acronyms, Abbreviations, and Symbols:

SEM	Scanning electron microscope
CCD	Carbonate compensation depth
K/Pg	Cretaceous/Paleogene

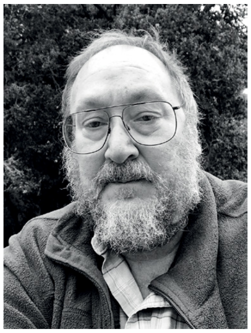
Authors' Biographical Notes

Hermann Darío BERMÚDEZ is a senior Colombian geologist and director of Grupo de Investigación Paleoexplorer. Although he is currently living in the United States, he continues to develop research projects focused on the geology of Colombia. He studied geology at the Universidad Nacional de Colombia (1995) and currently is working in his doctoral dissertation. For more than 25 years, he has studied the stratigraphy and paleontology of Colombia, especially the sedimentary sequences of the cordillera Oriental, Llanos, Magdalena Valley, Perijá, Sinú–San Jacinto, and Tumaco Basin. He serves as member of the Scientific Committee of Gorgona National Park, international editor of Paleontología Mexicana, and referee for the *Journal of South American Earth Sciences*. Currently his main research is focused on the study of the Gorgonilla Island K/Pg boundary section and the paleontology of crustaceans and mollusks of Colombia.

José Antonio ARZ is the vice dean for Quality and Teaching Innovation of the Faculty of Sciences and assistant professor in paleontology of the Department of Earth Sciences, Universidad de Zaragoza, Spain. He studied geology at the Universidad de Zaragoza, where he obtained his PhD degree in 1996, working on detailed studies on Upper Cretaceous biochronology and paleoenvironmental reconstruction with planktonic foraminifera. Since then, his main research has been focused on high–resolution micropaleontological analyses and their applications in biostratigraphy, paleoecology, paleoceanography, and paleoclimatology. He is particularly concerned with the study of geological and paleobiological events, such as the Chicxulub meteorite impact at the Cretaceous/Paleogene boundary and the Deccan Traps eruptions and oceanic anoxic events during the Late Cretaceous. For more than 20 years, he has studied the K/Pg boundary mass extinction event in sections around the world (Europe, North Africa, Gulf of Mexico–Caribbean, Argentina, and recently in Colombia). He has published more than 100 scientific articles, some of them in high–impact journals such as *Science*, *Nature Communications,* and *Geology*. He is coauthor of 4 new genera and 11 new species of Foraminifera. As a current member of the working groups of the International Subcommission on Cretaceous Stratigraphy, he has been involved in the definition of chronostratigraphic boundaries (GSSPs) of the Santonian and Maastrichtian. He has also been involved in projects such as the Chicxulub Scientific Drilling Project (IODP) and in others on Upper Cretaceous to Paleogene biochronology, paleoceanography, paleoclimatology, and mass extinction events.

Ignacio ARENILLAS is assistant professor of micropaleontology in the Department of Earth Sciences, Universidad de Zaragoza, Spain. He studied geology at the Universidad de Zaragoza, where he obtained his PhD degree in 1996, specializing in Paleocene and Lower Eocene biochronology and paleoenvironmental reconstruction with planktonic foraminifera. Passionate about the history of the earth, life, ocean, and climate, his main research is focused on high–resolution studies in biostratigraphy, paleoecology, paleoceanography, and paleoclimatology. He is particularly concerned with the study of geological and paleobiological events, such as the Chicxulub meteorite impact and mass extinction of the Cretaceous/Paleogene boundary, as well as global warming (hyperthermal) events of the Paleocene and early Eocene. He has published more than 100 scientific articles (some in journals such as *Science*) and is coauthor of 5 new genera and 12 new species of Foraminifera. He served as editor of the journal *Geogaceta* and assistant editor of the *Revista Española de la Sociedad Geológica de España*. Additionally, he has participated in and led projects on micropaleontology of the Upper Cretaceous and Paleogene. Arenillas has also participated in working groups such as those of the Chicxulub Scientific Drilling Project (IODP), specifically regarding the multidisciplinary study of the Chicxulub meteorite impact at Cretaceous/Paleogene boundary, and those of the International Subcommission on Paleogene Stratigraphy for the definition of chronostratigraphic boundaries (GSSPs) such as the Paleocene/Eocene, Danian/Selandian, Selandian/Thanetian, and Bartonian/Priabonian boundaries.

Vivi VAJDA is a Swedish paleontologist, professor, and head of the Paleobiology Department at the Swedish Museum of Natural History in Stockholm. She specializes in microscopic fossils, mostly pollen, spores, algae, and fungi from Earth's early history, with aims to resolve questions concerning the extinction and evolution of ecosystems related to major mass extinctions. By comparing the magnitude of the extinctions, the timing of recovery and radiation traced in the fossil vegetation, her research answers several major questions concerning Earth's history. The results from her research on New Zealand K/Pg boundary localities have, for example, been instrumental in resolving the global consequences of the Chicxulub impact. She coordinates several research projects and is active in the geo–community. In 2010, she received the national "Geologist of the Year" award, has served as chair of the Geological Society of Sweden, as Swedish delegate of the European Federation of Geologists, and is presently the chair of the Swedish National Committee for Geology.



Paul R. RENNE was born in 1957 in San Antonio, Texas. He received his AB with highest honors in geology from the University of California, Berkeley, in 1982. He received his PhD in Geology from the University of California at Berkeley in 1987. After a postdoctoral fellowship at Princeton University, he returned to Berkeley in 1990 as a research associate at the Institute of Human Origins and became director of Geochronology in 1991. He was the founding director of the Berkeley Geochronology Center in 1994 and has served in that role (and as board president) since then, with a hiatus from 2000 to 2003. In 1995, Renne was appointed adjunct professor in the Earth and Planetary Science Department at U.C. Berkeley, where he teaches courses in petrology, geochronology, and field geology and serves as formal research advisor to graduate and postdoctoral students. Renne specializes in $^{40}Ar/^{39}Ar$, geochronology and paleomagnetism applied to broad topics in the evolution of Earth's biosphere and lithosphere and to the relationships between these and extraterrestrial processes such as meteoroid impacts in the inner solar system. He is also heavily engaged in the refinement of the methodologies for these techniques. Renne's contributions are recognized by his election as a Fellow of the Geological Society of America, the American Geophysical Union, and the American Association for the Advancement of Science.

Vicente GILABERT is a PhD student of micropaleontology in the Department of Earth Sciences, Universidad de Zaragoza, Spain. His doctoral thesis and research pertain to the Cretaceous/Paleogene mass extinction event, using the planktonic foraminifera as proxies. His work is focused on the planktonic foraminifera assemblage turnovers and extinctions across the Cretaceous/Paleogene boundary, as well as their possible relationship with both the Chicxulub meteorite impact and the Deccan Traps eruptions. GILABERT obtained his degree in geology from the Universidad de Zaragoza in 2013 and a MS in geology in 2015. His master's thesis focused on biostratigraphy with planktonic foraminifera of the Upper Cretaceous of Zumaia (Basque Country, Spain), which served as the starting point of his current research career. In 2016, he obtained a predoctoral contract from the Ministry of Economy, Industry, and Competitiveness of Spain, and he also joined the micropaleontology research group of the Universidad de Zaragoza. Although he is an early–stage researcher, GILABERT has already published several scientific articles, participated in national and international conferences, and is coauthor of 3 new species of Foraminifera.

José Vicente RODRÍGUEZ received a BSc in geology and a MEng in materials from the Universidad Nacional de Colombia. He has vast first–hand knowledge of Colombian geology, which stems from extensive fieldwork experience including geological mapping, stratigraphy, and sampling in Colombia. He also has lab expertise on sedimentological core studies of Colombian Cretaceous rocks and on magnetic fabric studies of igneous rocks. His most relevant and recent work is related to participation in the discovery of a section within the Cretaceous/Paleogene boundary (K/Pg) at Gorgonilla Island.