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Geomaterials

Impact ejecta and carbonate sequence in the eastern sector of the Chicxulub crater

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Abstract

The Chicxulub 200 km diameter crater located in the Yucatan platform of the Gulf of Mexico formed 65 Myr ago and has since been covered by Tertiary post-impact carbonates. The sediment cover and absence of significant volcanic and tectonic activity in the carbonate platform have protected the crater from erosion and deformation, making Chicxulub the only large multi-ring crater in which ejecta is well preserved. Ejecta deposits have been studied by drilling/coring in the southern crater sector and at outcrops in Belize, Quintana Roo and Campeche; little information is available from other sectors. Here, we report on the drilling/coring of a section of ∼34 m of carbonate breccias at 250 m depth in the Valladolid area (120 km away from crater center), which are interpreted as Chicxulub proximal ejecta deposits. The Valladolid breccias correlate with the carbonate breccias cored in the Peto and Tekax boreholes to the south and at similar radial distance. This constitutes the first report of breccias in the eastern sector close to the crater rim. Thickness of the Valladolid breccias is less than that at the other sites, which may indicate erosion of the ejecta deposits before reestablishment of carbonate deposition. The region east of the crater rim appears different from regions to the south and west, characterized by high density and scattered distribution of sinkholes. ***To cite this article: J. Urrutia-Fucugauchi et al., C. R. Geoscience 340 (2008).***

Résumé

Projections d'impact et séquence carbonatée dans le secteur oriental du cratère Chicxulub, Mexique. Le cratère de Chicxulub, de 20 km de diamètre, situé sur la plate-forme du Yucatan dans le Golfe du Mexique a été formé, il y a 65 Ma et a été recouvert depuis par des carbonates post-impact tertiaires. La couverture sédimentaire et l'absence d'activité tectonique et volcanique significative dans la plate-forme carbonatée a protégé le cratère de toute érosion ou déformation, faisant du Chicxulub le seul grand cratère à plusieurs anneaux, dans lequel les projections d'impact aient été conservées. Celles-ci ont été étudiées par forage et carottage dans le secteur sud du cratère et à l'affleurement à Belize, Quintana Roo et Campeche ; peu d'informations sont disponibles pour les autres secteurs. Dans cet article sont présentés les résultats du forage/carottage d'une section de 34 m de

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brèches calcaires à 250 m de profondeur dans la région de Valladolid (à 120 km du centre du cratère) ; celles-ci sont interprétées comme les dépôts proximaux des projections d'impact. Ces brèches calcaires se corrèlent avec celles qui ont été carottées dans les puits de Peto et de Tekax vers le sud, à une distance radiale similaire. Cela constitue la première occurrence. Comme dans le secteur est proche de la bordure du cratère. L'épaisseur des brèches de Valladolid est moindre que dans les autres sites, ce qui peut indiquer l'érosion des dépôts d'impact avant le dépôt des carbonates. Le secteur est de l'anneau du cratère apparaît différent des régions sud et ouest, caractérisées par une forte densité et une distribution dispersée de dolines. ***Pour citer cet article : J. Urrutia-Fucugauchi et al., C. R. Geoscience 340 (2008).***

Keywords: Impact ejecta; Sedimentary cover; Multi-ring crater; Chicxulub crater; Yucatan peninsular; Mexico

Mots clés : Projections d'impact ; Couverture sédimentaire ; Cratère à plusieurs anneaux ; Cratère de Chicxulub ; Yucatan ; Mexique

1. Introduction

The Chicxulub structure in the northwestern Yucatan peninsula (Fig. 1) is currently interpreted in terms of a large bolide impact that occurred 65 Myr ago at the Cretaceous/Tertiary (K/T) boundary [6,7,20,21]. The impact produced a large 200 km diameter crater, as well as significant structural deformation on the target area and adjacent carbonate platform. The Chicxulub impact has been linked to the worldwide-distributed iridium-rich clay layer that has been the stratigraphic marker of the K/T boundary. The K/T layer formed as a result of ballistic-emplaced material and deposition of fine-grained particle material sent out high into the atmosphere by the impact. The reentry of ballistic material and dust that blocked incoming solar radiation caused severe global environmental and climatic effects and disruption of life support systems [1,15].

The Chicxulub crater is located half offshore and half on-land in the Yucatan platform of the southern Gulf of Mexico, and is buried by a sequence of Tertiary carbonate rocks [6,16]. The carbonate sedimentary cover has partly protected the impact ejecta from erosion and weathering. There is interest in studying the reestablishment of carbonate deposition and erosive processes after crater formation from slumping, sea water back surge and rim collapse. Impact polymictic breccias have been drilled at four localities inside the crater and at two localities outside the crater rim in the southern sector [23]. Carbonate breccias have been drilled outside the crater rim at six localities [23]. The western and eastern sectors of the crater have been less studied, as compared to the offshore northern sector and the sector to the south. Study of those sectors is important for a number of factors, including target pre-impact structures, platform evolution and karsticity and possible asymmetries in crater morphology and ejecta distribution inside and outside crater rim. Gravity and magnetic anomalies show departures from the concentric semicircular pattern, suggesting asymmetry of crater geometry and melt and breccia deposits. Outside the crater rim in the eastern sector, the cenotes show higher density and scattered distribution as compared to the south [4,12,16,17].

In this paper, we report on the initial results of the study in the eastern on-land sector of the crater, in the area between Merida and Valladolid (Fig. 1) and discuss their implications for crater morphology, ejecta deposit distribution and post-impact carbonate sequence.

2. Chicxulub crater

The Chicxulub crater has an approximate center at Chicxulub Puerto on the present coastline (Fig. 1); it has been imaged by geophysical surveys including gravity, magnetics, magnetotellurics and seismic reflection and refraction. Gravity anomalies delineate a series of nearly concentric anomaly patterns that have been related to crater morphology, which are enhanced in the horizontal gravity anomalies [4,7]. The central sector is characterized by high amplitude, high frequency magnetic anomalies, which are related to the central uplift and the magnetic breccias and melt. On the surface, the buried crater is expressed in the semi-circular array of sinkholes referred to as the cenote ring (Fig. 1). Analyses of topographic charts, digital terrain model and GPS measurements indicated the occurrence of a topographic depression related to the cenote circular ring [4,12,16,17].

It has been proposed that Chicxulub ejecta blanket may extend continuously in the peninsula region up to the Albion Island and other sites in Belize [18]. There are no surface outcrops of ejecta deposits and melt inside the crater and the adjacent area. Evidence for proximal ejecta deposits around the crater came from the Universidad Nacional Autónoma de México (UNAM) drilling program in the southern sector [25], where impact breccias were cored in three boreholes

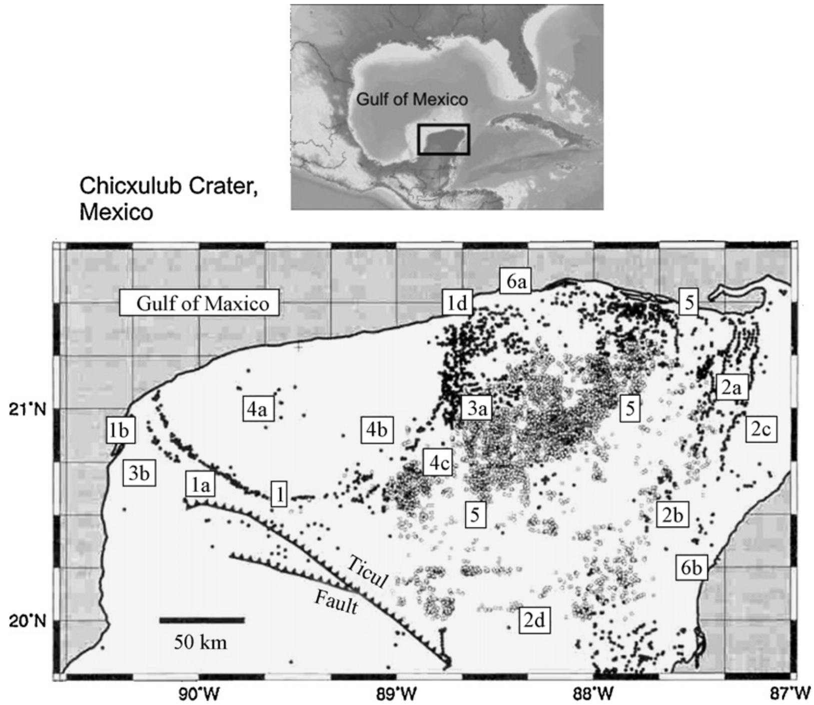

Fig. 1. Schematic map of northern Yucatan peninsula showing distribution of the cenotes (marked by the close and open circles). The numbers show distinct areas identified in Connors et al. [4] corresponding to different features related to the surface projection of Chicxulub crater (cenote rings 1, 1a and 1b) and the karstic cenote features. The study area corresponds to the eastern onshore sector between Merida area (4a) and Valladolid area (3a). Note the varying distribution and characteristics of the karstic features with the crater area and the surroundings, especially in the eastern sectors, which correlate with a peculiar anomaly pattern in the horizontal gravity in the eastern area. The zones marked as 3a and 1c show transition from water-filled cenotes (closed circles) to dry cenotes (open circles).

Fig. 1. Carte schématique du Nord du Yucatan montrant la distribution des cénotes (marquées par des cercles pleins ou vides). Les numérotations montrent les différentes zones identifiées par Connors et al. [4] comme correspondant aux différentes caractéristiques en relation avec la projection de surface du cratère Chicxulub (anneaux de cénote 1, 1a, 1b) et avec les cénotes à caractère karstique. La zone d'étude correspond au secteur oriental terrestre entre la région de Merida (4a) et de Valladolid (3a). À noter la distribution et les caractéristiques des traits karstiques variant avec la zone de cratère et ses environs, en particulier dans les secteurs orientaux, et qui se corrèlent avec un diagramme d'anomalie de la pesanteur horizontale dans le secteur oriental. Les zones marquées 3a et 1c montrent une transition entres cénotes remplies d'eau (cercles pleins) et cénotes sèches (cercles vides).

situated between 110 and 150 km from crater center, in the southern area adjacent to the crater rim. Outcrops of ejecta deposits reported in the Rio Hondo area of northern Belize and southern Quintana Roo (Chetumal area) may correspond to gravity or secondary flows [18] These outcrops are located at about 360 km radial distance from the crater center. The deposits grouped into the Albion Formation are composed of a ∼1 m thick clay and dolomite spheroid basal layer and a ∼15 m thick coarse diamictite bed. Pope et al. [18] interpret the clay and dolomite spheroids as altered impact glass and accretionary lapilli, respectively. The diamictite contains large accretionary blocks, striated polished cobbles, altered glass and occasional shocked quartz. Ejecta deposits are emplaced on top of the shallow water carbonate platform strata of the Late Cretaceous Barton Creek Formation. Samples from the impact polymictic breccias and melt were first recovered in the exploratory PEMEX drilling program at Chicxulub-1 (C1), Sacapuc-1 (S1) and Yucatan-6 (Y6) boreholes. Coring was intermittent and samples were only available in limited amounts [11,23], which have hampered detailed studies of the breccia sequence. The UNAM drilling program incorporated continuous coring and eight boreholes were drilled in the central and southern sectors of the crater (Table 1). Carbonate dissolution features including underground karst cavities restricted the depth of the drilling/coring efforts and the breccias were not reached in boreholes inside the crater. Drilling outside the crater rim in southern sector was more successful and three boreholes Santa Elena (U5), Peto (U6) and Tekax (U7) cored the breccias [19,25]. Core analyses indicate that breccias are formed by two distinct sequences: an upper breccia

Table 1
Boreholes with continuous coring programs in Chicxulub crater.
Tableau 1
Forages avec programmes de carottage en continu, dans le cratère de Chicxulub.

Borehole	Locality	Site coordinates		Coring[a] depth (m)	Ejecta+ (m)
		Longitude	Latitude		
BEM-1	Merida	89.60°W	20.91°N	350	–
BEH-1	Huhi	89.20°W	20.82°N	150	–
BEV-4	Valladolid	88.50°W	20.86°N	300	250
UNAM-5	Santa Elena	89.66°W	20.34°N	503	332
UNAM-7	Tekax	89.25°W	20.20°N	700	222
UNAM-6	Peto	89.04°W	20.07°N	702	257
UNAM-1	Timucuy	89.52°W	20.81°N	155	–
UNAM-8	Huhi	89.16°W	20.71°N	101	–
UNAM-3	Kancabdzanal	88.72°W	20.51°N	138	–
UNAM-4	Piste	88.80°W	20.56°N	63	–
UNAM-2	Tecoh	89.40°W	20.58°N	560	–
YAX-1	Yaxcopoil	89.72°W	20.74°N	1511	795

+ Depth to the top of impact ejecta layers in the borehole.
[a] Maximum coring depth in the borehole.

rich in basement and melt fragments and a lower breccia rich in carbonate clasts [25]. The upper breccia presents high magnetic susceptibility, low seismic velocities, low density and high porosity and permeability. The lower breccias are characterized by low susceptibility, variable high seismic velocities and higher porosity and permeability. The upper and lower breccias appear similar, with some differences, to the suevitic and Bunte breccias documented in the Ries crater in southern Germany [8].

3. Eastern sector

The area studied is located on the on-land portion between Merida and Valladolid, which is characterized by marked changes in distribution and density of karst features, fracture patterns and topographic landforms. These features have been found to be related to the buried crater through differential compaction of the breccia sequences, changes in crater morphology and groundwater flow patterns [4,7,12,13,16]. The higher number and density of cenotes occur east of the crater rim approximately between the (sinkhole) ‘‘cenote’’ ring and the Valladolid area; this zone extends towards the coast (Fig. 1). Karst features are largely absent in the coastal plain, suggesting a change in groundwater flow and characteristics of the aquifers. The northwestern Yucatan aquifer is largely unconfined, which accounts for the carbonate dissolution and karst features [13]. Near the coastline development of a caliche layer forms an impermeable layer, which has migrated inland as sea level rose during the Holocene, which was recognized by Perry et al. [12] (see also references [13,16]). The high density of cenotes and karst features in the area gives a distinctive surface landform (referred as the ‘‘pockmarked terrain’’ [14]), which has been related to the possibly occurrence of impact breccia deposits at depth. Gypsum and anhydrite dissolution by the deep saline intrusion in the ejecta deposits may account for the characteristic karst topography [14]. The cenotes in the southern group are generally dry, in contrast to the water-filled cenotes in the cenote ring and the groups near the coast. The change in the density distribution of karst features cuts SW–NE diagonally from about 20.5° N, 88.6° W to the coast, parallel to a gravity low and correlating with a magnetic low [4].

As part of the Comisión Federal de Electricidad (CFE) program, exploratory boreholes have been drilled in the eastern sector between Merida and Valladolid (Fig. 2). Macroscopic descriptions and petrographic studies on samples from three boreholes BEM-1, BEH-1 and BEV-4 have been undertaken. The BEM-1, BEH-1 and BEV-4 boreholes are located at increasing radial distance from crater center, along an east-west transect near Merida, Huhi and Valladolid, respectively (Table 1). Boreholes reach depths down to greater than 350 m, and cut the Tertiary carbonate sequence. The Tertiary limestone strata in the zone between Merida and Valladolid are formed by crystalline limestones, dolomitized limestones, clay-bearing limestones, and marls. Subunits can be distinguished by the intercalations of micrites, biomicrites, calcirudites, calcilutites of varying clay contents, dissolution and fracture features, fossil remains and textures. Colors and textures of the carbonate strata

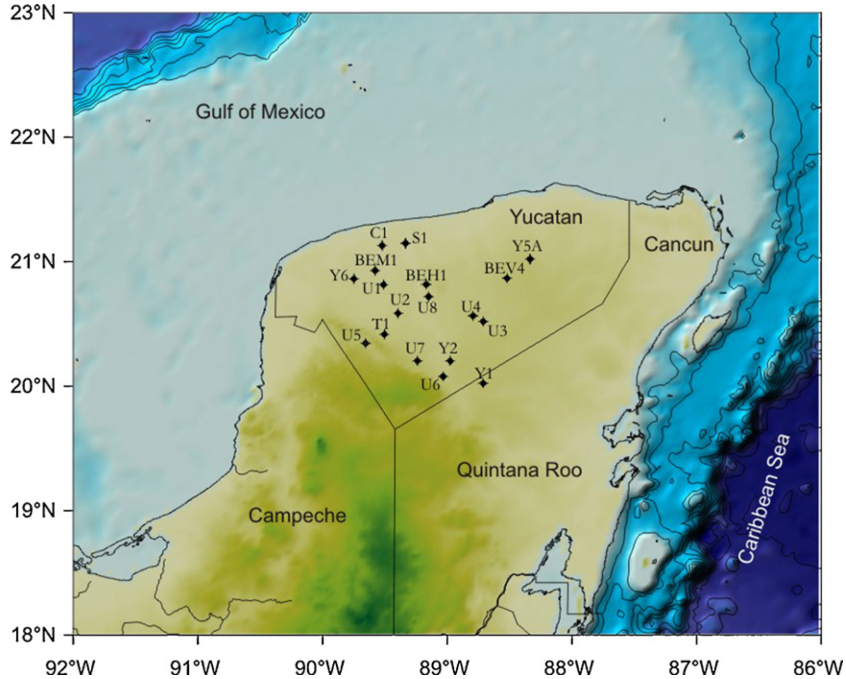

Fig. 2. Location of exploratory wells BEM-1 (Merida area; 50 km away from crater center), BEH-1 (Huhi area; 76 km away from crater center) and BEV-4 (Valladolid area; 120 km away from crater center). Other exploratory wells discussed in the text are indicated by the dots and the identification code for the wells. Drilling programs with continuous core recovery programs include the UNAM wells, CSDP Yaxcopoil well and this study. Geographic coordinates and information on the exploratory wells are included in Table 1.

Fig. 2. Localisation des puits d'exploration BEM-1 (région de Mérida, à 50 km du centre du cratère), BEH-1 (région d'Huhi, à 76 km du centre du cratère) et BEV-4 (région de Valladolid, à 120 km du centre du cratère). D'autres puits d'exploration, considérés dans le texte, sont indiqués par des points et le code d'identification de ces puits. Des programmes de forage avec programmes de carottage en continu incluent les puits UNAM, le puits CSDP Yaxcopoil et cette étude. Les coordonnées géographiques et les renseignements relatifs aux puits d'exploration sont fournis dans le Tableau 1.

vary from white, cream, reddish gray to gray (in BEV-4 borehole, some dolomite horizons are bluish and lutites beneath the breccia sequence show light green colors). The carbonate strata are part of the Icaiché, Chichen Itza and Carrillo Puerto Formations [11]. Beneath 200–250 m depths, the carbonate rocks show effects of deformation and fracturing. In Merida, the carbonate sequence in BEM-1 (Fig. 3) is formed by intercalations of micritic limestones, calcirudists, calcirudites, clay-rich gray limestones between 200 and 300 m. In the area between Merida and Huhi, the sequence is more abundant in white to cream coquina deposits, with fragments of bivalves, gastropods and corals. In parts, it is poorly consolidated with horizons of cream calcarenites towards the bottom. In Huhi area, BEH-1 borehole sequence (Fig. 3) is formed by micritic cream and white limestones and dolomitized gray to reddish gray limestones, which show fragments of macrofossils and in some parts dissolution features. In the area between Huhi and the crater rim, the sequence shows greater relative proportion of calcarenites, with limestones, dolomitized limestones, coquina and some recrystallized coralline structures. In the Valladolid area, the BEV-4 borehole sequence (Fig. 3) is formed down to 250 m by miciritc limestones with some clay-bearing horizons, partly altered and dissolution features and calcirudites, fossiliferous and clay-rich horizons. Carbonate breccias are present between 250 m and 284 m (see below). Beneath 284 m and down to 300 m, the sequence is composed by limestones, dolomitized light reddish limestones with light green lutite horizons.

An interval of about 34 m of carbonate breccias is present in the BEV-4 borehole at the Valladolid area (Fig. 3). The carbonate breccia interval occurs between about 250 and 284 m. Breccias are characterized by abundant clasts of limestone, dolomite, gypsum and anhydrite; the breccia section correlates with the carbonate breccias observed to the south in the Peto and Tekax boreholes [19,25]. Based on results from chemical analyses of deep-water samples in the Ucil cenote (located at about 20.99° N, 88.6°W), Perry and co-workers [14] proposed occurrence of an impact breccia layer at ∼200 m depth below the cenote area to account for the strontium contents of the cenote saline

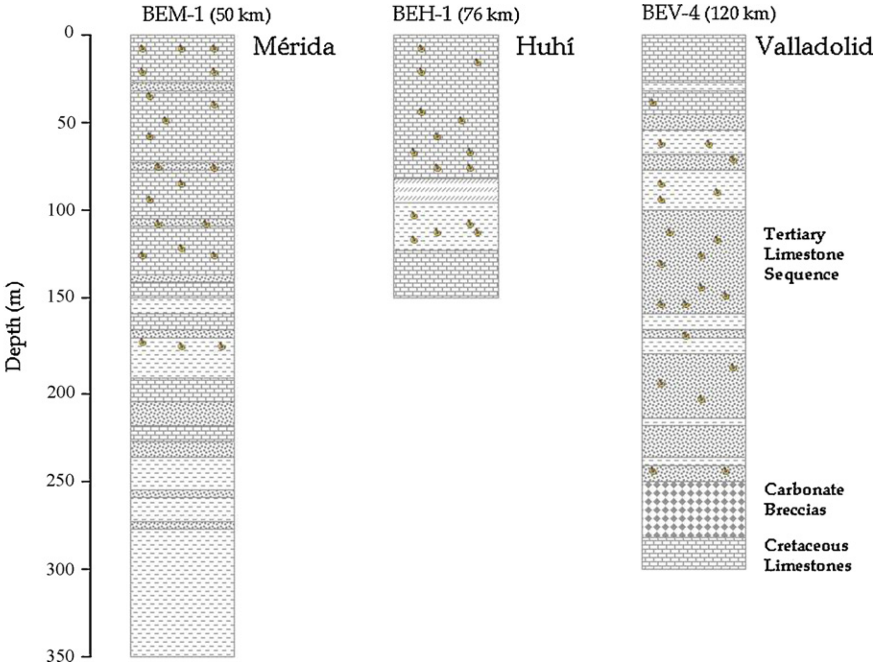

Fig. 3. Simplified lithological columns for exploratory wells BEM-1 (Merida area), BEH-1 (Huhi area) and BEV-4 (Valladolid area). The Tertiary limestone sequence in the eastern zone between Merida and Valladolid is formed by crystalline limestones, dolomitized limestones, clay-bearing limestones, and marls. Sequence shows intercalations of micrites, biomicrites, calcirudites, calcilutites of varying clay contents, dissolution and fracture features, fossil remains and textures. Colors and textures of carbonate strata vary from white, cream, reddish gray to gray. In BEV-4 borehole, some dolomite horizons are bluish and lutites beneath the breccia sequence show light green colors. In BEV-4 borehole, the carbonate breccia section was cored beneath 250 m depth and is 34 m thick. See text for description of lithological columns.

Fig. 3. Colonnes lithologiques relatives aux puits d'exploration (a) BEM-1 (région de Merida), (b) BEH-1 (région d'Huhi) et (c) BEV-4 (région de Valladolid). La séquence calcaire tertiaire dans le secteur oriental entre Merida et Valladolid est constituée de calcaires cristallins, de calcaires dolomitisés, de calcaires argileux et de marnes. La séquence montre des intercalations de micrites, biomicrites, calcirudites, calcilutites à teneurs en argile variées, des traits de dissolution et de cassure, des restes et des textures de fossiles. Les couleurs et les textures des strates carbonatées varient entre le blanc crème, gris rouge, gris. Dans le forage BEV-4, certains horizons dolomitiques sont bleuâtres et les lutites situées sous la séquence bréchique, montrent des couleurs vert clair. Dans le forage BEV-4, la section des brèches carbonatées a été forée au-dessous de 250 m de profondeur et sur une épaisseur de 34 m. Voir le texte pour la description des colonnes lithologiques.

waters. The coring in BEV-4 confirms the presence of the impact breccia layer, which is present beneath the Valladolid area and in the Ucil cenote. The BEV-4 borehole is located at approximately similar radial distances than the Tekax borehole in the southern sector. Impact breccias in the Tekax borehole are formed by two distinct units: an upper unit rich in basement and melt clasts located between 222.2 and about 384 m, and a lower unit rich in carbonate and evaporate clasts beneath 384 m and which grades downward into a sequence of marls and evaporites. In Peto borehole, the upper breccias are between 257 and 283 m, and the carbonate breccias are located approximately between 283 and 540 m. These boreholes lie outside the crater rim, and outside the external gravity anomaly ring [20]. The carbonate breccias rest on carbonate strata (Fig. 3), which may correspond to large displaced Cretaceous blocks (mega-breccia unit) or to the pre-impact Cretaceous target sequence. A similar carbonate sequence is also observed in the Peto borehole, which shows higher abundance of anhydrites and gypsum.

The seismic reflection data along the east-west profiles offshore parallel to the coastline show that Tertiary carbonates are characterized by high frequency reflections that can be followed across the basin [2,3,7]. The eastern sector displays different characteristics as compared with the western sector, with a distinct infill history characterized by more complex geometries and clinoform packages [2]. The deep one shows relatively steep westward dipping sigmoid-oblique clinoforms, which, together with the offlap relationships, are characteristic of regression on a prograding slope. The shallow clinoform package shows shallower dips, and its lower part contains discontinuous low-amplitude reflectors with complex geometries. Bell et al. [2] indicate that its lower part is a mass flow deposit and that the dip decrease between the clinoform packages resulted from clinoform/slope system reorientation or development of a gentle slope after the mass wasting. The reflectors above the clinoform packages show clinoform surfaces draping and onlap, indicating a passive sedimentation stage [2].

4. Discussion

Results from macroscopic descriptions and petrographic studies on the boreholes located between Merida and Valladolid provide a preliminary stratigraphy for the carbonate sequence and carbonate breccias in the eastern crater sector. Boreholes reach depths to greater than 350 m, and cut the Tertiary carbonate sequence (Fig. 3). Tertiary limestone strata can be correlated in the zone between Merida and Valladolid and are formed by crystalline limestones, dolomites, clay-bearing dolomitized limestones, and marls. Beneath about 200–250 m, carbonates show effects of tectonic deformation and fragmentation. In the Valladolid BEV-4 borehole at 250 m depth an interval of about 34 m of carbonate breccias (Fig. 3), characterized by angular fragments of crystalline limestones, gypsum, anhydrites and dolomites in a carbonate matrix with marked color changes, has been cored. This is the first time, breccias have been documented in the eastern crater rim sector, and they correlate with the carbonate breccias in the Peto and Tekax boreholes in the southern sector.

The Peto and Tekax carbonate breccias are similarly formed by limestone, gypsum, anhydrite and dolomite fragments of the surface target lithologies and they lie beneath the basement and melt rich breccias in the Tekax borehole, showing an inversion of target rock stratigraphy. The carbonate breccias are not observed in the lithological columns of boreholes near the crater center C1, S1 and Y6 boreholes and farther away at the terrace zone in the Yaxcopoil-1 borehole. The Yaxcopoil-1 breccias [26] occur at about 800 m and are formed by a 100 m thick sequence of basement and melt rich breccias lying on top of Cretaceous limestone blocks of the terrace, tilted blocks forming the crater rim (or mega-block breccias). The Yaxcopoil-1 breccias are formed by several subunits with distinct characteristics reflecting their emplacement from hot flow-like bottom units to rework upper deposits. From the analyses of borehole information [10,22,26], it then appears that carbonate breccias are absent inside the crater basin. The basement and melt rich breccias are not present in the BEV-4 borehole, and they have been eroded away in the area.

The carbonate breccias may be compared with the Bunte breccias of the Ries crater. The Bunte breccias have been interpreted in terms of ballistic deposition and a surface flow with large blocks scouring and transporting material, resulting in ejecta and target rock fragments [16]. Altered glass and accretionary clasts have not been reported for the Bunte breccias. Microscopic examination of the BEV-4 breccias does not show occurrence of melt fragments, altered glass or accretionary clasts. Magnetic susceptibility logging of the Peto and Tekax boreholes showed dominantly low values corresponding to mainly diamagnetic minerals (paramagnetic values are also present) [25]. Rare millimeter sized altered melt fragments are however present in the Peto carbonate breccias, indicating the need for further detailed examination of the carbonate breccia sequences in the UNAM and the BEV-4 boreholes.

The satellite radar image of the northern Yucatan peninsula (Fig. 4) shows the surface expression of the buried crater structure. The surface projection of the crater rim is marked by a semi-circular topographic depression that forms above the terrace zone near the rim, which coincides on the surface with the cenote ring and stands out of the flat carbonate terrain in the peninsula. The depression zone is associated with the differential compaction of the impact breccias inside the crater basin as compared with the Mesozoic carbonate sequence outside the crater. The satellite radar image shows the presence of ancient coastlines that reflect past sea level changes. Offshore, the marine seismic reflection profiles show differences in the Tertiary infill sediments between the western and eastern sectors of the crater, with sediments in the eastern sector displaying clinoform features related to regression during relative falling sea level [2]. The sediments were likely deposited from the east. The location and orientation of the ancient coastlines that roughly follow the present coastline (Fig. 4) suggest relatively recent sea level changes that affected carbonate deposition across the carbonate platform, in which particular conditions related to the basin depression of the crater may have been superimposed. Regional surface fracture patterns documented in the peninsula relate to the NW-SE Ticul and NE-SW Holbox fault zones, and may correlate to extensive karstification in the zone, which contrasts with the absence of karst features west and south of the crater rim.

The Chicxulub ejecta blanket may extend continuously in the Yucatan peninsula up to the ejecta outcrops of Albion Island and other sites in Belize [18]. There are no surface outcrops of ejecta deposits and melt

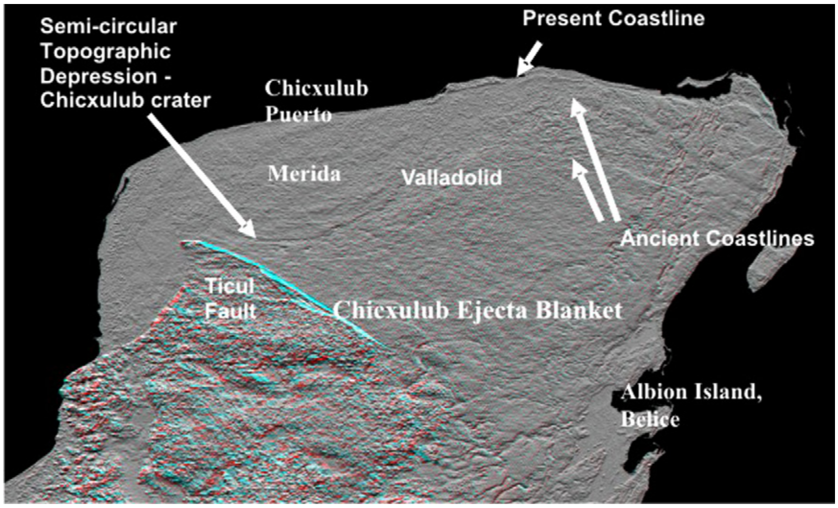

Fig. 4. High resolution satellite interferometric radar image of the northern Yucatan peninsula (see also reference [9]). The surface projection of the crater rim is marked by a semi-circular topographic depression, which coincides with the cenote ring and stands out of the flat carbonate terrain in the peninsula. The depression is associated with the differential compaction of the impact breccias inside the crater basin as compared with the carbonate sequence outside the crater. Note the presence of ancient coastlines that reflect Quaternary sea level changes. Base map from C-band interferometric radar image, Earth Shuttle Radar Topography Mission (SRTM) (Courtesy NASA/JPL-Caltech).

Fig. 4. Image haute résolution satellitaire par radar interférométrique du Nord de la Péninsule du Yucatan (voir aussi, la référence [9]). La projection de surface de la ride du cratère est marquée par une dépression topographique semi-circulaire, qui coïncide avec l'anneau de cénote et qui se dessine sur le terrain carbonaté plat de la péninsule. La dépression est associée à une compaction différentielle des brèches d'impact dans le bassin du cratère, comparée à la séquence carbonatée hors du cratère. À noter la présence d'anciennes lignes de rivage qui reflètent des changements de niveau marin au cours du Quaternaire. Carte de référence obtenue par image radar interférométrique à bande-C, SRTM (Courtesy NASA/JPL-Caltech).

inside the crater and the adjacent area. Carbonate breccias reported [11,23] in oil exploration boreholes Y1 (135 km), Y5A (138 km), Y2 (160 km) and Y4 (205 km) further support a continuous ejecta blanket. Deposits of proximal ejecta or continuous ejecta blanket from large impact craters are relatively rare. Besides the Ries crater ejecta, other possible example is the Onaping Formation of the Sudbury crater in eastern Canada. The diamictite unit from the Albion Formation in Belize has been compared to the Sudbury Onaping Formation, where the Onaping represents a crater fill deposit and the Albion diamictite represents the distal portion of the continuous ejecta blanket [18], at considerable distance from the crater rim. Apparent similarities may derive from their formation related to the turbulent collapse of the ejecta curtain [18]. The ejecta blanket was deposited after deposition of the ballistic deposits represented by the basal spheroid bed. The Ries Bunte breccias and the Chicxulub carbonate breccias drilled close to the crater rim immediately outside the basin structure may represent proximal ejecta deposits emplaced in the first instants of crater formation from surface lateral ejecta curtains and (perhaps?) collapse of the ejecta cloud prior to emplacement of the (suevite-like) basement and melt rich breccias.

Thickness of the carbonate breccia unit in the Valladolid area is small compared to those documented in UNAM boreholes in the southern sector (around 200–400 m) and in the Y5A borehole (breccia interval between 400 and 900 m). The reduced thickness in the Valladolid BEV-4 breccia section may relate to significant erosion that removed the basement and melt rich breccias and a significant portion of the lower carbonate breccias. Studies suggest that back surge of the sea into the crater resulted in reworking and erosion of the breccia deposits, possibly also affecting the crater rim morphology [5]. If the rim remained above sea level [22], it may have been exposed to erosion and slope collapses. Conditions after the crater formation and ejecta deposition and reestablishment of marine carbonate deposition are yet poorly constrained [5,10,13,22,24]. The thin unit of reworked basement and melt-rich breccias in the Peto borehole, the short interval of carbonate breccias in Valladolid BEV-4 borehole and the reworked breccias in the upper subunit of Yaxcopoil-1 borehole support significant erosive processes at the crater rim area.

Studies of topography, karst landforms and subsurface stratigraphy have been used to locate and investigate major crater features including the topographic rim [4,9,12,16]. In the eastern area, where borehole information has been lacking, the topographic rim has been inferred at distances of about 120–130 km [16,17] and 180 km [7]. The apparent extreme erosion of the ejecta deposits at BEV-4 borehole could be related to a relative slightly higher elevation of the Cretaceous basement associated as suggested to the topographic rim in the eastern crater sector [4,16]. Further drilling in the area is needed to investigate the subsurface stratigraphy, lateral extension of the ejecta deposits and relation to the Cretaceous sequence.

5. Conclusions

This is the first report on the occurrence of carbonate breccias close to the rim in the eastern sector of the crater (120 km away from crater center), which are interpreted as part of the Chicxulub proximal ejecta deposits. The Valladolid breccias correlate with the carbonate Bunte-type breccias cored in Peto and Tekax boreholes south of the crater rim and at similar crater radii distance. Contact between the breccias and the Tertiary carbonates lies at about 250 m. Thickness of the Valladolid breccias is ∼34 m and thinner than that observed at other sites, which may indicate significant erosion of the ejecta deposits around the crater rim before reestablishment of carbonate deposition. Active dissolution processes of evaporite minerals by deep saline intrusion in the area have been documented from chemical analyses of water samples in cenotes and related to presence of breccia deposits [9]. The region east of the crater rim appears different from regions to the south and west, which is reflected in the karstic features with high density and scattered distribution of cenotes. The buried crater, through differential compaction of the impact breccias and radial faulting/fracturing, controls the topography, groundwater flow and development of karstic features (cenote ring and circular topographic depression). Further study of the post-impact sequence inside and outside the crater rim will permit to better understand the crater morphology, stratigraphy and Tertiary development of the Yucatan carbonate platform.

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References

[1] L.W. Alvarez, W. Alvarez, F. Asaro, H. Michel, Extraterrestrial cause for the Cretaceous-Tertiary extinction, Science 208 (1980) 1095–1108.

[2] C. Bell, J.V. Morgan, G.J. Hampson, B. Trudhill, Stratigraphic and sedimentological observations from seismic data across the Chicxulub impact basin, Meteor. Planet. Sci. 39 (2004) 1089–1098.

[3] J. Brittan, J.V. Morgan, M. Warner, L. Marin, Near-surface seismic expression of the Chicxulub impact crater, Geol. Soc. Am. Sp. Pap. 339 (1999) 269–279.

[4] M. Connors, A. Hildebrand, M. Pilkington, C. Ortiz, R. Chavez, J. Urrutia-Fucugauchi, E. Graniel, A. Camara-Zi, J. Vasquez, J. Halpenny, Yucatan karst features and the size of Chicxulub crater, Geophys. J. Int. 127 (1996) F11–F14.

[5] K. Goto, R. Tada, E. Tajika, T.J. Bralower, T. Hasegawa, T. Matsui, Evidence for ocean water invasion into the Chicxulub crater at the Cretaceous/Tertiary boundary, Meteor. Planet. Sci. 39 (2004) 1233–1247.

[6] A. Hildebrand, M. Penfield, D. Kring, M. Pilkington, A. Camargo, S.B. Jacobsen, W. Boynton, Chicxulub crater: a possible Cretaceous/Tertiary boundary impact crater on the Yucatan peninsula, Mexico, Geology 19 (1991) 867–871.

[7] A. Hildebrand, M. Pilkington, C. Ortiz, R. Chavez, J. Urrutia-Fucugauchi, M. Connors, E. Graniel, A. Camara-Zi, J. F. Halpenny, D. Niehaus, Mapping Chicxulub crater structure with gravity and seismic reflection data, in: M.M Grady, R.G. Hutchinson, G. MacCall (Eds) Meteorites: flux with time and impact effects, Geol. Soc. London Sp. Publ. 140, 1998, pp. 155–176.

[8] F. Hoerz, R. Ostertag, D.A. Rainey, Bunte breccia of the Ries: continuous deposits of large impact craters, Rev. Geophys. Space Phys. 21 (1983) 1667–1725.

[9] G. L. Kinsland, K. O. Pope, M. Hurtado, G.R.J. Cooper, D. R. Cowan, M. Kobrick, G. Sanchez, Topography over the Chicxulub impact crater from Shuttle Radar Topography Mission (SRTM) data, in: T. Kenkemann (Ed), Large Meteorite Impacts III, Special Paper Geological Society of America, 384,2005, pp. 141–146.

[10] D.A. Kring, F. Hoerz, L. Zurcher, J. Urrutia-Fucugauchi, Impact lithologies and their emplacement in the Chicxulub impact crater: initial results from the Chicxulub Scientific Drilling Project, Yaxcopoil, Mexico, Meteor. Planet. Sci. 39 (2004) 879–897.

[11] E. Lopez Ramos, Geologia de Mexico, 3 Edn., Edicion Privada, Mexico City, Mexico, 1983, 450 pp.

[12] E.C. Perry, J. Swift, J. Gamboa, A. Reeve, R. Sanborn, L. Marin, M. Villasuso, Geologic and environmental aspects of surface cementation, North coast, Yucatan, Mexico, Geology 17 (1989) 818–821.

[13] E.C. Perry, L. Marin, J. McClain, G. Velazquez, The ring of cenotes (sinkholes), Northwest Yucatan, Mexico: Its hydrogeologic characteristics and possible association with the Chicxulub impact crater, Geology 23 (1995) 17–20.

[14] E.C. Perry, G. Velazquez-Oliman, L. Marin, The hydrogeochemistry of the karst aquifer system of the northern Yucatan Peninsula, Mexico, Intern. Geol. Rev. 44 (2002) 191–221.

[15] K.O. Pope, Impact dust not the cause of the Cretaceous-Tertiary mass extinction, Geology 30 (2002) 99–102.

[16] K.O. Pope, A.C. Ocampo, C.E. Duller, Surficial geology of the Chicxulub impact crater, Yucatan, Mexico, Earth Moon Planets 63 (1993) 93–104.

[17] K.O. Pope, A.C. Ocampo, G.L. Kinsland, R. Smith, Surface expression of the Chicxulub crater, Geology 24 (1996) 527–530.

[18] K.O. Pope, A.C. Ocampo, A.G. Fisher, F. Vega, D.E. Ames, D.T. King, B. Fouke, R.J. Wachtman, G. Kleteschka, Chicxulub impact ejecta deposits in southern Quintana Roo, Mexico, and central Belize, Geol. Soc. Am. Sp. Pap. 384 (2005) 171–190.

[19] M. Rebolledo-Vieyra, J. Urrutia-Fucugauchi, L. Marin, A. Trejo-Garcia, V. Sharpton, A. Soler, UNAM scientific shallow-drilling program of the Chicxulub impact crater, Inter. Geol. Rev. 42 (2000) 928–940.

[20] V. Sharpton, G. Dalrymple, L. Marin, G. Ryder, B. Shuraytz, J. Urrutia-Fucugauchi, New links between the Chicxulub impact structure and the Cretaceous/Tertiary boundary, Nature 359 (1992) 819–821.

[21] V. Sharpton, K. Burke, A. Camargo, S. Hall, L. Marin, G. Suarez, J. Quezada, P.D. Spudis, J. Urrutia-Fucugauchi, Chicxulub multiring impact basin: size and other characteristics derived from gravity analysis, Science 261 (1993) 1564–1567.

[22] D. Stoeffler, N. Artemieva, B. Ivanov, L. Hecht, T. Kenkemann, R.T. Schmidtt, R. Tagle, A. Wittman, Origin and emplacement of the impact formations at Chicxulub, Mexico, as revealed by the ICDP deep drilling Yaxcopoil-1 and by numerical modeling, Meteor, Planet. Sci. 39 (2004) 1035–1068.

[23] J. Urrutia-Fucugauchi, L. Perez-Cruz, Deep drilling into the Chicxulub impact crater: Pemex oil exploration boreholes revisited. Am. Geophys. Union Joint Assembly, CD Program & Abstracts) U33A-07, 2007.

[24] J. Urrutia-Fucugauchi, L. Perez-Cruz, Post-impact carbonate deposition in the Chicxulub impact crater region, Yucatan platform, Mexico, Curr. Science 95 (2008) 248–252.

[25] J. Urrutia-Fucugauchi, L. Marin, A. Trejo-Garcia, UNAM scientific drilling program of Chicxulub impact structure: Evidence for a 300 kilometer crater diameter, Geophys. Res. Lett. 23 (1996) 1565–1568.

[26] J. Urrutia-Fucugauchi, J. Morgan, D. Stoeffler, P. Claeys, The Chicxulub Scientific Drilling Project, Meteor. Planet. Sci. 39 (2004) 787–790.