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Explosive interaction of impact melt and seawater following the Chicxulub impact event

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ABSTRACT

The impact of asteroids and comets with planetary surfaces is one of the most catastrophic, yet ubiquitous, geological processes in the solar system. The Chicxulub impact event, which has been linked to the Cretaceous-Paleogene (K-Pg) mass extinction marking the beginning of the Cenozoic Era, is arguably the most significant singular geological event in the past 100 million years of Earth's history. The Chicxulub impact occurred in a marine setting. How quickly the seawater re-entered the newly formed basin after the impact, and its effects of it on the cratering process, remain debated. Here, we show that the explosive interaction of seawater with impact melt led to molten fuel–coolant interaction (MFCI), analogous to what occurs during phreatomagmatic volcanic eruptions. This process fractured and dispersed the melt, which was subsequently deposited subaqueously to form a series of well-sorted deposits. These deposits bear little resemblance to the products of impacts in a continental setting and are not accounted for in current classification schemes for impactites. The similarities between these Chicxulub deposits and the Onaping Formation at the Sudbury impact structure, Canada, are striking, and suggest that MFCI and the production of volcaniclastic-like deposits is to be expected for large impacts in shallow marine settings.

INTRODUCTION

It has become apparent over the past few decades that impact cratering has played an important role in the geological, climatological, and biological evolution of Earth (e.g., Melosh, 1989; Osinski and Pierazzo, 2012). The 66-m.y.-old, ~200-km-diameter Chicxulub impact structure in Mexico (Hildebrand et al., 1991) is proposed to have caused the Cretaceous-Paleogene (K-Pg) mass extinction (Schulte et al., 2010) and is one of the largest known impact structures on Earth. Chicxulub is buried by up to ~1 km of post-impact sedimentary rocks, and unravelling details of its character, subsequent geological history, and implications for the environmental and biological record remains the topic of scientific inquiry (Schulte et al., 2010). The most recent drill hole (M0077A) at Chicxulub was a joint effort by the International Ocean Discovery Program (IODP) and the International Continental Scientific Drilling Program (ICDP) during Expedition 364 in 2016 at Site M0077 (21.45°N, 89.95°W). The Expedition 364 cores have already revealed important new insights into the formation of so-called peak rings in large impact structures (Morgan et al., 2016; Riller et al., 2018), the physical properties of impact rocks (Christeson et al., 2018), and the surprisingly fast post-impact recovery of biota following the impact (Lowery et al., 2018; Gulick et al., 2019).

The Chicxulub impact occurred in a marine setting, although estimates of the pre-impact water depth vary (Gulick et al., 2013). What is clear, however, is that the post-impact water depth in the environs of Site M0077 was on the order of ~600 m, and ~1 km in the surrounding crater floor (Gulick et al., 2008; Lowery et al., 2018). It has been recognized for some time that meteorite impacts in a marine setting differ in several fundamental ways from impacts on land (Dypvik and Jansa, 2003). Whereas previous works have discussed the formation of impact-generated tsunamis and their roles in modifying and eroding the Chicxulub crater rim and surrounding regions in the Gulf of Mexico (e.g., Smit et al., 1996; Schulte et al., 2011), Expedition 364 results highlight the need for attention to be paid to the role that seawater may have played in generating and modifying the lithological products of the Chicxulub impact. The data presented here reveal new insights into one effect of this seawater re-entry following impact.

METHODS AND SAMPLES

Expedition 364 specifically targeted Site M0077 to provide the first-ever samples of the peak ring of the Chicxulub structure. We investigated the nature of the core samples from the so-called Upper Peak Ring interval (617.33–747.02 m below seafloor), which is composed of

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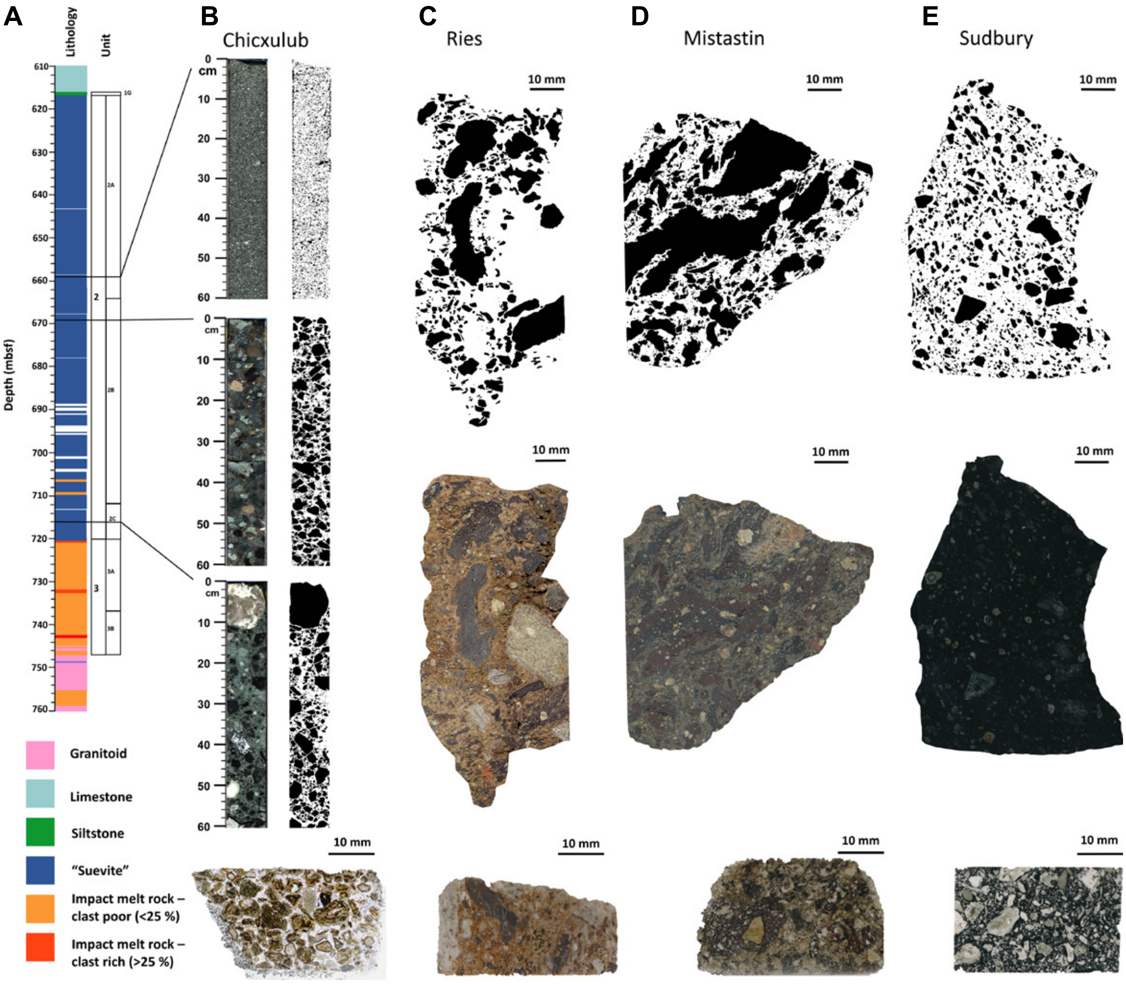

Figure 1. Comparison of Chicxulub impact structure (Mexico) Upper Peak Ring lithologies with rocks from the Ries (Germany), Mistastin (Canada), and Sudbury (Canada) impact structures. (A) Lithostratigraphic overview of the upper part of International Ocean Discovery Program (IODP) and International Continental Scientific Drilling Program (ICDP) Expedition 364 Hole M0077A at Chicxulub impact structure (Mexico, 21.45°N, 89.95°W) (core diameter 83 mm), modified from Gulick et al. (2018). mbsf—meters below seafloor. (B–E) Core and hand-specimen images with corresponding black-and-white image analysis products highlighting impact glass in black (right in B, top in C–E) and scanned thin-section images (bottom). See Figure DR1 (see footnote 1) for additional image analysis of the Chicxulub cores.

two units: units 2 and 3 (Fig. 1A). The overlying unit 1 comprises post-impact sedimentary rocks and is not considered here. We obtained a total of 59 samples from throughout units 2 and 3. Polished thin sections from 31 samples were examined using a Nikon Eclipse LV100POL compound petrographic microscope and via backscattered electron imagery and energy dispersive X-ray spectrometry using a JEOL JXA-8530F Field Emission Electron Probe Microanalyzer. Semi-automatic digital image analysis was conducted on scanned core images following the methods of Chanou et al. (2014). See the GSA Data Repository[1] for further details of the samples and methods.

PROPERTIES OF THE CHICXULUB UPPER PEAK RING LITHOLOGIES

Based on drill core observations and optical microscopy of thin sections, the Upper Peak Ring interval has been described as polymict breccia with impact melt rock fragments, interpreted to be suevite (unit 2), and impact melt rock (unit 3) (Gulick et al., 2018). Here, we compare the key characteristics of the dominant Upper Peak Ring lithologies (units 2A and 2B) with those of suevite from the Ries impact structure (Germany)—the type locality of suevite (von Engelhardt, 1997)—and from the Mistastin Lake impact structure (Canada) where suevite is also abundant (Mader and Osinski, 2018) (Table 1; Figs. 1 and 2). Most notably, units 2A and 2B from Chicxulub are moderately to very well sorted (Figs. 1B and 2; Figs. DR1 and DR2 in the Data Repository), possess internal layering and grading (Fig. 1B; Fig. DR2), and are dominated by vitric particles rather than lithic clasts (Fig. 1B; Fig. DR1), and the mineral and lithic clasts that are present display low abundances of shock effects, all properties that fundamentally differ from those of traditional suevite (Figs. 1C and 1D; Table 1). Sedimentary (aqueous) reworking of a primary suevite is incompatible with the high proportion of glass clasts relative to shocked material in these units, nor does it explain the properties of the vitric particles, with relatively low amounts of clasts and schlieren, and dominantly equant shapes (Fig. 1B; Fig. DR1), which are markedly different from those of traditional suevite (Figs. 1C and 1D; Table 1). It is clear from this comparison that there are significant lithological, stratigraphic, and petrographic differences between the Chicxulub deposits in question and the Ries and Mistastin impactites.

A MOLTEN FUEL–COOLANT INTERACTION ORIGIN FOR THE CHICXULUB UPPER PEAK RING LITHOLOGIES

Critically, units 2A and 2B share many key similarities with the products of phreatomagmatic volcanic eruptions formed via molten fuel–coolant interactions (MFCIs) (Büttner et al., 2002; Wohletz et al., 2013) and with the Onaping Formation of the Sudbury impact structure (Canada; Fig. 1E), which has also been interpreted to have formed via MFCI (Grieve et al., 2010). These similarities include the predominance of vitric particles, the low abundance of shocked lithic and mineral clasts, the similar shapes of the vitric particles, their overall fine-grained and well-sorted nature, and the presence of internal layering on the large-scale and centimeter- to decimeter-scale grading (Table 1; compare Figs. 1B and 1E; see also Grieve

[1]GSA Data Repository item 2020034, additional details of methods, Figure DR1 (photomicrographs of the Upper Peak Ring interval), Figure DR2 (core images), and Figure DR3 (interactive image of a section of unit 2A), is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.

TABLE 1. BASIC CHARACTERISTICS OF THE CHICXULUB UPPER PEAK RING INTERVAL (UNITS 2A AND 2B), COMPARED WITH RIES AND MISTASTIN "SUEVITE", THE SUDBURY ONAPING FORMATION, AND VOLCANIC MFCI DEPOSITS (EXPANDED FROM

	Ries impact structure (Germany) (von Engelhardt and Graup, 1984; von Engelhardt, 1997; Osinski et al., 2004)*	**Mistastin impact structure (Canada)** (Mader and Osinski, 2018)	**Chicxulub impact structure (Mexico)** (this study and as noted)	**Sudbury impact structure (Canada)** (Muir and Peredery, 1984; Ames et al., 2002, 2008; Grieve et al., 2010)	**MFCI deposits** (Büttner et al., 1999; Büttner et al., 2002; Wohletz et al., 2013)
Stratigraphy	No internal stratigraphy	No internal stratigraphy	Internal lithologies; layered	Internal lithologies; layered	Internal lithologies; layered
Relationship to topography	Deposits infill topography	Deposits infill topography	Deposits drape topography (Christeson et al., 2018)	Deposits drape topography	Deposits drape topography
Sorting	Poorly to very poorly sorted	Poorly to very poorly sorted	Well to very well sorted	Well to very well sorted	Well to very well sorted
Graded?	No	No	Yes	Yes	Yes
Vitric clasts:					
Volume percent	Average 16 vol% (although finer fraction of the groundmass also has glass particles)	Average 15–20 vol%	>50 vol%	>60 vol%; up to 80 vol% in Sandcherry Member	Typically>80–90 vol%
Size	Typically 1–10 cm, but up to 1 m long in places	Typically 1–10 cm, but up to 0.8 m long in places	Typically hundreds of µm to ~5 mm; rarely >1 cm	Typically hundreds of µm to 1–5 mm; rarely >1 cm	Typically tens to hundreds of µm
Shape	Irregular	Irregular	Regular, equant	Regular, equant	Regular, equant
Alignment?	Yes	Yes	No	No	No
Mineral and/or lithic fragments in clasts?	Abundant	Abundant	Rare	Rare	N/A
Vesicles?	Abundant	Abundant	Rare	Rare	Rare
Schlieren?	Abundant	Abundant	Rare	None or rare	None or rare
Quench crystallites?	Abundant	Abundant	None or rare	None	None
Impact melt rock clasts?	None	None	Yes	Yes	N/A
Deposition temperature	High (>900 °C)	High (>900 °C)	Low (<580 °C)	Low	Low
Shock level of lithic clasts	>90% shocked to >10 GPa	>75% shocked to >10 GPa	<<5% shocked†	<<5% shocked	N/A

Note: MFCI—molten fuel–coolant interaction; N/A—not applicable.

*Following early proposals that the Ries suevites were deposited from an ejecta plume (von Engelhardt, 1997), Stöffler et al. (2013) and Artemieva et al. (2013 proposed an MFCI origin for the Ries suevites. However, as evidenced by this table, Osinski et al. (2016) and Siegert et al. (2017) showed that the Ries suevites bear no resemblance to volcanic MFCI deposits, and thus cannot share the same origin. Instead, Osinski et al. (2004, 2016) and Siegert et al. (2017) proposed a ground-hugging flow or density current origin for the Ries suevites.

†A caveat to this estimate is that the recognition of shock in carbonate minerals, which are common in these samples, is a difficult and unresolved problem (Stöffler et al., 2018); however, we offer that the amount of shocked carbonate material would also be low, particularly given that it is in the shallowest parts of the target stratigraphy.

et al. [2010, their figure 6 and associated text] for a discussion of these properties in the Onaping Formation). Based on these observations, we propose that MFCI was the major factor responsible for forming the Chicxulub Upper Peak Ring lithologies.

In the hours and days following the impact, seawater re-entered the crater depression, where a lining of impact melt was present (cf. Gulick et al., 2019). MFCI occurs from the interaction of a hot fluid or fuel (i.e., impact melt) with a cold fluid or coolant (i.e., seawater), which transiently creates a vapor film at the interface (Wohletz, 1983; Wohletz et al., 2013). This vapor film expands and then collapses rapidly, resulting in the direct contact of the impact melt with seawater, and in the quench fragmentation of the melt. The final stage is vaporization and expansion of the mixture. At Chicxulub, these particles would have been entrained into the overlying water column and subsequently deposited subaqueously. Millimeter- to centimeter-size fragments, as in unit 2B, are consistent with the submarine setting and higher water-to-melt mass ratio, which decreases efficiency of the MFCI process and increases the average grain size of melt (Wohletz, 1983). A blocky equant shape is the most commonly observed shape of coarse volcanic MFCI particles, which is also the case at Chicxulub (Fig. 1B; Figs. DR1 and DR3) and at Sudbury (Fig. 1E).

While units 2A and 2B share many similarities, there are some differences worth noting (Fig. 1B; Fig. DR1). In addition to being finer grained overall, unit 2A consists of >20 repeated upward-fining or upward-coarsening features and other sedimentary structures, such as cross lamination (Gulick et al., 2018). Unit 2B differs in being devoid of major sedimentary structures other than a general fining-upward succession (Gulick et al., 2018). We suggest that these different properties represent the decreasing intensity and eventual cessation of MFCI activity during the deposition of unit 2B through to unit 2A, such that increasingly throughout unit 2A, deposition was dominated by the effect of resurge and settling of MFCI-generated melt fragments as seawater re-entered the basin, followed by as a series of seiches (temporary disturbances or oscillations in the water level of a partially enclosed body of water).

A further notable difference between traditional suevite and the Chicxulub rocks is that the lower parts of unit 2B and unit 2C contain numerous clasts of hypocrystalline impact melt rock (Fig. DR1), including two large clasts (~60 and 90 cm across) at depths of 706.60 and 708.50 mbsl, respectively (Gulick et al., 2018). For this to occur, impact melt must have had some time to cool and crystallize, and then been fragmented and transported. Fragments of impact melt rock do not occur in suevites, where the melt is cogenetic and glassy (Figs. 1C and 1D) due to rapid emplacement during crater formation. However, the presence of such clasts is predicted by the MFCI model (Table 1), whereby water intrudes into the rapidly crystallizing impact melt pool, explosively fracturing and ejecting partly crystallized melt rock and quenching the still-liquid melt into glass (cf. Grieve et al., 2010). The ~9-m-thick unit 2C is notably more lithologically heterogeneous than the overlying units 2B and 2A (Fig. 2), with evidence for flow in the matrix and a large proportion of impact melt rock clasts; also, the contact with overlying unit 2B is gradational. We consider unit 2C as representing the contact zone between the product of the highly energetic MFCI explosions and the underlying impact melt rock of unit 3 that we interpret as a melt veneer on the underlying uplifted peak-ring rocks.

An MFCI origin for the Chicxulub deposits explains other enigmatic properties of this unit. First, paleomagnetic studies reveal that unit 2C exhibits an intense remanent magnetization, with highly consistent ~–46° inclinations of remanent magnetic vectors that suggest that this unit recorded a thermal remanent magnetization during cooling from >580 °C (i.e., the Curie temperature of magnetite) just after the impact during chron 29r (Gulick et al., 2019). This cooling history is consistent with unit

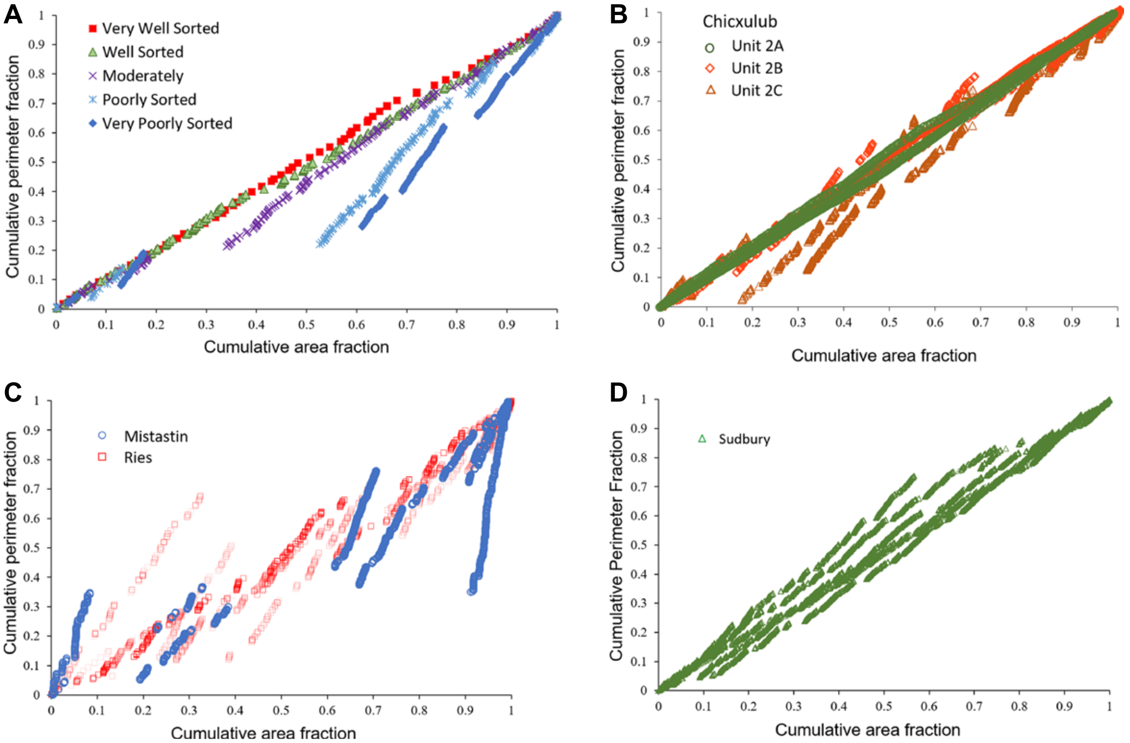

Figure 2. Differentiation of the degree of sorting using cumulative area and perimeter fractions. (A) Following the methods of Chanou et al. (2014), results for typical sorting scale clearly differentiate each sorting level. Very well-sorted samples have a slope of ~1 and show continuous linear distribution. Less-sorted samples have steeper and more discontinuous distributions, with very poorly sorted samples possessing slopes >3. (B) Results for Chicxulub (Mexico) impact deposits (*n* = 8) clearly demonstrate the high degree of sorting of Upper Peak Ring units 2A (green) and 2B (red); unit 2C is moderately sorted (orange). (C) Traditional suevite from the Ries (Germany; *n* = 7) and Mistastin (Canada; *n* = 4) structures are clearly more poorly sorted than the Chicxulub deposits. (D) The Sudbury structure (Canada) Onaping Formation (*n* = 6), like the Chicxulub deposits, is well sorted.

2C's high content of impact melt rock clasts and its juxtaposition with the underlying melt rock (unit 3) which would have baked it from below. In contrast, the Upper Peak Ring rocks in units 2A and 2B exhibit weaker magnetization intensities and more scattered (positive and negative) magnetic inclinations (Gulick et al., 2019). These paleomagnetic characteristics suggest that units 2A and 2B were deposited relatively cold (<580 °C), and display (1) chemical remanent magnetization produced by the creation of secondary magnetite during protracted activity of a hydrothermal system, (2) inherited magnetization from rotated impact melt clasts, or (3) inefficient detrital remanent magnetization (possible for portions of unit 2A, which displays sedimentary structures), or combinations thereof. For comparison, Ries suevites were deposited at minimum temperatures >900 °C (Osinski et al., 2004).

Second, there is a substantial amount of Cretaceous-age sedimentary rock clasts in the core, with the lowest fossil-bearing carbonate near the base of unit 2C (Gulick et al., 2018). This, together with the low abundance of shock effects in lithic clasts as noted above, would not be expected for suevite deposits that are derived entirely from within the transient cavity (Grieve et al., 1977). An influx of seawater bearing sedimentary rock clasts is the simplest explanation, such that the Upper Peak Ring interval represents melt dispersed from MFCI activity mixed with low-shock impact ejecta and/or unshocked material—dominated by sedimentary rocks—from outside the Chicxulub transient cavity. This MFCI origin also explains the most fundamental difference between these Chicxulub deposits and traditional suevites: namely, that the Chicxulub rocks contain a high percentage of melt with very little shocked material, in stark contrast to traditional suevites (Table 1).

WIDER IMPLICATIONS

While a single drill core offers only an isolated one-dimensional window into the stratigraphy of the Chicxulub impact structure, it enables correlation with high-resolution two-dimensional seismic surveys. Importantly, the Upper Peak Ring sequence has been equated with a low-velocity zone present across the Chicxulub basin (Christeson et al., 2017). This is consistent with the report of "sorted suevite" in the upper parts of the Yaxcopoil-1 (Tuchscherer et al., 2004) and Yucatàn 6 (Claeys et al., 2003) drill holes. In light of our work, we suggest that these drill cores need to be revisited, but we postulate that the sorted deposits in these cores are also the product of MFCI throughout the Chicxulub basin. The lower temperature (<580 °C) of deposition of these deposits than that of traditional suevite (>900 °C) from continental impacts (e.g., Ries and Mistastin) also has important implications for the heat source(s) responsible for the generation of the hydrothermal system within the Chicxulub structure (Abramov and Kring, 2007). Specifically, the protracted activity of the Chicxulub hydrothermal system was likely driven by long-term cooling of the main impact melt sheet rather than by heat entrained within the Upper Peak Ring deposits.

In conclusion, we note that the Chicxulub Upper Peak Ring deposits are not accounted for in the current proposed classification scheme for impactites (Stöffler and Grieve, 2007). They bear little resemblance to traditional suevite as exemplified here by examples from the Ries and Mistastin structures, yet these rocks are not the product of sedimentary reworking of primary suevite. Instead, we propose that these types of deposit—now recognized at two of the largest impacts on Earth (Chicxulub and Sudbury)—represent a new class of impact product, akin to volcaniclastic rocks. We suggest that the production of well-sorted, glass-rich breccias is a signature product of large marine impacts, and furthermore, given their similarity to volcaniclastic rocks and the low abundance or even absence of shocked material, additional occurrences may lie hidden and misidentified in the rock record.

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