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The Cretaceous–Palaeogene boundary at Gorgonilla Island, Colombia, South America

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ABSTRACT

The discovery of a new Cretaceous/Palaeogene (K/Pg) bathyal marine sequence on Gorgonilla Island, SW Colombia, extends the presence of Chicxulub impact spherule deposits to the Pacific region of northern South America and to the Eastern Pacific Ocean. The Gorgonilla spherule layer is approximately 20 mm thick and consists of extraordinarily well-preserved glass spherules up to 1.1 mm in diameter. About 70–90% of the spherules are vitrified, and their chemical composition is consistent with Haiti (Beloc) impact glass spherules. Normal size-grading, delicate spherule textures, welded melt components and an absence of bioturbation or traction transport suggest that the Gorgonilla spherule layer represents an almost undisturbed settling deposit.

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Introduction

Since the discovery of the Chicxulub impact crater in the subsurface of Yucatan, Mexico, in the early 1990s (Hildebrand *et al*., 1991; Pope *et al*., 1991), an impact-spherule-rich unit (microtektites) with a similar chemical composition to glass from the Yucatan impact breccia has been documented throughout Central and North America and the Caribbean (e.g. Izett, 1991; Koeberl and Sigurdsson, 1992; Bohor and Glass, 1995; Norris *et al*., 1999; Keller *et al*., 2003a,b, 2011, 2013; Schulte *et al*., 2003). The discovery of impact spherules on Gorgonilla Island, Southwest Colombia (Fig. 1) now extends the occurrence of the Chicxulub spherule deposits to the Pacific Ocean of northwestern South America. Here, we document the spatial and stratigraphic distribution of the spherules and analyse their mineralogic and chemical compositions as well as their sedimentologic and petrologic characteristics.

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Methods

In the field, the Gorgonilla section was measured and examined for lithological changes, sedimentologic structures, trace fossils, erosion surfaces and deformation. Sediments were sampled at close intervals for microfossils, and mineralogical and geochemical analyses. To investigate shapes and surface structures, spherules were hand-picked from gently disintegrated samples. Imaging, chemical analysis and mapping of spherules were performed at the Institut für Geowissenschaften of Ruprecht-Karls-Universität, Heidelberg, with a 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. The operating conditions for clinopyroxenes and glass spherules were 15 kV accelerating voltage, 20 nA beam current and a beam diameter of ~1 µm for clinopyroxenes and a defocused beam (~10 µm) for the glass spherules in order to minimize loss of alkalis. Counting times were 10 s for Na and K, and 30 s for the other measured elements. Synthetic and natural oxide and silicate standards were used for calibration. PAP correction was applied to the raw data. Detection limits are generally of the order of 0.02–0.09 wt%. Planktic foraminiferal biostratigraphy was determined from washed residues (methods described in Keller *et al*., 1995) and thin sections. Preservation of these microfossils is generally good in shale or marly sediments, although affected by dissolution.

Location and geological setting

The Gorgonilla K/Pg section is located on the SW coast of Gorgonilla Island, approximately 35 km off the Colombian coast, at 2°56′N and 78°12′W (Fig. 1). The island is 0.5–1 km in diameter and located about 500 m SW of the larger Gorgona Island. Rock units only crop out along the coast. Gorgona and Gorgonilla Islands are among the less deformed and last accreted pieces of the Caribbean plateau and expose a mafic and ultramafic magmatic sequence of Late Cretaceous to early Palaeocene age (98.7 ± 7.7–64.4 ± 5 Ma), including basalts, gabbros and peridotites intercalated with basaltic komatiites and microgabbroic intrusions; pyroclastic sediments of Palaeocene age overlie this sequence (Serrano *et al*., 2011). Gorgonilla is interpreted to form the southernmost part of the Caribbean plateau, formed *c.* 90 Ma ago in the vicinity of the present-day Galapagos hotspot; it was accreted to northern South America in the middle Eocene (Kennan and Pindell, 2009). At the time of the Chicxulub impact, the Gorgonilla site was thus located approximately 2700–3000 km south-west of the impact site in northern Yucatan.

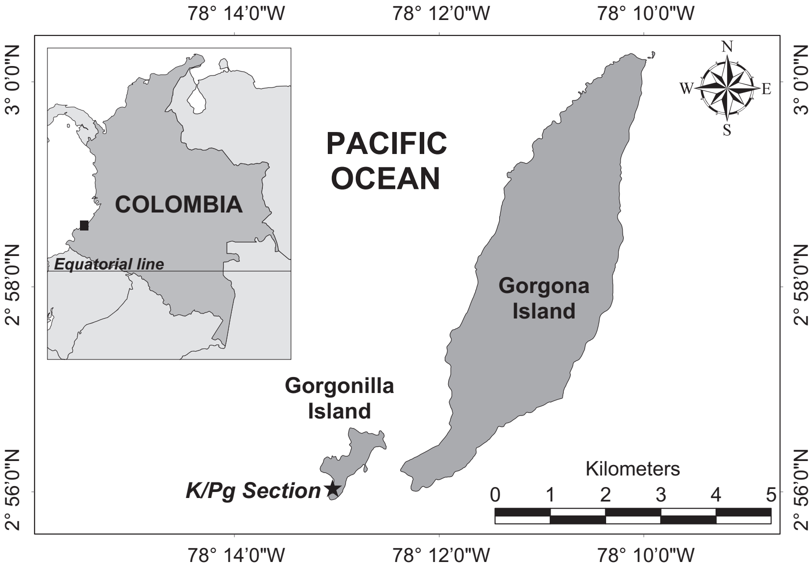

Fig. 1 Location of the Gorgonilla K/Pg section, Colombia, South America.

Gorgonilla K/Pg section

Stratigraphy

The Gorgonilla K/Pg section is composed of thin–medium-bedded light olive gray tuffaceous sandstone, rhythmically alternating with massive gray–yellow tuffaceous marl, siltstone and claystone (Fig. 2). Sandstone components are lithic and include feldspar, olivine, quartz, pyroxene and mica, as well as abundant lithoclasts of eroded and redeposited volcanic ash (tuff), and floating clasts of siliciclastic sedimentary rocks. The deposition of individual sandstone beds as turbidites is likely, as suggested by tabular and tapered bed geometry, faint normal grain size gradation and sorting (Amy *et al.*, 2005). Diverse microfossils are present in the intercalated mudstones, including coccoliths, planktic and benthic foraminifers,

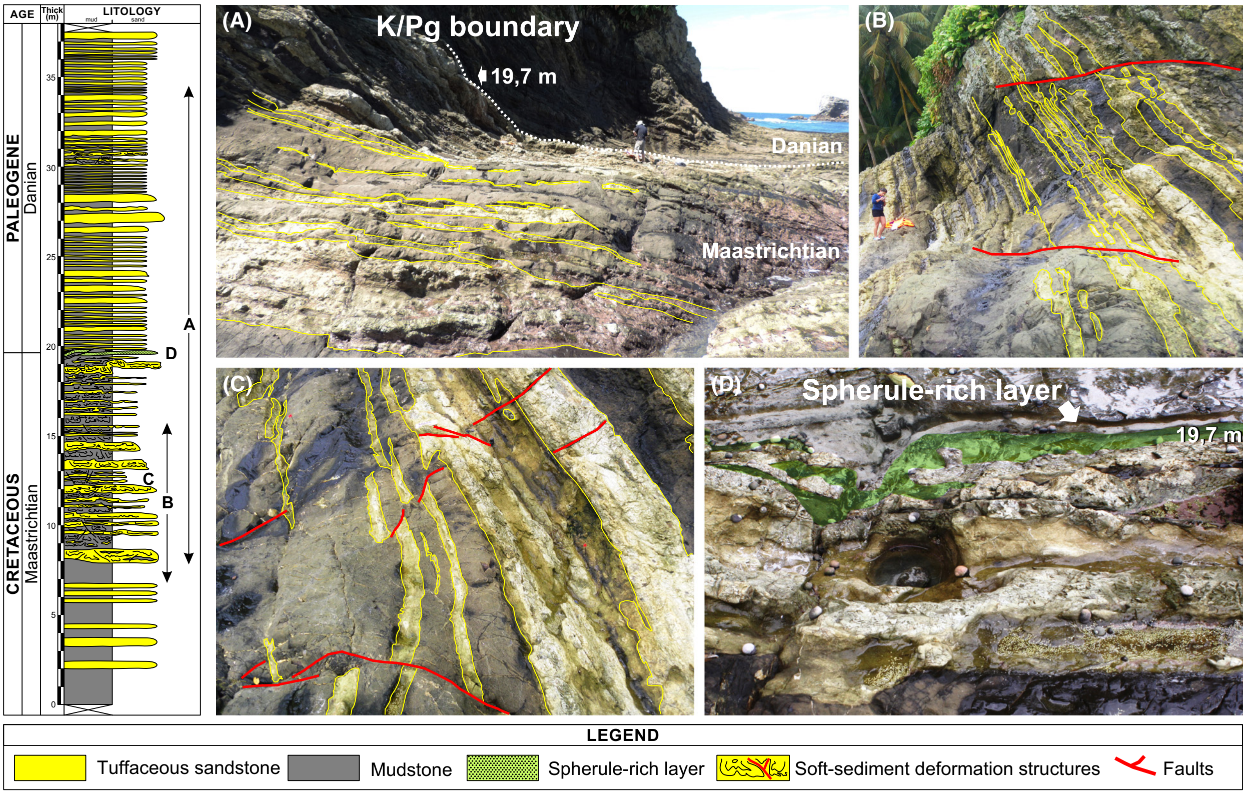

Fig. 2 Stratigraphic section and deformation structures in the Gorgonilla K/Pg section. (A) Outcrop overview. (B) Interval 2–13.5 m. (C) Soft-sediment deformation structures and micro-faults in the interval 11.5–14 m. (D) Interval 19–20 m: beds underlying the spherule-rich layer (K/Pg boundary).

radiolarians (spumellariids and nassellariids), sponge spicules and rare poorly preserved benthonic foraminifers (see Figures B1–3 in Appendix S2). These microfossil assemblages and mudstones are interpreted to represent pelagic bathyal deposition.

Intense ductile and brittle deformation reaches to 12 m below the spherule layer, but did not disrupt the stratigraphic succession, which appears structurally intact. Slumps and other soft-sediment deformation features are ubiquitous at Gorgonilla in the sedimentary unit underlying the spherule layer, leading to uneven surfaces and disrupted bedding. Upsection from the spherule layer, soft-sediment deformation is occasionally present, but restricted to small-scale slumps and contortion of individual thin sediment units.

Spherule-rich layer

The Gorgonilla spherule-rich layer is easily identified in the outcrop at 19.70 m (Fig. 2) by its gray-green to dark green colour and the abundance of spherules visible by eye or hand lens. The unit is approximately 20-mm thick and characterized by a sharp undulating lower contact (Fig. 3A). Above the spherule layer is a radiolarian-rich tuffaceous mudstone that gradually transitions (fining-upward) into mudstone. The spherule layer is traceable over about 20 m laterally without significant changes in thickness or lithology. Synsedimentary bed disruption, small shear zones and contortion are present and are likely responsible for local duplication of the spherule layer. The spherule deposit is well cemented in the basal millimetres and nearly devoid of clastic sediments; whereas in the upper part spherules are less cemented and more friable with increasing detrital content grading into brown siltstone. The maximum size of spherules is between 1.0 and 1.1 mm in diameter and was detected near the base of the layer. Spherules gradually decrease in diameter, with the smallest present near the top of the layer, thus indicating a normal size-graded deposit (Fig. 3A). There are no morphological differences between large spherules at the base and smaller spherules at the top of the unit, and no sedimentary structures suggestive of traction or mass flow transport were detected (e.g. cross-bedding, basal or internal scours, reversals or interruptions in grading [see Figures B1–3 in Appendix S2 for illustrations)].

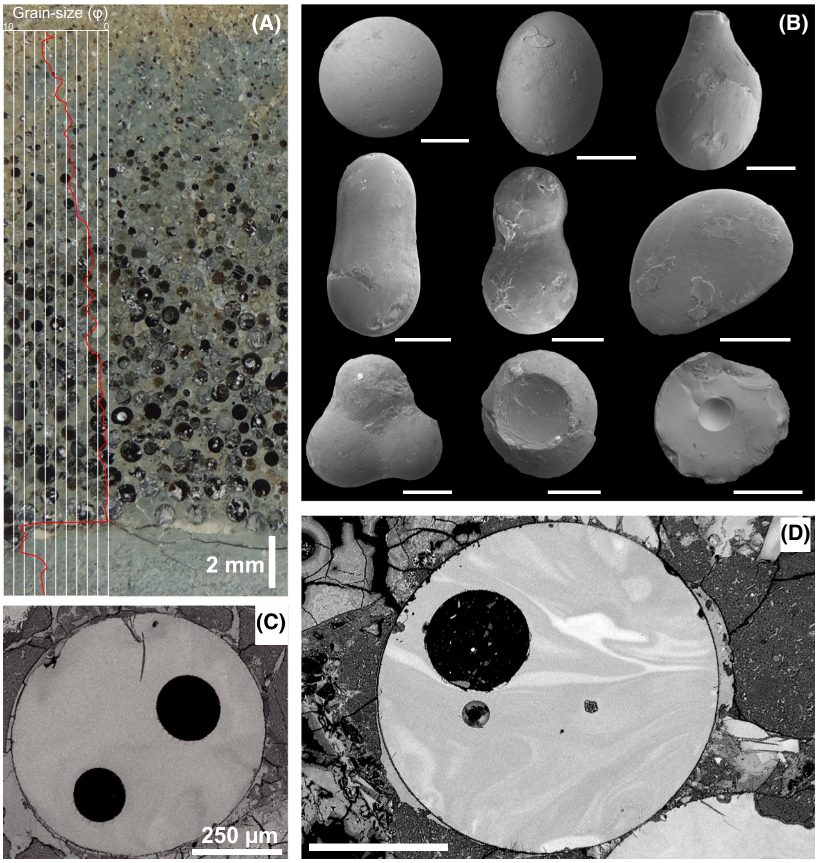

Fig. 3 Impact spherules of the K/Pg section at Gorgonilla Island, SW Colombia. (A) Close up showing polished section of normally graded spherule layer including a graph of the size distribution. (B) SEM photomicrograph of selected glass spherules. (C) Backscattered electron microscope image of a fresh glass spherule with vesicular texture and only a faint schlieren structure. (D) Backscattered electron microscope image of a fresh glass spherule with a pronounced schlieren structure. Light-coloured schlieren are Ca-rich and Si-poor (see Figure A1B in Appendix S1). Scale bar = 500 μm unless otherwise indicated.

Petrology of the spherule-rich deposit

Spherules are black to olive or translucent honey coloured. The majority are round, but oval, teardrop and dumbbell shaped morphologies are also frequent, in addition to irregular grape-like clusters with convex–concave contacts (Fig. 3B). About 70% of the spherules are massive glass (microtektites), while the other 30% contain single, or more rarely two or more, vesicles. These are either completely hollow (Fig. 3C) or totally to partly filled with secondary calcite or brown smectite. Vesicles reach ~30% of the spherule volume and are usually spherical, isolated and generally infilled with calcite. 70–90% of the glass spherules are unaltered or only partly altered, consisting of colourless or faintly green to yellow glass. Schlieren textures are frequent and expressed by differences in refraction indices and chemical composition (Fig. 3D and Figure A1B in Appendix S1). In the remaining spherules, devitrification is partial or complete and results in complex internal textures and the formation of carbonates, clay minerals and silicate minerals. The most common replacement products are yellow–brown-coloured clay minerals of the smectite group, hypidiomorphic to fibrous calcite and partially hypidiomorphic Ba-rich zeolite group minerals (Figure A1D in Appendix S1). Some spherules are even entirely pseudomorphed by hypidiomorphic zeolite group minerals.

Backscattered electron microscope images occasionally reveal the presence of tiny dendritic and/or fibrous crystals (Fig. 4), which suggests that some Gorgonilla spherules are microkrystites (Glass and Burns, 1988) that formed as droplets condensed from vaporized target rock and the impactor. The crystals are diopsides (Table C1 in Appendix S3), formed both in SiO_2-poor CaO-rich and in SiO_2-rich CaO-poor spherules, observed in the bottom of the spherule-rich layer.

Interstitial areas and spaces between the glassy spherules are composed of clay and severely altered glass with presumably cryptocrystalline secondary minerals and show brownish colours in thin sections. Angular fragments of mafic minerals, plagioclase and glass shards sometimes with microcrysts, secondary calcite and even well-preserved radiolaria and foraminifera are present between the glass spherules. Thin joints are filled with calcite and occasional zeolite and, rarely, open fissures are filled with idiomorphic zeolite crystals (Figure A2 in Appendix S1). The chemical composition of unaltered or little altered glass spherules is variable, especially in spherules with schlieren textures (Figures A1A–C in Appendix S1, Table 1 and Table C2 in Appendix S3). Totals of the microprobe analyses are close to 100 wt%, indicating rather low volatile contents. Chemical mapping reveals significant differences in the chemical composition of spherules, even when in close spatial vicinity, with significant differences in SiO_2, CaO and Na_2O contents (Figure A1C in Appendix S1).

Age of the spherule-rich deposit

Planktic foraminifera in the sediments above and below the spherule layer yield excellent age control. In the 0.25 m below the spherule layer a diverse late Maastrichtian assemblage is present including *Plummerita hantkeninoides*, the index species for zone CF1, which marks the last ~100–150 ka of the Maastrichtian (Fig. 5, see supplementary file B4; biozonation based on Keller *et al.*, 1995, 2013). This indicates that at least part of zone CF1 is present. The undulating contact at the base of the spherule layer suggests some erosion of zone CF1 sediments. The lower boundary of zone CF1 has not been determined.

Above the spherule deposit early Danian species are common and include the zone P1a index species *Parvularugoglobigerina eugubina*, which spans the interval of C29r above the K/Pg boundary. The presence of *Parasubbotina pseudobulloides* and *Subbotina triloculinoides*, which evolved nearly simultaneously in the upper half of P1a and divide this zone into P1a(1) and P1a(2), indicate that only the uppermost part of C29r, zone P1a(2), is present; the basal Danian zones P1a(1) and P0 are missing (Keller *et al.*, 2013; Mateo *et al.*, 2015). The presence of clasts with early Danian species marks erosion, probably associated with a short sea-level fall in zone P1a as documented throughout the Caribbean and North Atlantic (Keller *et al.*, 2013; Mateo *et al.*, 2015).

Based on planktic foraminiferal age control, spherule deposition could have occurred any time between the latest Maastrichtian zone CF1 and the early Danian P1a(2), an interval spanning about 200 ka across the K/Pg boundary.

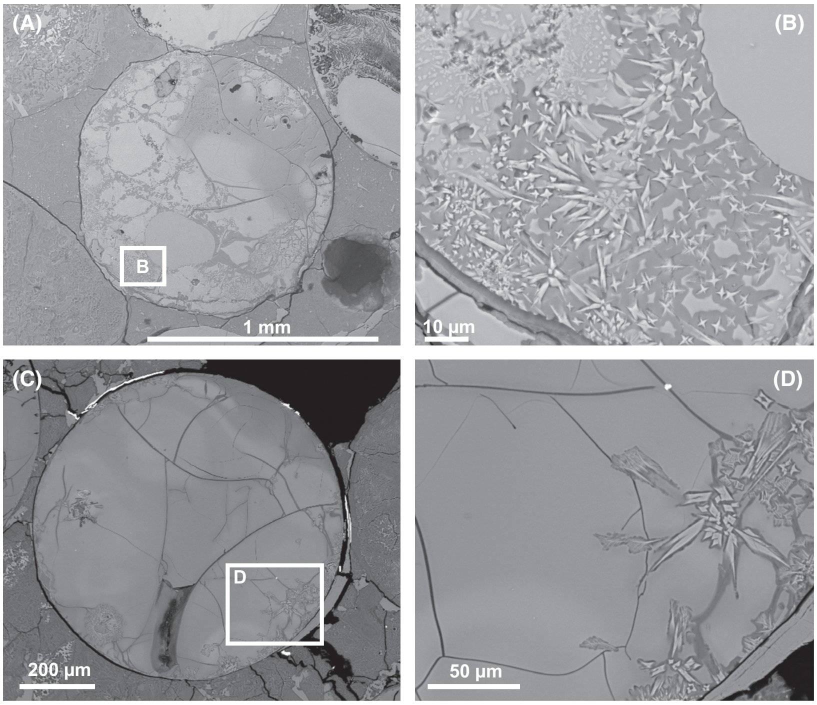

Fig. 4 Microkrystites of the Gorgonilla K/Pg section. (A and C) Backscattered electron microscope images of glass spherules. (B and D) Details, illustrating primary microlites (diopside crystals, see Table C1 in Appendix S3).

Discussion

Spherules

Fluidal-shaped forms, smooth surfaces and internal textures, such as vesicles and streaked schlieren, as well as complex petrologic features, geochemical ranges and mixing trends (Fig. 3) are similar to those of glass spherules in North and Central America (e.g. northeastern Mexico). These are generally interpreted as molten droplets from a highly fluid melt with subsequent exsolution of a gas phase due to pressure release and cooling (Schulte *et al.*, 2003, 2009). Round to teardrop and dumbbell shapes suggest a range of ballistic

Table 1 Compositional range of Gorgonilla glass spherules (average) compared with spherule compositions from literature data. Oxides in wt%.

Source	Locality	Remark	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O
This study	Colombia (Gorgonilla Island)	Spherule	46.43–68.41*	8.69–15.85	3.68–6.45	1.88–4.84[†]	5.45–30.26*	0.97–4.00	0.28–1.87[‡]
Sigurdsson *et al.* (1991)	Haiti (Beloc)	Spherule	44–67*	12–16	4.5–6.5	2–4.5[†]	5–30*	2–4	0.5–2[‡]
Koeberl and Sigurdsson (1992)	Haiti (Beloc)	Black glass	61–66 (86)	15–16 (7)	4.9–5.5 (2.5)	2.3–2.8 (1.2)	5.5–8.5 (0.4)	2.8–4.1 (0.4)	1.5–1.8 (2.2)
		Yellow glass	47–50	12.5–13.5	4.9–5.1	3.8–4.2	23.5–26.5	2.1–2.9	0.5–0.8
Smit *et al.* (1992)	Mexico (Mimbral)	Range of dark brown–black glass and Ca-rich glass	52–66*	12–19	4–12	0.4–9.3	0.8–23*	0.1–3.9	0.6–3.7
Schulte *et al.* (2003)	Mexico (La Sierrita area)	Spherule Fe rich	25–29	20–23	23–26	9–12	0.3–0.8	0–0.1	0–0.6
		Spherule K-rich	50–51	29–30	1–2	2–3	0.5–0.6	0–0.2	7–8
		Spherule schlieren	18–34	18–24	19–29	7–10	0.3–1.1	0–0.2	0–3
Schulte *et al.* (2009)	ODP Leg 207 Demerara Rise, Western Atlantic	Spherule smectite	58–62	20–26	1.6–3.3	2.5–3.7	0.3–0.6	1.4–2.1	0.1–0.3
		Fe, Mg, Ti-rich	49–63	16–19	4–6	2.9–4.6	0.5–1.4	2.0–2.9	0.2–0.4

*Spherules with high CaO have low SiO_2 content.

†Spherules with high MgO have low SiO_2 content.

‡Spherules with low K_2O have low SiO_2 content.

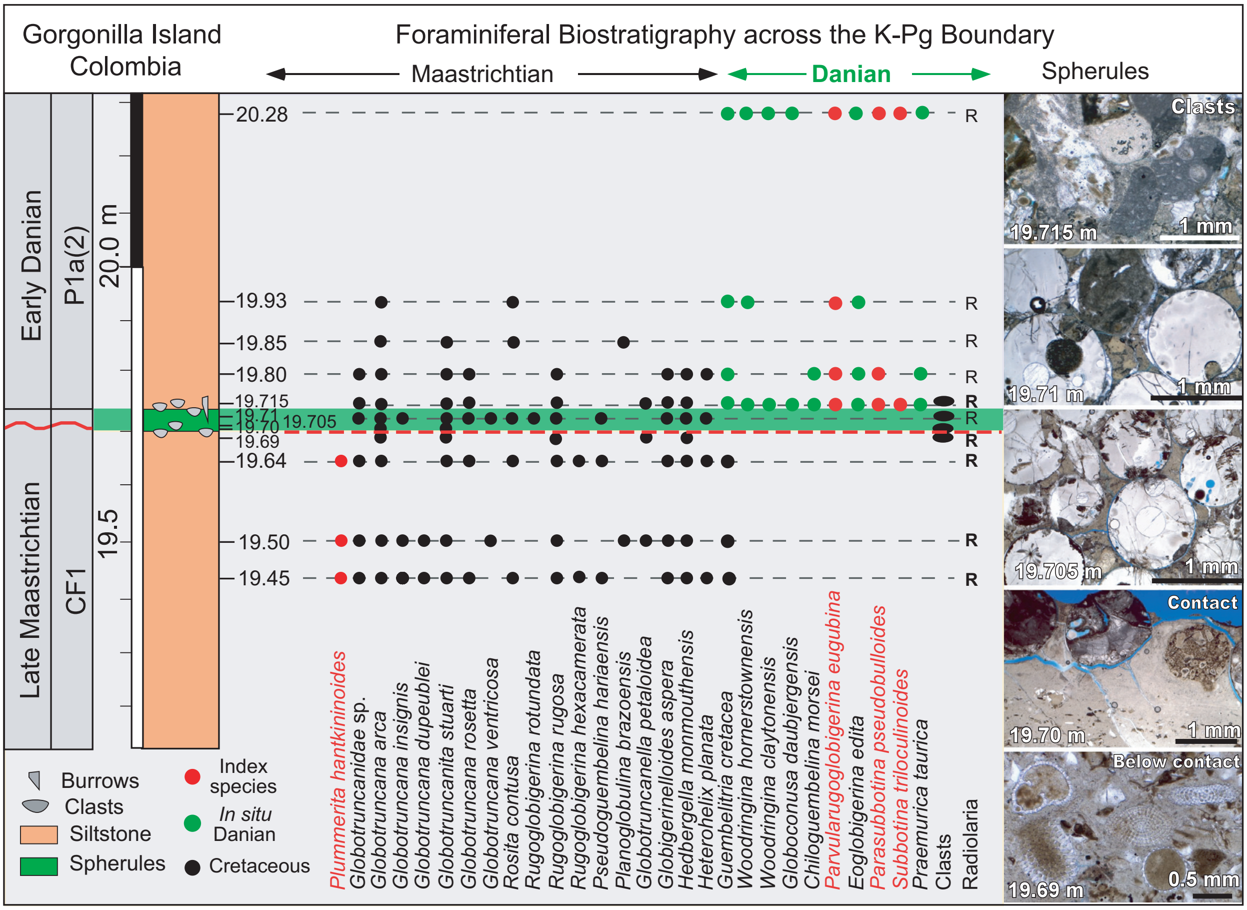

Fig. 5 Planktic foraminiferal biostratigraphy and lithology across the K/Pg boundary and spherule layer in the Gorgonilla section. Spherule deposition occurred sometime between the latest Maastrichtian zone CF1 and the early Danian upper zone P1a(2), an interval spanning about 200 ka. The spherule layer consists almost entirely of spherules, except for rare small clasts and Maastrichtian species.

paths and cooling histories (Martínez-Ruiz *et al.*, 1997), also consistent with a common impact origin, presumably the Chicxulub crater on the Yucatan peninsula, located at about ~2700–3000 km to the north of Gorgonilla.

In Central America, the North Atlantic and the Caribbean, Chicxulub spherules are frequently altered to smectite clay. Relict glass is extremely rare and known only from a few sites in northeastern Mexico, Haiti and the North Atlantic Demerara Rise (e.g. Izett *et al.*, 1990; Koeberl and Sigurdsson, 1992; Smit *et al.*, 1992; Keller *et al.*, 2002, 2009; Schulte *et al.*, 2003, 2009). The state of preservation of the glass spherules of the Gorgonilla section is thus unique. The range of main element compositions and the oxide variation trends (Table 1, Fig. 6 and Table C2 in in Appendix S3) of these glasses are compatible with those from Haiti (Beloc) and Mexico (Mimbral); average chemical compositions are similar to those of yellow and black glasses from Beloc (Izett *et al.*, 1990; Koeberl and Sigurdsson, 1992; Glass and Simonson, 2013).

Gorgonilla spherule layer – an undisturbed settling deposit?

Impact spherule layers from North and Central America and the Caribbean are generally affected by erosion and redeposition in the early Danian zone P1a about 100–200 ka after the K/Pg boundary (Keller *et al.*, 2003a,b, 2013). Spherule layers that potentially represent undisturbed ejecta deposits are known from only a few locations in NE Mexico (e.g. La Sierrita, El Tecolote and El Peñon; Schulte *et al.*, 2003; Keller *et al.*, 2009) and Texas (Brazos River; Adatte *et al.*, 2011), based on their stratigraphic position in zone CF1 that spans the last ~100 ka of the Maastrichtian. These deep-water spherule deposits are characterized by angular to flaser-like shards, 'welding', plastic deformation, calcite cement and an absence of reworked shallow-water debris (e.g. Stinnesbeck *et al.*, 2001; Keller *et al.*, 2002, 2009; Schulte *et al.*, 2003). Also in zone CF1, but 4–9 m above these deposits, are multiple reworked spherule layers with abundant siliciclastic debris from shallow-water areas, indicating erosion, reworking and downslope transport from an original near-shore deposit during a sea-level fall. Alternatively, Soria *et al.* (2001) and Schulte *et al.* (2003) suggested that all zone CF1 spherule layers

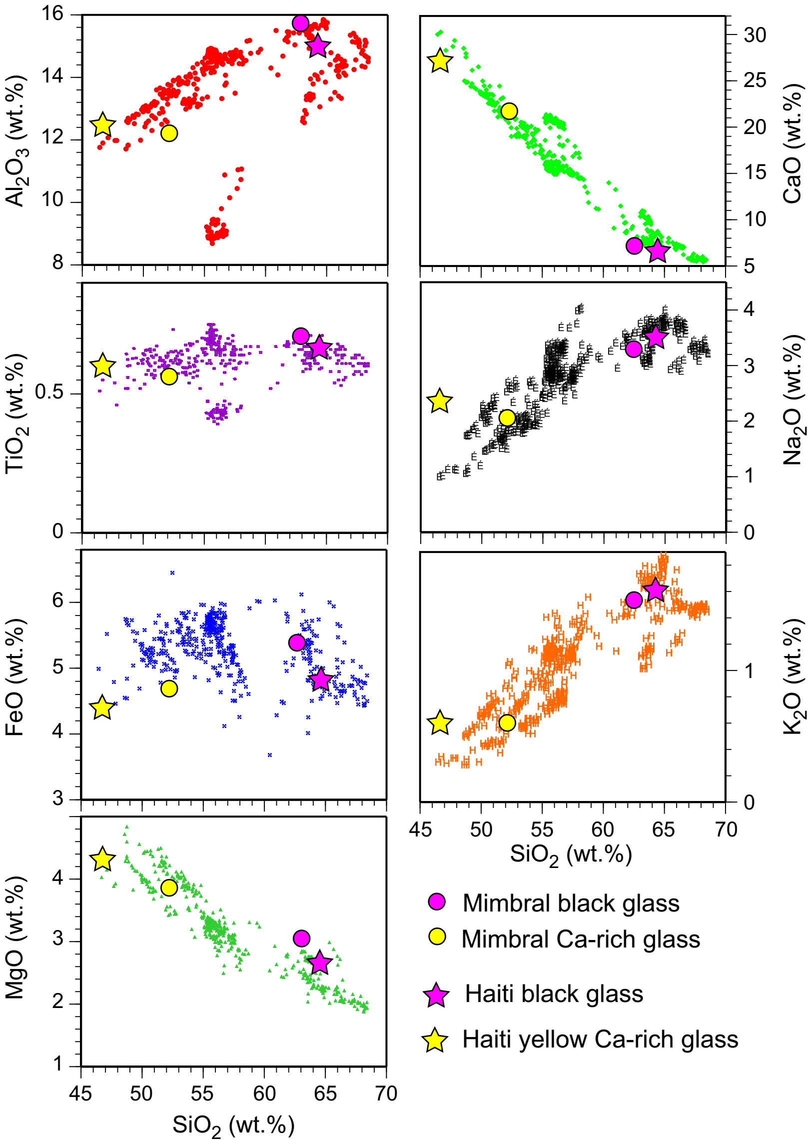

Fig. 6 Harker diagrams of selected main and minor elements of the Gorgonilla glass spherules. For comparison average compositions of glasses are shown from the Mimbral and Haiti sites, according to Glass and Simonson (2013).

represent slumping by Chicxulub-induced seismicity, although no such disturbance could be documented for El Peñon or Brazos, Texas (Keller *et al.*, 2009; Adatte *et al.*, 2011).

The Gorgonilla spherule layer is remarkably undisturbed and a strong potential candidate for a primary suspension settling deposit with ejecta material from the Chicxulub impact event. The near absence of siliciclastic input or fossils in the basal portion of the unit indicates rapid deposition and an absence of reworking, as also suggested by the excellent spherule preservation. This suggests para-autochthonous deposition of at least the basal part of the Gorgonilla spherule-rich deposit. Only in the upper part is there an increased input of microfossils and clastic sediments mixed with sparse spherules, suggesting current activity. The precise age of spherule deposition is uncertain but must be somewhere between CF1 and P1a(2), or between 100 ka below and at least 100 ka above the K/Pg boundary. Further research is necessary to evaluate both the age and the type of deposition of the Gorgonilla spherule deposit.

Conclusions

A 2 cm thick normally graded spherule layer on Gorgonilla Island, SW Colombia, extends the Chicxulub impact spherule ejecta to the Pacific region of northern South America. The size, morphology and chemical composition of these spherules are similar to those of Chicxulub spherule ejecta from North and Central America and the Caribbean, but the Gorgonilla spherules are notable for their unrivaled excellent preservation. The absence of detritus and the presence of convex–concave contacts and agglutinated spherules suggest a para-autochthonous deposit. Further fieldwork and analyses are necessary to better understand the nature of the Chicxulub impact deposit at Gorgonilla.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Spherule geochemistry.

Appendix S2. Stratigraphy of Gorgonilla section.

Appendix S3. Spherule geochemistry tables.