CHICXULUB, ANATOMY OF A LARGE IMPACT STRUCTURE: FROM IMPACTITE TO EJECTA DISTRIBUTION

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ABSTRACT
The impactites from the Cretaceous-Tertiary boundary Chicxulub crater in Yucatan are described. Chicxulub is one of the largest and best-preserved terrestrial craters. It is thus one of the only places where cratering process and distribution of ejecta on rocky planets with an atmosphere can be directly documented. The Chicxulub impactites originated from a series of wells ranging from the crater center to outside the rim. The impactites were emplaced by either ground surge transport on the crater floor or settled out of the vapor cloud; for the last debris to fall back sorting through the air or water occurred. The possible existence of suevite in outcrops in Yucatan and southern Mexico indicate that the vapor cloud probably had a very wide geographic extension.

1. INTRODUCTION
The Cretaceous-Tertiary (KT) boundary Chicxulub crater buried under the Yucatan peninsula in Mexico is one of the largest impact structures on Earth. This crater is now accepted as the cause of the KT boundary mass extinction that led to the demise of the dinosaurs and 50 to 60 % of the fauna and flora on Earth. Another major scientific significance of Chicxulub lies in the fact that it is a young and well preserved, large impact structure. It is the only pristine crater in the size range > 150 km on Earth (Table 1). After formation, the crater was rapidly buried under Cenozoic sediments, which limited erosion and hampered major modifications of the original morphology. Moreover, little tectonic activity affected the Yucatan peninsula during the Cenozoic.
Currently, the Chicxulub structure is interpreted either as a peak-ring or a multi-ring basin between 180 and 200 km in diameter [1;2;3;4;5]. It was formed some ~ 65 million years ago, by the impact of either an asteroid or a comet between 10 and 12 km in diameter. The recovery, at the KT boundary in a Pacific Ocean deep-sea core, of a small piece of carbonaceous chondrite, inferred to derive from the Chicxulub projectile, favors perhaps an asteroidal origin [6]. The impact occurred on a shallow water carbonate platform with interlayered evaporites overlying a Pan African basement, probably essentially gneissic or granitic in composition [7].
Buried under ~ 1 km of Cenozoic sediments, the crater is not directly accessible and must be investigated using geophysical methods and deep drilling. Seismic data and impact-modeling indicate that the crater transient cavity was between 80 and 110 km in size, reached at least 30 km in depth and excavated the Yucatan crust down to ~ 15 km [3;5;8;9;10]. Although, several geophysical surveys led to major progresses during the last decade, key questions remain open concerning the formation, structure and exact dimensions of the Chicxulub crater. The difficulties in constraining its diameter are in part semantic and related to the precise concept of crater size and crater rim [see discussion in 11].

Table 1: Comparison of the 3 largest terrestrial craters

	Vredefort	**Sudbury**	**Chicxulub**
Age (Ma)	2023 ± 4	1850 ± 3	65.0 ± 0.1
Method	U/Pb, zircons	U/Pb, zircon	Ar-Ar, impact melt
Diameter in km	~ 300	~ 250	~ 180
Position	surface	surface	buried
State of preservation	eroded to sub-crater basement	crater basement to sediments	quickly buried, presumably v. good
Impact melt sheet	relics only dikes, bronzite-granophyre	> 2.5 km, differentiated, SIC	exact size unknow
Target rock	crystalline basement + metasediments?	crystalline basement + metasediments	carbonate evaporite + crystalline basement
Ejecta blanket	eroded	unknown	continuous
Distant ejecta	unknown	Gunflint-Rove Fm	worldwide KTB
Effects	unknown	unknown	mass extinction

The ejecta material produced by this impact spread worldwide and is relatively easy to find as it marks the KT stratigraphic boundary [12]. At this point ejecta have been identified at more than hundred KT boundary sites worldwide, in depositional settings ranging from deep marine to continental [13]. Starting at the crater margin, the continuous ejecta blanket extends over the Yucatan platform all the way to Belize, more than 400 km from the rim [14]. In the Gulf of Mexico region, impact glass and ejecta-spherules are associated with high-energy sedimentation induced by the collapse of the Yucatan platform margin [15] and the production of giant tsunami-waves [12;16]. This ballistic ejecta deposition stretches to the continental sites in the US Western Interior, forming a double ejecta layer [17;18]. At more distal locations worldwide, the products of the Chicxulub vapor plume, which covered the whole planet, are concentrated in the fine KT layer. They mainly consist of shocked materials, Ni-rich spinels and the now classic enrichment in platinum group elements (known as the *positive Ir anomaly*) [12]. The detailed study of Chicxulub provides a unique view of the processes leading to the formation of a complex impact structure and the production and distribution of ejecta debris on a rocky planet with an atmosphere.

2. Implications for cratering on other planets

Impact craters occur on most solar system bodies and attest of the importance of collisions in planetary evolution [see 19 for a discussion of crater terminology]. However, despite several decades of multidisciplinary efforts, the process of crater formation is far from being fully understood, in particular for large complex structures. The formation of complex crater releases so much energy that the fundamental properties of a sizeable volume of the target rock are modified. These lithologies become capable of flowing, and large volume of rocks can be displaced in various directions. The final crater morphology is the result of complex interactions between the propagation of shock waves, strength and viscosity of the target rock, and gravity. Terrestrial craters are so far the only place where the relationships between crater size and morphology on the one side and subsurface structure and lithology on the other side can be established. On planetary bodies, craters show, with increasing size, a drastic change in morphologies, essentially marked by trend towards flatter structures of higher internal complexity [19]. The trend is best documented from the Moon, which thanks to its lack of geological activity ideally preserves crater morphologies (Fig. 1). Good examples are also known from Venus and Mars.

On the Moon, small structures display a simple bowl-shaped morphology. With size, the crater evolves into a central-peak crater, characterized by a flat central zone marked by a central protuberance. As size continues to augment, this central peak transforms into an almost circular peak-ring surrounding an inner basin (Fig. 1). A succession of concentric uplifted rings, and down-faulted grabbens, appears in the largest craters, forming what is characterized as a multi-ring basin morphology. The “bulls-eyes” structure of the 900 km in diameter Mare Orientale basin is a classic example of a multi-ring basin.

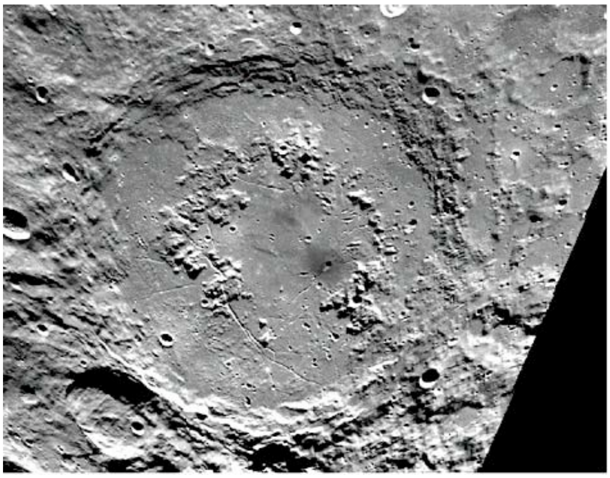


Fig. 1 Schroedinger central peak-ring crater on the Moon (320 km in diameter)

About 170 impact craters are known on Earth. Geological activities bias their distribution towards young craters (< 200 Ma). On average, small size structures are underrepresented because quickly eroded. It is difficult to establish clear size limits for the different crater morphologies. Depending on the composition of the target rock, structures less than 2 to 4 km display a bowl-shaped morphology such as Barringer crater (1.1 km) in Arizona. Central peak craters do form between 2 and 20 km, such as Sierra Madera, (13 km) in Texas. Above ~25 to 30 km, the craters develop a peak-ring morphology, as shown by the Ries (25 km) in Southern Germany, Mjølnir (40 km) in the Barents Sea, Clearwater West (36 km) in Canada [20]. The presence of multi-ring basins on Venus indicates that such huge impact basins should also exist on Earth [4]. In this size range (>> ~ 100 km), the lack of understanding of the ring formation process, coupled with erosion and post-impact deformations renders the determination of morphology of the largest terrestrial crater more difficult and in some cases rather controversial. In multi-ring basins, the post-impact movements of the target rock affecting the transient crater are far more complex and extensive than in smaller structures [19;20].

Only three recognized complex structures > 150 km in diameter are known on Earth. These 3 large craters are Vredefort in South Africa, 2023 Ma old and estimated between 250 to 300 km in size; Sudbury in Canada, 1850 Ma old and estimated to be 250 km in size, and Chicxulub, 65 Ma, between 180 and 200 km in size. Table 1 compares the 3 structures. At Vredefort, erosion has removed the original features down to a depth between 5 and 11 km, preserving only the deeper inner structure [21]. On top of 1.8 billion years of erosion, the shape of Sudbury has been severely distorted by post-impact tectonic activity. The exact morphology and size of these two ancient craters is thus difficult to reconstruct. The well-preserved

Chicxulub crater probably represents an ideal candidate for a terrestrial multi-ring basin [2;3]. The rings could be marked by small topographic elevations recognized on the Yucatan platform [22], which seem to correlate with concentric highs of the target lithology, detected by seismic reflection profiling (Fig. 2) [4]. However, the case is far from being settled and major discussions remain [see 5;11;23].

3. Drilling in the Chicxulub crater

Several drilling campaigns took place within or at the margin of the Chicxulub crater (Fig. 3). Several decades ago, PEMEX, the Mexican oil company, drilled Chicxulub as a petroleum exploration target. Three holes penetrated the structure and another 5 were set outside the rim. Some information from the ditch cuttings and logging data are still available and a few pieces of cores have been preserved mainly form well Yucatan 6 (Y6), and to a much lesser extend Chicxulub 1 (C1). The holes Sacapuc 1 (no core preserved) and C1 were drilled in the central peak-ring of the crater, and Y6 on the flank of the uplifted central zone. In 1994, the Universidad Nacional Autonoma de Mexico (UNAM) started a shallow drilling campaign outward from the crater margin [24]. Three holes intersected the impactite lithologies, UNAM 5, 6 and 7. In 2002, the International Continental Scientific Drilling Project (ICDP) drilled the hole Yaxcopoil 1 (Yax1) in the structural low zone, between the inner peak-ring and the crater rim [25].

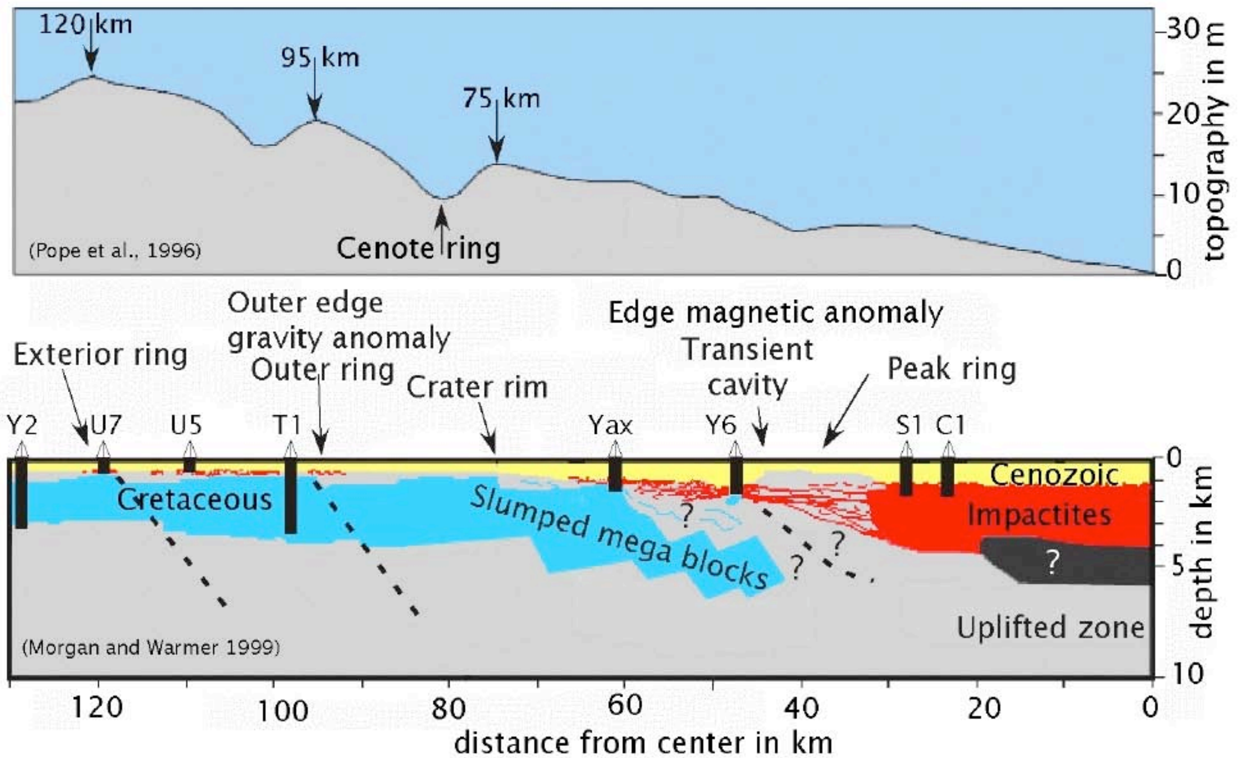


Fig 2 Above: topography of the Yucatan Peninsula showing local elevations, possibly reflecting the ring structure from the underlying Chicxulub crater. The aligned cenotes are most likely also related to the intense fracturing of the crater lithologies. Below: projection of the onshore wells on a crater model based on the offshore seismic line. The advocated expansion of the impact melt-rock outside the peak ring central depression is indicated (modified after [11]). As documented in Yax1 and Y6, layers of melt breccia settled on the flank of the peak ring and became very thin in the annular trough

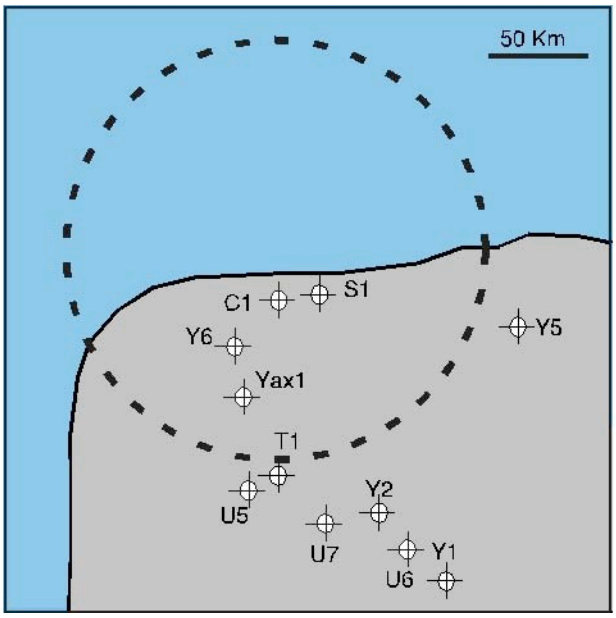


Fig. 3 Location of the existing wells in Chicxulub

4. THE PEMEX CORES: CHICXULUB 1 AND YUCATAN 6

Fig. 4 shows the stratigraphy of the impactites and the samples available from wells C1 and Y6. Near the center of the peak-ring, the Chicxulub-1 well seems to have reached the melt-rock around 1250 m. The only two preserved samples (C1-N9 and C1-N10 around 1400 m) show a classic melt-rock texture with an abundant millimeter sized melt-fragments floating in a rather coarse matrix (Fig. 5). All the clasts show various degree of melting and the majority is clearly digested in the matrix. The clasts are composed of plagioclase and pyroxene and their original composition cannot be identified. The matrix contains small (0.5 mm) augitic pyroxene and lath-shaped plagioclase grains, which calcic core is often surrounded by albite. Slightly larger K-feldspar crystals are also present. Less abundant minerals are epidote, magnetite, sphene, pyrite and Fe – Mg - alumino-silicates. Calcite and anhydrite are rare, and when present clearly form a secondary replacement phase. The presence of albite rim around plagioclases indicates some hydrothermal alteration of this locally porous matrix. However, this alteration appears less intense compared to the samples from Y6 or Yax1 (see below). This is supported by the $^{40}Ar/^{39}Ar$ dating of the C1 samples that produced flat Ar release spectra and yielded reliable KT boundary ages [26].

In C1, the melted material is derived from the deep basement part of the target rock, with little contribution from the overlying sedimentary rocks. The absence of unmelted fragments and the coarse-grained matrix support a rather slow cooling process within the inner part of a probably thick melt-sheet. The Chicxulub C1 melt-rock resembles the thick melt sheets described at other large (> 100 km) craters such as Manicouagan and Sudbury. C1 is so far the only site within the Chicxulub crater where real impact melt-rock has been recovered.

More samples are available from well Y6 (Fig. 4). Despite their sporadic distribution, the sequence of impactite can be reconstructed. Below the Cenozoic sequence, suevite is encountered at ~ 1100 m, its thickness is estimated around 170 m. Three different types of suevitic lithologies have been described in details by [13].

A fine-grained carbonate-rich suevite occurs at the very top of the impactite (upper suevite, 1100-1103 m). This unit is dominated by small size (~ 0.5 mm) solid and formerly molten fragments of the carbonate layers forming the upper part of the Yucatan target. Some solid fragments still display fossils, while others are characterized by feathery textures supporting the existence of carbonate melt [13]. Melted basement clasts, most of them altered to phyllosilicates are also present. Carbonate globule are closely associated with the silicate melt. These clasts are embedded in a porous, matrix composed mainly of small (~10 to 30 µm) crystals of calcite, feldspar, and quartz.

The underlying unit is a coarser and more clast-rich suevite (middle suevite, 1208-1211 m). The clasts are distinctively larger and more distinct than in the overlying unit. The proportion of unmelted basement (mm to cm in sizes) and altered silicate melt increases while the carbonate clasts clearly decrease. The silicate clasts reflect the composition of the deep Yucatan basement (gneiss and quartzite) and show a high degree of shock metamorphism (several sets of PDF and mosaics in quartz). The clasts are floating in much more compacted but still very calcite-rich (~ 40 wt%) matrix. Rare anhydrite clasts are present. This unit resembles the “classic” fall-back suevite described at the Ries crater for example.

The last unit of the sequence is an annealed suevite (thermometamorphic or lower suevite, 1253-1256 m). It contains essentially shocked basement clasts and silicate-melt fragments. Carbonates, both as clasts or in the matrix are much less abundant in this unit. The matrix is dense, recrystallized and composed of intergrown feldspar and pyroxene grains. Locally, anhydrite fragments are present, but most likely as a secondary replacement, as are the calcite veins running through parts of the rock. This unit lies on top of several hundred meters of impact melt breccia (Fig. 4). The clastic matrix was probably thermometamorphosed and recrystallized at the contact on the hot underlying unit.

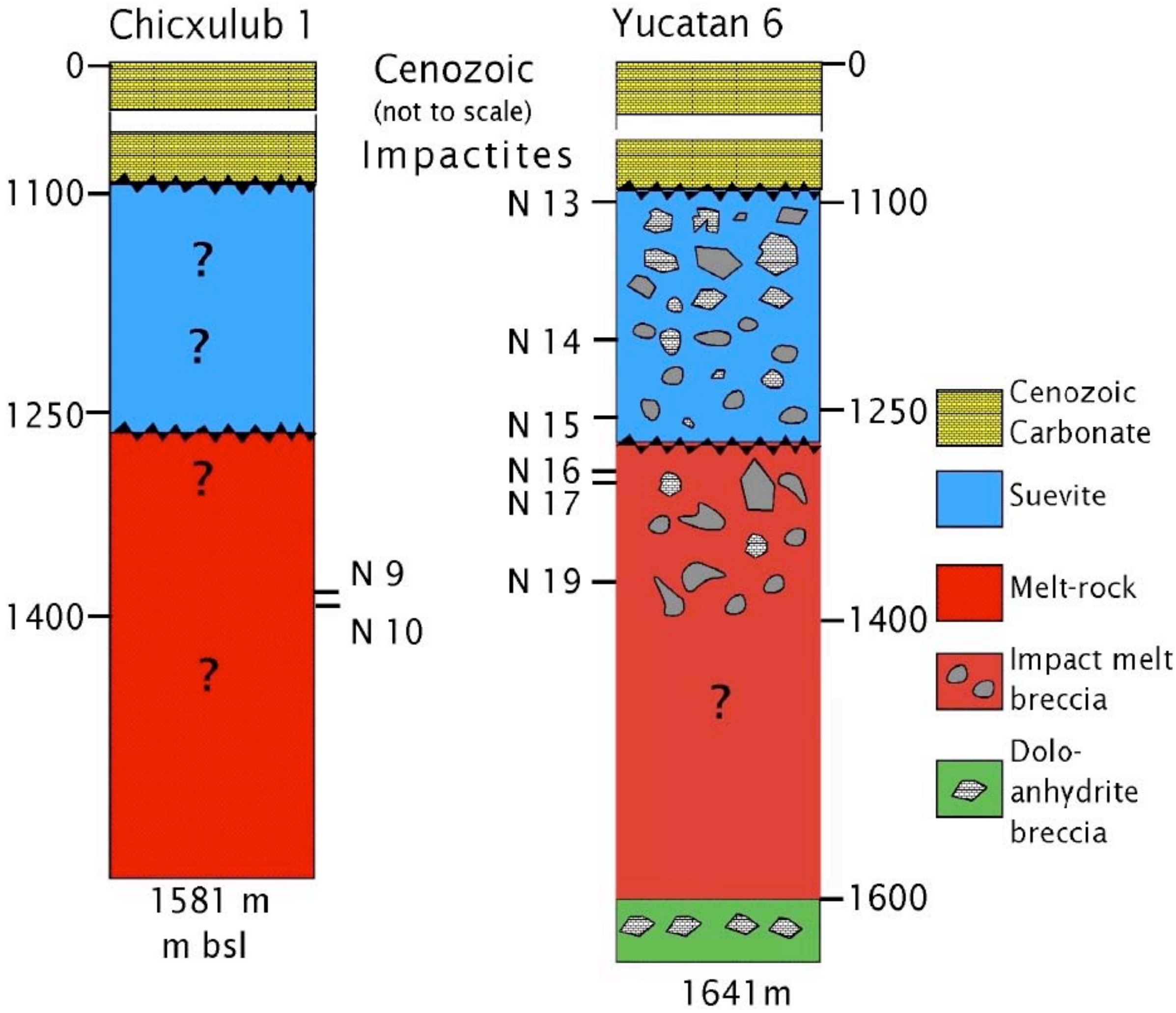


Fig 4 Schematic representation of the impactite lithologies encountered in the PEMEX cores C1 (peak ring) and Y6 (flank of peak ring), the depth of the preserved core fragments in indicated. In Y6, carbonate content decreases with depth.

The Y6 suevite, despite the lack of continuity in the available samples, is clearly stratified. Carbonates from the upper part of the Yucatan target rock noticeably dominate the composition of the top of the suevite. With increasing depth, it is replaced by a more basement-derived composition. In terms of bulk chemistry, SiO_2 is negatively correlated with both CaO and MgO. Evaporite clasts are underrepresented compared to their proportion (~1/3) in the upper part of the Yucatan target rock.

Below ~ 1260 – 1270 m (?), the suevite is replaced by an impact melt-breccia, which seem to extend down to a depth of more than 1600 m. According to the ancient PEMEX logging reports, Y6 bottomed in a dolomite-anhydrite breccia at ~ 1641 m. The thickness of the impact melt-breccia is about 330 m, but unfortunately, only its upper part has been sampled. It is composed of solid and melted basement clasts, a few mm in size dispersed in a fine matrix. Some gneiss clasts can be recognized, but the majority is composed of recrystallized quartz and feldspar. The silicate basement clasts display clear evidence of PDF. The fragments are well distinct in the matrix and often are surrounded by a corona of pyroxene. Other clasts are assimilated in the matrix but to a much lesser extend than in C1. The matrix is abundant (70% of the rock) and composed of microcrystals (< 10 μm) of pyroxene and plagioclase embedded in a loose cryptocrystalline groundmass. Carbonate and anhydrite are not common in this unit. Locally veins of anhydrite occur but clearly representing secondary hydrothermal processes. The upper part of this unit down to ~1400 m (Fig. 4) appears rather homogeneous in terms of clast and matrix composition.

The Y6 impact melt-breccia is clearly finer grained and significantly, more altered than the impact melt material described in C1. It differs also from the "classic" melt-rocks known at other large craters. In terms of bulk chemistry, the Y6 impact melt-breccia is similar to the lower suevite unit and is more carbonate-rich than the C1 melt-rock. Based on its fine texture and undigested clasts, it crystallized more rapidly, probably from a thinner melt pool than its C1 counterpart. The components are clearly derived from the shock melting of the deep Yucatan target rock, with limited contribution from the overlying sedimentary units.

Little is known about the dolomite / anhydrite breccia reported to occur at the bottom of Y6. This well is located in or near the rim of the collapsed transient cavity [3;4;5]. This is most likely, a rather complex structural zone. One simple explanation is that this breccia represents the top of a series of mega-blocks of the stratified Yucatan target rock, as in Yaxcopoil 1 (see below). However, this remains to be confirmed, as the mega-blocks could also have been scraped off and slumped away from this very zone. The breccia would then represent deeper lithologies. The offshore seismic profiles do not permit to clarify this question. This polymict breccia constrains the thickness of the melt material to ~ 360 m. The Y6 impact melt breccia probably formed a tongue of melt material spilled over from the central zone and emplaced on the flank of the central peak-ring (Fig. 2).

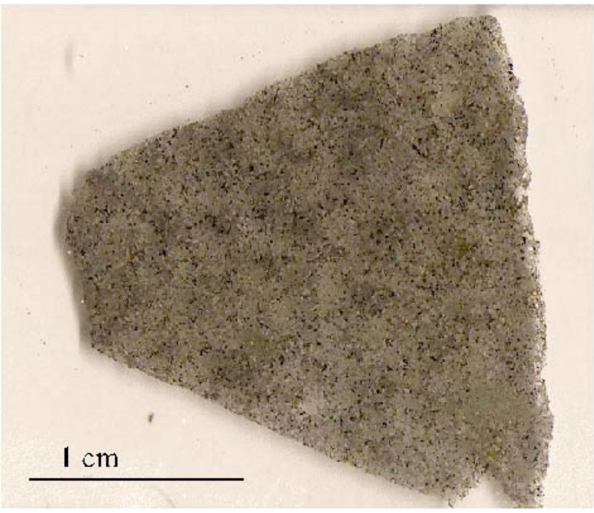


Fig. 5 Chicxulub coarse grained impact melt-rock from well C1. This sample orginates from the top of a thick impact melt sheet (photograph of a thin section).

5. The ICDP Yaxcopoil-1 (YAX1) core

The ICDP drilling at Hacienda Yaxcopoil took place between December 2001 en March 2002 and reached a depth of 1511 m. The well was located some 62 km south from the center of the Chicxulub crater, and ~15 km south of previously described well Y6 (Fig. 3). In term of the crater structure, this location corresponds to the depression zone between the inner peak-ring and the crater rim.

Post-impact Cenozoic sediments form the top 795 m of the encountered lithologies (cored only from 495 to 795 m). They overlie 100 m of allochtonous polymict breccia (794.63 to 894.94 m) characterized as suevites according to [27]. Below, a 616-m thick sequence of Mesozoic carbonate and anhydrite layers occurs from a depth of 895 m all the way to the bottom of the well (1511 m).

The thin impactites sequence has been described by several authors and subdivided in 6 units [23]. Only, [28] preferred to group to upper two units (sorted suevite), what appears reasonable considering that they form a continuous fining upward sequence. Bulk rock chemical analyses of these units are given by [28].

In general, the Yax1 suevites are rich in melt particles, mostly derived from the silicate basement. They are clast supported and the percentage of matrix varies significantly throughout the sequence. Carbonates form a major component of the matrix and occur as solid clasts. These characteristics were also reported for Y6 and in general distinguish Chicxulub from the suevites described at other craters [13]. In the suevite units, basement fragments contain indications of shock metamorphism, mainly in the form of quartz grains displaying 2 or 3 sets of PDF. There is no marked increase in shock metamorphism with depth. Some of the shock features were perhaps recrystallized in unit 5, but unit 6 seems to contain fewer shocked grains than the overlying units. Yax1 is more affected than Y6 by hydrothermal alteration that has transformed most of the formerly melt or glass components in phyllosilicates or has caused the precipitation of secondary K-feldspars [23]. Within the matrix, calcite often appears recrystallized. The nomenclature of the Yax1 suevite given below follows that of [23]. It is the most consistent with the one used for Y6 [13], facilitating the comparison and correlation between the two wells.

1) Unit 1 (upper sorted suevite) occurs between 794.63 m and 807.75 m. This homogeneously fine grained (1 to 2 mm), and in part, laminated unit is composed of greenish to brownish melt particles mixed with carbonates and a lesser proportion of basement fragments. It is clearly clast supported. The matrix, composed of fine calcite and some silicates occurs only as local patches between the clasts. Shocked minerals are rare, and there is no traces of former calcite melt as in the Y6 upper suevite, except perhaps as small inclusions in altered silicate melt particles.

Unit 2 (lower sorted suevite) is found between 807.75 m and 823.25 m. It is similar in terms of components and matrix to the overlying suevite. This unit is coarser grained, with some clasts reaching several centimeters. In general, the sorting is not as good, as in unit 1. There is a clear decrease in grain size upward from unit 2 to unit 1 [28]. This supports a continuous deposition in a relatively quiet environment with sorting of the grains during settling through the air or the water column. The sorted suevites in Yax1 share many similarities with the upper suevite of Y6. Both resulted from the same sedimentation process: an air fall deposition with possible aquatic interactions [13;23].

Unit 3 (upper suevite) occurring between 823.25 m and 846.09 m is noticeably distinct from the overlying units. In this unit, also rich in shard-like melt particles, basement clasts are floating in a clearly clastic matrix, representing more than 50% of the rock. The matrix is essentially composed of calcite, lithic particles and phyllosilicates. Among the clasts, the silicate basement dominates over carbonates. The melt particles show fluidal texture and often contain vesicles and carbonate inclusions aligned parallel to the direction of flow. Anhydrite occurs but it is difficult to say if it is as clasts or most probably as a secondary replacement.

Unit 4 (middle suevite) is comprised between 846.09 m and 861.06 m. It resembles unit 3, except that the clasts and melt particles are more variable in colors and have somewhat larger sizes. The amount of matrix is also significantly lower (<30 %). These last two units are genetically linked and can be correlated with the middle suevite in Y6. A fall-back process deposited them as the vapor cloud rising on top of crater collapsed.

Unit 5 (brecciated impact melt-rock), occurring between 861.06 m and 884.92 m is not a suevite sensus stricto. It can be considered an impact-melt breccia, although it differs from that underlying the suevite units in Y6. Basement and carbonate clasts commonly occur in this unit but they are always less abundant than the melt particles. Some of the clasts and melt particles display rather large sizes (> 20 cm). The not-clastic matrix is composed of recrystallized plagioclase and pyroxene, mixed with calcite and phyllosilicates. It represents less than 10% of the rock. This unit can perhaps be considered as a reworked and more carbonate-rich equivalent (both as clast and matrix) to the much thicker impact melt-breccia at Y6.

Unit 6 (lower suevite) occurs between 884.96 m and 894.94 m and is rather different from the overlying sequence. It consists essentially of melt particles and clasts dispersed in a very carbonate-rich groundmass. The solid clasts are mostly limestone and dolomite and often are completely integrated and assimilated in this groundmass. A few rather large (10 cm) silicate basement clasts are present. This unit has no known equivalent in Y6. It appears be a mixture of the material forming the overlying impact melt-breccia, diluted in a poorly sorted carbonate breccia. The underlying thick sequence of carbonates and evaporitic sediment is interpreted as tilted mega-blocks, displaced during the excavation process. They are cut by a series of impact-related dikes containing suevite, impact-melt and monomict breccias [29]. The carbonates are composed of alternating layers of limestone and dolomite. Locally, some organic-rich and oil-bearing layers are present (1410 to 1455 m). The anhydrite layers vary in thickness from a few cm to more than 12 m and represent between 25 and 30 % of the mega-block sequence. They display textural characteristics indicative of deposition in shallow-water restricted environment, such as sebkha. The 616 m of underlying Mesozoic sediments have so far not been studied in details, except for the small intervals cut by impact related dikes. An in depth biostratigraphic study of these Mesozoic sedimentary units is urgently needed to document the pre-impact position, source and amount of displacement of the mega-blocks.

6. The UNAM shallow cores outside the crater rim

Below Cenozoic carbonates, well UNAM 5, located some 105 km south of the crater center, (Fig. 2) encountered a polymict impact breccia from a depth of ~ 332 m all the way to the bottom at 504 m [24]. This ~ 172 m thick breccia contains melt particles and qualifies as fall-out suevite according to the definition of [27]. The whole sequence appears rather homogenous and composed of various proportions of melt particles, some of them with a well preserved glassy textures, carbonate and anhydrite fragments as well as basement clasts. These fragments are floating in a clastic carbonate-rich matrix. The proportion of clast versus matrix varies significantly. Clasts of anhydrite and dolomite are much more widespread than in the suevite contained within the crater.

Well UNAM 7 is located some 125 km from the crater center [24]. This same suevite unit as in UNAM 5 is encountered, below the Cenozoic carbonates, from a depth of 222.20 m to 348.40 m. A polymict chaotic breccia, with no or only very rare melt fragments occurs below. The clasts are composed of carbonates (limestone and dolomite) and numerous evaporite fragments. The well bottoms in stratified layers alternating between carbonates and evaporites.

Well UNAM 6, some 150 km from the crater center contains no suevite unit. The basal polymict breccia of UNAM 7, containing clasts of limestone, dolomite and evaporite occurs from a depth of 282.80 m below the Cenozoic sediments. The stratified carbonate and evaporite layers appear around 540.50 m. Either the fall-out suevite was eroded from this location before the deposition of the overlying carbonates or it was not deposited.

The observed succession of polymict breccia topped by suevite is similar to the Bunte breccia – fall-out suevite units seen outside the Ries crater. At this point, it remains rather difficult to correlate the fall-out suevite with the units found within the crater in either Yax1 or Y6 and to invoke similarity in their depositional processes. The fall-out suevite is much richer in sedimentary clasts in particular anhydrite and dolomite than its crater counterpart. It also contains no indication of carbonate melt. This must be viewed as an indication that the fall-out suevite sampled another part - perhaps towards the outside - of the vapor cloud, enriched in these sedimentary components.

7. EXPANSION OF THE FALL-OUT SUEVITE

Several elements may indicate a greater geographic distribution of the deposition of the fall-out suevite outside the crater rim. The continuous ejecta blanket extends over Yucatan and reaches Central Belize, some 360 km from the crater [14]. This unit is essentially composed of authochtonous small and large blocks of dolomite, eroded from the underlying layers and transported over relatively short distances. A finer groundmass of highly crushed carbonates rims the blocks, which size reach several meters. This unit is still about 15 m thick near the Mexican-Belize border. If fall-out suevite ever covered this part of the ejecta blanket, it has now been completely eroded. However, within the top of this is diamictite-like breccia, meter-size clasts composed of greenish to brownish clay material occur (Fig. 6). Small (< cm) fragments of the Yucatan basement can be extracted from these large clasts. They could perhaps represent highly altered suevite debris, lofted from the crater and incorporated in the upper part of ejecta blanket as it was spreading over the Peninsula.

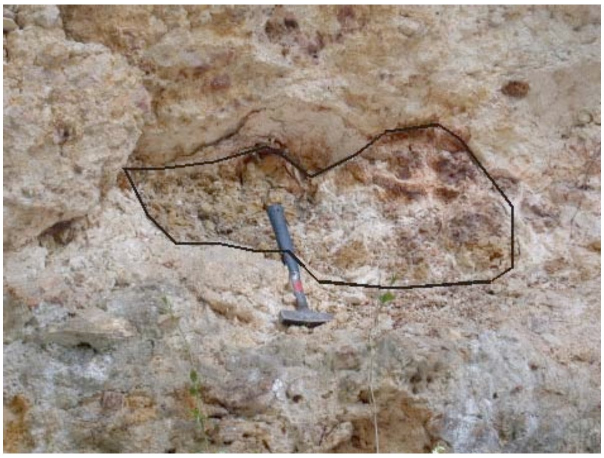


Fig. 6 Diamictite-like ejecta blanket made of autochtonous blocks of dolomite and finely crushed carbonate. This unit crops out in Yucatan, Quintana Roo and Belize [14]. A clay-aggregate is outlined; it could represent what remains of a suevite fragment incorporated in the top of the ejecta blanket as it was deposited all over the Yucatan peninsula. Basement clasts probably originating from the crater can be extracted from such sample.

Further away, in the zone extending today from Campeche to the Northern part of the Chiapas region, the deep-water setting KT boundary is characterized by thick carbonate breccias formed by the collapse of the margin of the Yucatan platform [15]. In El Guayal (State of Tabasco), some 650 km from the crater, the breccia is covered by a ~ 9 m thick succession of calcareous sands and silts rich in impact material. The same succession has been reported from the oil wells offshore in the Campeche area [15]. The grain size fines upward and the ejecta are essentially composed of altered glass particles, basement clasts, shocked quartz and carbonate fragments. Microfacies analyses indicate that these carbonate fragments formed on a shallow water carbonate platform, such as that covering Yucatan. This unit also contains an 80 cm-thick layer with accretionary lapillis (~ 2 cm, Fig. 7).

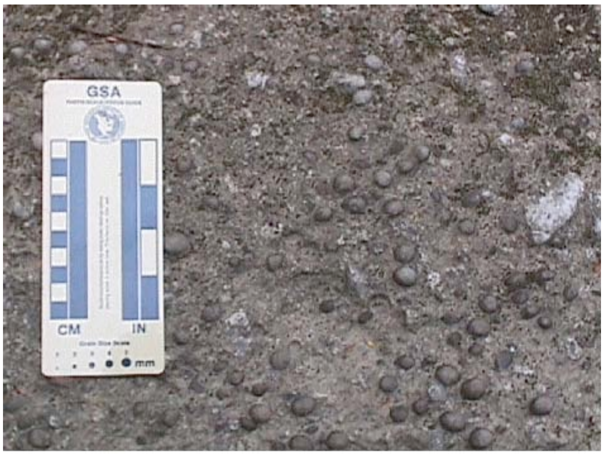
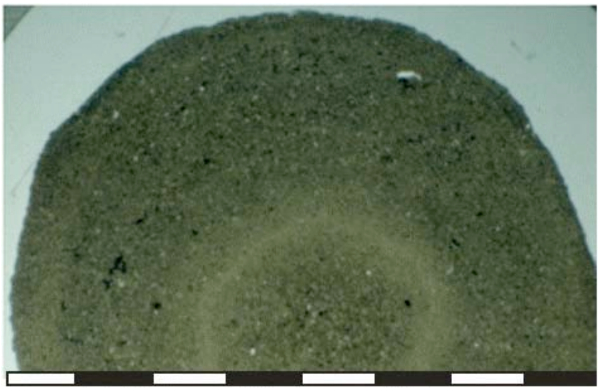


Fig. 7 A. Lapilli unit found ~ 2 m below the KT clay containing the platinum group anomaly in El Guayal (Tabasco). The lapillis are up to 2 cm in size and composed of aggregated small grains of calcite and silicates. They are interpreted to be part of a distal fall-out suevite and to have formed in the turbulent part of the vapor cloud.



B. Cross section of lapilli showing the concentric structure. The rings formed by accreted submillimetric grains of calcite, quartz and melt particles can be distinguished.

The lapillis are composed of concentric laminations of accreted carbonates, melted particles and shocked grains, less than a few hundred microns in size. This unit is separated from the Ir-enriched KT boundary clay by a < 2 m thick, poorly consolidated siltstone, rich in ejecta. Similar lapillis, but significantly smaller, are known in the Ries crater suevite [30]. Although, highly altered this whole succession is intepreted as fall-out suevite. Its mineralogical composition clearly links it to the turbulent vapor and debris cloud that expanded from the crater. Its deposition in the El Guayal area attests of the lateral extension and magnitude of the cloud. A very similar unit, displaying a succession of carbonate breccia, topped by possible fall-out suevite with accretionary lapillis has been reported from Central Cuba [31].

8. Emplacement of the impactites in Chicxulub (Fig. 8)

In the light of the current Chicxulub situation, it is possible to propose scenarios explaining the emplacement of the impactites. So far, most of the seismic lines are located offshore while the core data come from onshore wells. By projecting the well locations on the existing seismic lines, a transversal sequence of crater locations is established (Fig. 2). This projection of course implies a perfect symmetry of the crater, which is unlikely to be the case. The wells spread from the central peak ring area (C1) to the flank of the central peak ring (Y6) to the annular through outward from the peak ring (Yax1) to the outside crater margin (UNAM 5, 6, 7 wells). Considering the fragmented aspect of the information provides by C1 and Y6, this sequence is far from ideal, nevertheless interesting observations can be made (Fig. 8)

Based on seismic data and the rare samples from C1, it is clear that an impact melt sheet lies within the central part of the peak-ring area. This coherent melt sheet cooled off slowly and must be rather thick (Fig. 2). Based on its chemical composition (highest SiO2/(CaO+MgO of all the analyzed units)) it is essentially derived from the melting of the deep silicate basement under Yucatan. The contribution of the overlying carbonate and evaporite target lithologies was minor. The offshore seismic data coupled with modeling results support the presence of a coherent impact melt sheet, 3 to 4 km thick. The transition with the underlying uplifted deep crustal lithologies remains to be clarified [5;10;32].

Some of this impact melt escaped the central depression and accumulated on the flank of the peak ring forming the impact melt-breccia encountered in Y6 (Fig. 2;8). This tongue of impact melt was deposited on top of a polymict breccia of dolomite and evaporite. The structural relationships of this breccia remain to be clarified. It is certainly related to the excavation of the transient cavity, and the outward displacement of mega-blocks from the target lithologies. The tongue of impact melt-breccia extended further out- and downward, cooling down, thinning and in part solidifying. The presence of brecciated clasts indicates that it was already solid as the reworking took place. As it propagated on a carbonate-rich substrate, it picked up more and more clasts. When this ground surge reached the lower zone of the annular trough, its base was laden with solid and melted carbonate fragments of various sizes. It forms the “lower suevite” identified at Yax1. The same type of mass flow transport is responsible for the emplacement of the overlying unit, with reworked consolidated melt fragments but less carbonates. This ground-surge unit was still hot, when fall-back suevite landed on top of it, as documented by the recrystallization of the matrix in the lower suevite unit in Y6 [13]. The melt-rich fall-back suevite described in Y6 and Yax1 share enough similarities to be both explained by the collapse within the crater of the vapor and debris plume. The observed variation in composition and proportion of the different melt components and clasts can be attributed to different thermal regimes of the plume, and/or a sorting effect during sedimentation.

Later, the fining upward suevite settled, through interaction and sorting by the atmosphere. It is unclear if water effectively rushed back in the crater shortly after the impact [33]. In both Yax-1 and Y6, there is evidence for fine scale laminations, which could be interpreted to indicate gentle settling through the water column [13]. This unit is clearly derived from the hottest zone most likely in the upper and central part of the plume that was rich in carbonate (both as melt and solid) and silicate melts, but depleted in solid basement clasts.

The fall-out suevite deposited on top of the ejecta blanket outside the crater rim is probably derived from a different part of the vapor cloud. Based on the Mesozoic Yucatan stratigraphy [7] and field observation over the Yucatan peninsula, it appears plausible that the dolomite and evaporite clasts were lofted from a more superficial part of the target rock, outward from the excavation zone. The possible wide extension (> 500 km) of the fall-out suevite deposition seems to indicate that the vapor cloud also had a considerable lateral expansion. The presence of accretionary lapillis in the region of Tabasco and in Central Cuba [31], which in the late Cretaceous was located somewhere to the southwest of Yucatan, attest of the lateral magnitude of the cloud. A more in detailed study of these outcrops in term of ejecta transport and deposition is required.

9. Perspectives

The scenario proposed here is preliminary and schematic as it based on limited impactite samples. It could be improved by a better correlation with the offshore seismic lines, and of course by obtaining more continuous cores in Chicxulub as planned by the ICDP/IODP drilling project [34]. Stratigraphic and biostratigraphic studies of the sedimentary Mesozoic sequence underlying the impactite in Yax1 will shed light on the original position and the amount of displacement of the mega-blocks away from the transient cavity zone. In these mega-blocks, evaporites represent between 25 and 30 % of the upper 3 km of the sedimentary target rock. This resolves in part the controversy as to the amount of sulfate involved in the cratering process and eventually vaporized [13]. The relative absence of evaporite clasts in the crater's suevite can then be interpreted to reflect the (almost) complete vaporization of the evaporitic layers in the upper part of the target rock. It is likely that the amount of released SOx reached the saturation effect in the climate forcing advocated by [35]. The association of impactite studies with numerical modeling as developed by [23] for the Yax1 well certainly deserves to be applied to the whole crater. Numerical models could also document the amount of lateral expansion of the vapor cloud, and test if it is compatible with suevite deposition at more than 500 km from the crater rim.

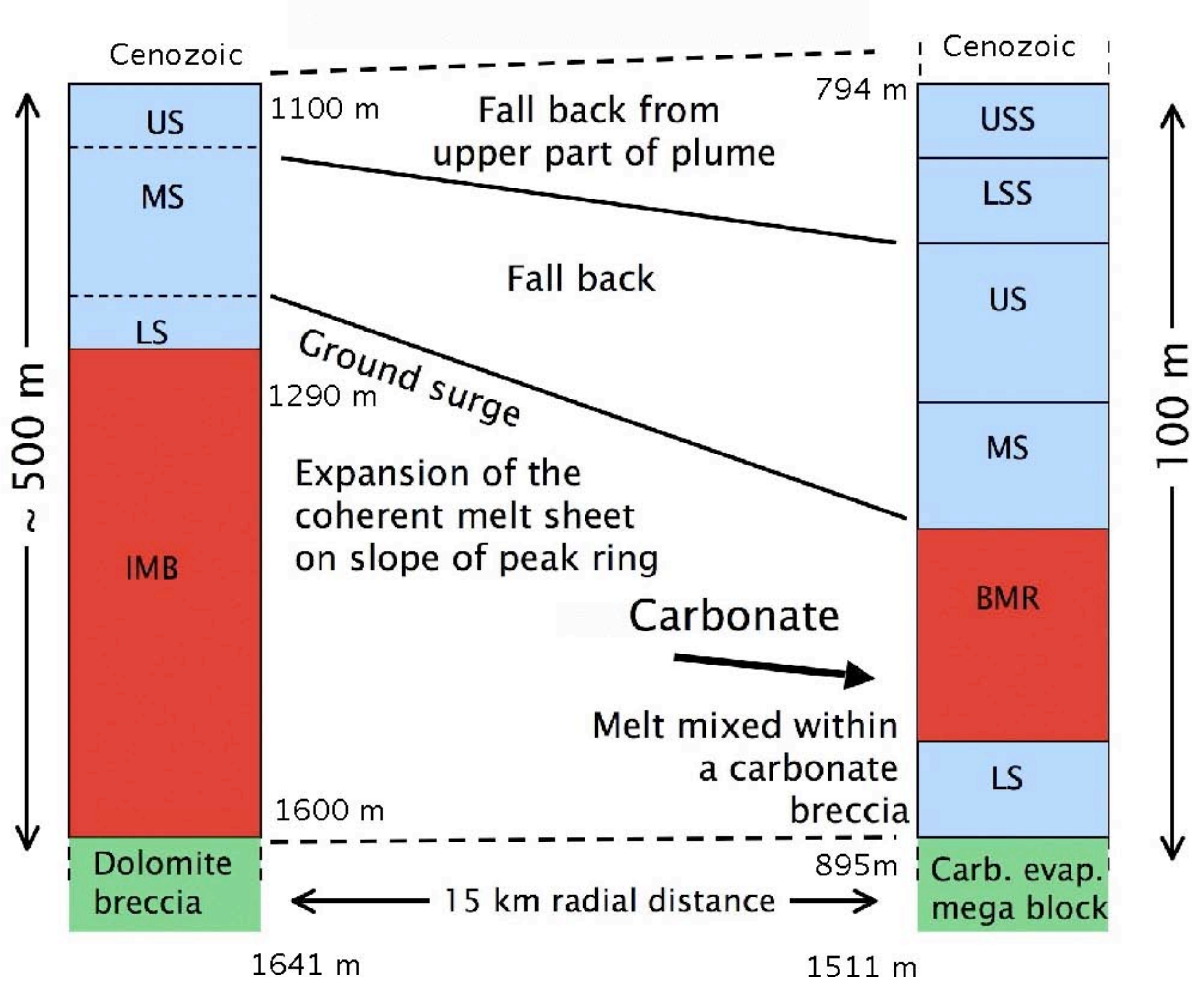


Fig. 8 correlation of the impactite lithologies encountered in Y6 and Yax1, with the three major emplacement processes, ground hugging transport of the basal units, classic fall-back suevite and fall-back with a sorting agent such as air or water for the upper part of the sequence. (Y6: US=upper suevite, MS=middle suevite, LS=lower suevite, IMB=impact melt breccia; Yax1: USS=upper sorted suevite, LSS=lower sorted suevite, US=upper suevite, MS=middle suevite, BMR=brecciated melt rock, LS=lower suevite) [13;23].

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