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Multi-proxy record of the Chicxulub impact at the Cretaceous-Paleogene boundary from Gorgonilla Island, Colombia

Paul R. Renne[1,2], Ignacio Arenillas[3], José A. Arz[3], Vivi Vajda[4], Vicente Gilabert[3], and Hermann D. Bermúdez[5]

[1]*Berkeley Geochronology Center, Berkeley, California 94709, USA*

[2]*Department of Earth and Planetary Science, University of California, Berkeley, California 94709, USA*

[3]*Departamento de Ciencias de la Tierra, and Instituto Universitario de Investigación en Ciencias Ambientales de Aragón, Universidad de Zaragoza, E-50009 Zaragoza, Spain*

[4]*Swedish Museum of Natural History, P.O. Box 50007, SE-104 05 Stockholm, Sweden*

[5]*PaleoExplorer Research Group, St. George, Vermont 05495, USA*

ABSTRACT

A 40 m stratigraphic section at Gorgonilla Island, Colombia, provides a unique deep marine, low-latitude, Southern Hemisphere record of events related to the end-Cretaceous Chicxulub impact and the global Cretaceous/Paleogene boundary (KPB). The KPB is marked by a 20-mm-thick densely packed spherule bed as defined by planktic foraminifera, in contrast to complex relationships found in high-energy, impact-proximal sites in the Gulf of Mexico and Caribbean basins. The absence of basal Danian foraminiferal Zone P0 may indicate a possible hiatus of <10 ka immediately above the spherule bed, but is most probably an artifact of deposition below the CCD as suggested by the nearly complete absence of calcareous fossils for 20 m below the Zone Pα. A

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weighted mean $^{40}Ar/^{39}Ar$ age of 66.051 ± 0.031 Ma for 25 fresh glassy spherules unequivocally establishes both their derivation from Chicxulub, and the association between the impact and the KPB. The spherule bed, and Maastrichtian strata below it, display soft-sediment deformation features consistent with strong seismic motion, suggesting that seismic activity in the immediate aftermath of the Chicxulub impact continued for weeks. We discovered a fern-spike immediately above the spherule bed, representing the first record of this pioneer vegetation from the South American continent, and from a low-latitude (tropical) environment.

INTRODUCTION

The Chicxulub impact in the Yucatan Peninsula of Mexico deposited ejecta (e.g., iridium, shocked minerals, Ni-rich spinels and tektites) worldwide (Schulte et al., 2010). Large sedimentary disturbances, such as tsunamites and massive debris flows are reported in the Gulf of Mexico, Caribbean and Atlantic continental margins (Claeys et al., 2002, and references therein). In more distal and/or deeper areas (e.g., Haiti, northeastern Mexico and Texas), ejecta form part of a decimeter-thick spherule bed followed by a sandstone unit, which at some sites terminate with a thin Ir-rich clay layer (Smit, 1999). In distal areas (e.g., Tunisia, Spain, Italy and Denmark), ejecta is mainly concentrated in a millimeter-thick air fall layer at the base of the well-known “KPB clay” (Claeys et al., 2002). The thickness of the Chicxulub ejecta deposits and their deposition energy decrease with the distance from the impact site, which is consistent with Chicxulub as the unique source of ejecta material.

The age of Chicxulub impact has remained controversial since Stinnesbeck et al. (2001) reported two to four altered impact glass spherule layers in the uppermost marly

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deposits of the Maastrichtian near La Sierrita, northeastern Mexico. According to Stinnesbeck et al. (2001), the older (primary) spherule layer is interpreted as to be located near the base of the planktic foraminifera Zone CF1 (*Plummerita hantkeninoides*), and it was thereby inferred that the Chicxulub impact predated the KPB by 300 ka. This interpretation was refuted by Soria et al. (2001), who showed that these layers in fact comprise one single spherule layer that is repeated and locally mixed with remobilized Maastrichtian marls due to slumping processes seismically induced by the Chicxulub impact.

The diverse interpretations arising from stratigraphic complexities in impact-proximal sites can be obviated to some extent by radioisotopic dating. Renne et al. (2013) presented $^{40}Ar/^{39}Ar$ data for an Ir-bearing KPB bed in Montana and fresh glassy tektites from Haiti that establish synchrony between the KPB and associated mass extinctions with the Chicxulub bolide impact to within 32,000 years. However, unaltered tektite glasses linked to the Chicxulub impact have only been reported from proximal and/or intermediate areas such as Beloc (Haiti), where tektites are abundant, and El Mimbral and La Lajilla (northeastern Mexico), where preserved glassy spherules are scarce (Belza et al., 2015).

Although intense work has sought to identify traces of the Chicxulub impact ejecta on the South American continent (e.g., Gertsch et al., 2013 and references therein), the first tektite deposit connected to this asteroid impact was described by Bermúdez et al. (2016), who concluded that the spherule-bearing layer at Gorgonilla Island could have been deposited at any time within 200 ka of the KPB, which would permissibly support the persistent contention that the Chicxulub impact preceded the KPB by >100 ka

(Stinnesbeck et al., 2001; Keller et al., 2007, and references therein). Here we present new micropaleontological data (planktic foraminifera and palynomorphs) and geochronological data ($^{40}Ar/^{39}Ar$) showing that the Gorgonilla spherule bed was synchronous with the KPB to within ~10 ka or less.

GEOLOGIC CONTEXT

The Gorgonilla section (Fig. 1) overlies mafic and ultramafic basement rocks that form part of the Caribbean plateau, generated by the present Galapagos hotspot in the mid Cretaceous (Kennan and Pindell, 2009). It was located at 2000–3000 km southwest of the Chicxulub crater and represents a bathyal depth deposit (Bermúdez et al., 2016). Exposed near the southern tip of Gorgonilla Island, the section comprises ~40 m of interbedded tuffaceous sandstones and marls, with a ~20 mm-thick bed of normal-size-graded spherules occurring in mid-section (Fig. 1A). Sediments underlying the spherule bed were affected by intense soft-sediment deformation and bed disruption (Fig. 1C), and provide evidence for syndepositional faulting, injectites, hydroplastic mixed layers, pillar and flame structures, small-scale slumping, and fault-graded beds; features typical of seismites (e.g., Montenat et al., 2007). These features are absent in strata overlying the spherule bed (Fig. 1B).

NEW DATA AND THEIR IMPLICATIONS

$^{40}Ar/^{39}Ar$ Geochronology

Twenty-five spherules were analyzed individually by incremental heating $^{40}Ar/^{39}Ar$ methods. Nineteen of these yielded 100% concordant age plateaux, and the remainder yielded plateaux comprising >85% of the ^{39}Ar released. For the six spherules displaying discordant age spectra, the discordance is due to anomalously young ages in

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the initial steps, which we interpret as being due to post-formation alteration that was not mitigated during sample preparation. The weighted mean of all plateau ages is 66.051 ± 0.031/0.054 Ma (Fig. 2). Ar isotope data are given in Table DR1.

As with the Haitian tektites, the Ca/K values (derived from $^{37}Ar/^{39}Ar$ data) of Gorgonilla samples display a large range both between and within individual tektites. This is consistent with the observations of Bermúdez et al. (2016) from Gorgonilla, and of several electron probe microanalysis (EPMA) studies (Izett et al., 1991; Sigurdsson et al., 1991) of Haitian tektites, showing that individual tektites commonly contain mixtures of compositionally distinct glasses. Comparing plateau ages with integrated plateau values of Ca/K shows no correlation, verifying that the spherules of diverse composition were cogenetic, and that the Ca-interference corrections (for reactor-produced ^{36}Ar and ^{39}Ar) are accurate.

The weighted mean plateau age of 66.051 ± 0.031 Ma is indistinguishable from that (66.038 ± 0.025 Ma) determined by three independent $^{40}Ar/^{39}Ar$ studies of the Haitian tektites (Renne et al., 2013). In view of the indistinguishable age and compositional similarities shown here and by Bermúdez et al. (2016), it is clear that the Gorgonilla tektites are cogenetic with the Haitian ones, and moreover that they were produced by the Chicxulub impact dated at 66.030 ± 0.051 Ma (Renne et al., 2013). Thus we conclude that the Gorgonilla spherules are tektites unequivocally produced by the Chicxulub impact and represent the KPB, which has been dated at 66.043 ± 0.010 Ma (Sprain et al., 2015). All of these relevant ages are based on $^{40}Ar/^{39}Ar$ dating using the same calibration (see Data Repository), hence meaningful comparison requires neglecting systematic uncertainties such as those arising from decay constants and the age of the

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standard. The maximum age difference between any two of these ages is 21 ± 60 ka, i.e., they are all indistinguishable within uncertainties.

Micropaleontology

The abundance of radiolarians and siliceous sponge spicules in the Gorgonilla section contrasts with the absence of planktic foraminifera tests within and below the deformed tektite bed, except for very scarce specimens of *Heterohelix globulosa, Pseudotextularia elegans, Gublerina cuvillieri, Globigerinelloides praevolutus, Rugoglobigerina rugosa,* and *Pseudoguembelina palpebra* identified in samples 15.30 and 11.20 (Fig. DR1 and Table DR2). These species are known from the Campanian to the KPB, but *P. palpebra* is restricted to the Maastrichtian, from 71.75 to 66.04 Ma according to GTS2012 (Gradstein et al., 2012).

Bermúdez et al. (2016) assigned the 25 cm below the spherule layer to the Zone CF1, which spans the last 140 ka of the Cretaceous (Husson et al., 2014). However, we have not found specimens of *P. hantkeninoides*, the index species for Zone CF1. Scarcity of planktic foraminifera, absence of index-species and intense soft-sediment deformation affecting the sediments underlying the tektite bed hamper high-resolution age assessment of the Maastrichtian interval.

Planktic foraminifera are more abundant in the first meter above the spherule bed, and the taxa identified belong to Zone Pα (basal Danian) following the zonation scheme of Berggren and Pearson (2005) (Fig. 3). The basal assemblage identified includes species such as *Parvularugoglobigerina longiapertura,* and *Guembelitria cretacea*, distinctive of the lower part of the Zone Pα. The identified youngest assemblage (in sample 21.10), which include *Parvularugoglobigerina eugubina* and *Eoglobigerina*

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simplicissima (Fig. 3; Table DR2), is characteristic of the upper part of the Zone Pα, ca. 50–60 ka younger than the KPB event according to the biochronological scale of Arenillas et al. (2004). The basal Danian biozone (Zone P0 of Berggren and Pearson, 2005) has not been identified in the Gorgonilla section. However, a bloom of opportunistic genus *Guembelitria* s.l. was identified in the sample 19.98 at 5 cm above the top of the spherule bed (Fig. 3; Table DR2). This bloom corresponds to the Planktic Foraminiferal Acme Stage 1 (PFAS-1) of Arenillas et al. (2006), and is followed immediately by a second bloom of *Parvularugoglobigerina* s.l., corresponding to PFAS-2 of Arenillas et al. (2006). Collectively, the absence of a diagnostic P0 assemblage but the presence of PFAS-1 suggests a possible hiatus of no more than 10 ka.

Palynology

The palynological residues include abundant pyrite crystals but are poor in organic matter. Most samples include green algal colonies but no other palynomorphs are encountered below the spherule bed. Although the Maastrichtian samples are devoid of pollen and spores, fern spores are notably present in the samples above the spherule bed (Fig. DR2; Table DR3). Fern spores first occur in sample 19.86, only 1 cm above the spherule layer, where they are represented by sparse *Cyathidites minor.* A more diverse assemblage is recorded 12 cm above the spherule layer, from sample 20.05, where *Cyathidites australis, Cyathidites minor*, *Gleicheniidites circinidites*, *Cibotiidites tuberculiformis, Deltoidospora toralis*, and the angiosperm pollen *Tricolpites reticulatus* co-occur indicating the presence of an advanced pioneer succession (Fig. DR2). Fern spores occur consistently and dominate the assemblages above the spherule bed. The aquatic fern *Azolla*, represented by both massulae and microspores, appears above the spherule layer in sample 20.15.

DISCUSSION AND CONCLUSIONS

$^{40}Ar/^{39}Ar$ dating and planktic foraminiferal assemblages clearly indicate that the Gorgonilla section records deposition of tektites derived from the Chicxulub impact in a relatively complete section with a possible hiatus of <10 ka following the KPB. The absence of foraminifera in the basal 5 cm above the spherule bed suggests deposition below the CCD (as with the Maastrichtian beds), preventing the identification of the Zone P0. Preserved planktic foraminiferal assemblages confined to the Zone Pα in Gorgonilla section may be a consequence of the rapid and pronounced deepening of the local CCD, during a period of ocean alkalinity build-up and $CaCO_3$ preservation globally enhanced, following the Chicxulub impact (e.g., Henehan et al., 2016).

Deposition of the tektites was closely synchronous with ongoing seismic activity. Given the probable flight time (minutes to tens of minutes; Alvarez et al., 1995) of tektites deposited >2000 km from their source, and a minimum settling time of ~550 s estimated for 2 km water depth, it is unlikely that the seismic activity affecting the spherule bed records the initial ground motion from the impact. A seismic wave propagation velocity of 2–5 km/s implies a delay of only 400–1000 s between the impact and the onset of ground motion at Gorgonilla, by which time the tektites would not have been deposited. Thus it follows that strong seismicity was ongoing episodically for at least several tens of minutes following the impact, consistent with the inference of Norris and Firth (2002) of seismically induced mass wasting around the Atlantic margin for weeks after the impact. 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 uppermost Maastrichtian sediments over a vast region (Smit, 1999).

The results and interpretation of the planktic foraminiferal record are supported by the terrestrial palynological record, which represents the first evidence of a “fern-spike” following the Chicxulub impact from a tropical habitat. The fern spores, which only occur above the KPB at Gorgonilla, are represented by both ground- and tree ferns and, in some samples, also by water-ferns (*Azolla*). The genus *Azolla* consistently characterizes warm-climate lacustrine environments and first appears in the geological record in Lower Cretaceous successions (Vajda and McLoughlin 2005). Aquatic ferns such as *Azolla* can reproduce asexually through vegetative regeneration in association with nitrogen-fixing cyanobacterial symbionts, which occurred in abundance in the post-impact environment, providing advantages in the aftermath of the KPB and high-lights their potential to endure altered environmental conditions. Fern spikes are so far known only from high paleolatitude sites (Vajda et al., 2001; Schulte et al., 2010 and references therein),

Importantly, the general characteristic of the latest Maastrichtian and Paleogene pollen and spores assemblages of paleotropical Colombia, Bolivia, Brazil and Venezuela is the predominance of angiosperm pollen grains, whereas fern spores are extremely sparse (Jaramillo et al., 2007 and references therein). The fern-spore dominance in the Gorgonilla samples suggests that a fundamental change in local paleogeography occurred coincident with the Chicxulub impact, possibly a result of rapid seismically-induced tectonic emergence of nearby landmasses that were quickly colonized by ferns.

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FIGURE CAPTIONS

Figure 1. Location map and lithostratigraphy of the section. Insets show details of (A) Spherule bed, (B) Danian beds immediately above spherule bed (shaded green), and (C) Distorted Maastrichtian beds immediately below spherule bed.

Figure 2. Rank order plot of $^{40}Ar/^{39}Ar$ plateau ages for individual spherules. The weighted mean is shown with uncertainty excluding/including systematic sources.

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Figure 3. Stratigraphic ranges of planktic foraminifera, spores and pollen, and planktic foraminiferal acme-stages (PFAS). *Guembelitria* s.l. includes *Guembelitria* and *Chiloguembelitria* species, and *Parvularugoglobigerina* s.l. includes *Parvularugoglobigerina* and *Palaeoglobigerina* species. Planktic foraminifera Abbreviations: *Gg. = Guembelitria*, *Pc. = Pseudocaucasina*, *Pg. = Palaeoglobigerina*, *Pv. = Parvulorugoglobigerina*, *W. = Woodringina*, *Ch. = Chiloguembelina*, *E. = Eoglobigerina*, *G. = Globalomalina*, *P. = Parasubbotina*. Spores & pollen Abbreviations: *C. = Cyathidites*, *T. = Tricolpites*, *D. = Dictyophyllidites*, *Cb. = Cibotiidites, Dt. = Deltoidospora*, *G. = Gleicheniidites*, *Ds. = Densoisporites*, *Cg. = Cingutriletes*, *P. = Peromonelites*.

[1]GSA Data Repository item 2018xxx, supplemental text, figures and tables, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.