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Magnetostratigraphy of the Cretaceous/Tertiary boundary and early Paleocene sedimentary sequence from the Chicxulub Impact Crater

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We report on the magnetostratigraphy of the Chicxulub crater impact breccias and first 15 meters of the Paleocene sedimentary sequence recovered in three boreholes of the UNAM Scientific Drilling Program. Three geomagnetic polarity zones are documented in the impact breccias and sedimentary sequence, which span from chron 29R to 28N. For the 15 m interval they represent ∼2.5 Ma, which yields low apparent sedimentary rates for boreholes UNAM-5 (110 km from the center of the crater) and UNAM-7 (127 km from the center of the crater). The carbonate sedimentary sequence can be associated to a shallow basin depositional environment. In these boreholes the thickness between the 29R and the 29N chrons is just 0.5 m, suggesting that during the 100 ka from the K/T boundary to the polarity transition sediments were not deposited or eroded. Within borehole UNAM-6 (152 km from the center of the crater) it appears that sediments containing chron 29N are missing, the lack of the upper breccias, the long duration of a reversal event within the base of the sequence and low apparent sedimentary rate of 3.3 m/Ma, suggests a hiatus within the impact breccias and the basal Paleocene sedimentary sequence. Magnetic susceptibility logs confirm absence of the upper breccias at UNAM-6 borehole. Magnetic susceptibility values increase towards the base of the sequence, suggesting that basement and melt clasts were subjected to a low temperature hydrothermal alteration.

Key words: Chicxulub Crater, Cretaceous/Tertiary boundary, magnetostratigraphy, paleomagnetism, Gulf of Mexico.

1. Introduction

Several studies have been conducted in the last fifteen years on the Chicxulub impact crater, which have greatly contributed to our understanding of the crater structure, characteristics and its formation, and on the effects of the impact event. The Chicxulub impact has been related to the events marking the Cretaceous/Tertiary (K/T) boundary and to the extinction of organisms. However several questions remain unanswered, particularly those related to the post-impact processes. One of the questions is the reestablishment of sedimentary deposition within the crater and the nature of the contact between the impact breccias and the Tertiary carbonates. Controversies exist regarding many aspects of the K/T boundary stratigraphy and the impact ejecta layer, its age and its relationship to the K/T extinction are also controversial in several aspects (e.g., Ward *et al.*, 1995; Smit, 1999; Keller *et al.*, 2004; Urrutia-Fucugauchi *et al.*, 2004a). Therefore it is important to study the sedimentary record and reconstruct the paleoenvironment of the impact basin. In this paper, we report results of the magnetostratigraphy obtained from three boreholes of the UNAM Scientific Drilling Program, UNAM-5, UNAM-6 and UNAM-7 (Fig. 1), corresponding to the upper (melt and basement-rich clasts) breccias, the breccias-carbonates contact and the first 15 m of the Tertiary carbonate sequence.

2. Stratigraphy

As part of the UNAM scientific drilling program 8 boreholes have been drilled in the southern sector of the crater (Fig. 1), with high core recovery rates (up to 99% in UNAM-5, with overall average recovery rates of ∼87%) that permit detailed stratigraphic investigation. Three boreholes sampled the impact lithologies (UNAM-5, UNAM-6 and UNAM-7), which are here used for the paleomagnetic and rock magnetic investigations. Two units are documented as impact lithologies, an upper breccia sequence (comparable to the suevitic and bunte breccias documented in the Ries crater, Von Engelhardt, 1990; Newsom *et al.*, 1990). In UNAM-5 (Fig. 2(a)), the contact with the Tertiary carbonates is at 332.0 m deep and the upper breccias have a thickness of 146 m (the borehole did not reach the bottom of the unit). In UNAM-7, it is 126.1 m thick (Fig. 2(b)) and the contact with the Tertiary carbonates is at 222.2 m deep. The lower breccias (carbonate-rich or bunte type, also described in the Ries crater, Stöffler, 1977; Hörz *et al.*, 1983; Von Engelhardt, 1990; Newsom *et al.*, 1990) in UNAM-7 lies at 348.4 m deep, with a thickness of 180 m (Fig. 2(b)). In UNAM-6, the upper breccias are not present;

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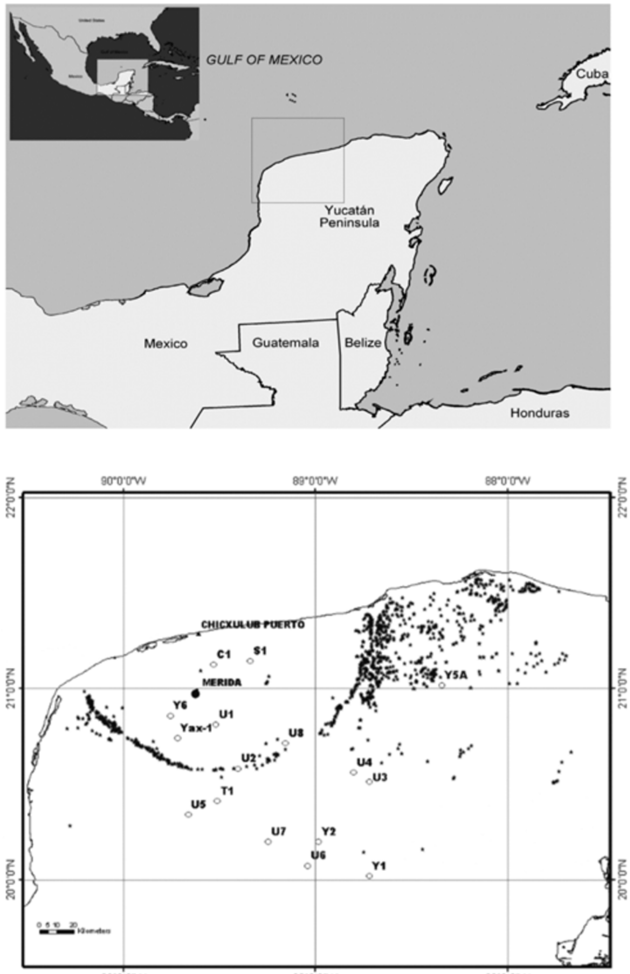

Fig. 1. Upper box Map of Mexico showing the Yucatan Peninsula. Lower box map showing location of the boreholes: PEMEX: Chicxulub-1, C1; Sacapuc-1, S1; Ticul-1, T1; Yucatan-1, Y1; Yucatan-2, Y2; Yucatan-5a, Y5a; Yucatan-6, Y6; UNAM boreholes: UNAM-1, U1; UNAM-3, U3; UNAM-4, U4; UNAM-5, U5; UNAM-6, U6; UNAM-7, U7; UNAM-8, U8 and Yaxcopoil-1, Yax-1. Stars indicate sinkholes, locally called “cenotes”. (Modified from Urrutia-Fucugauchi *et al.*, 2004a).

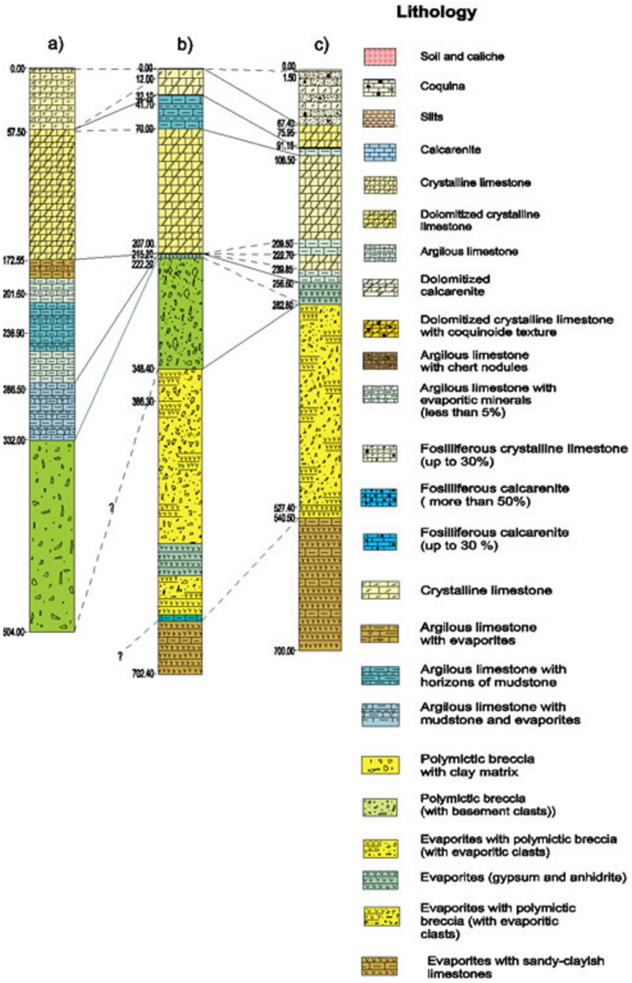

Fig. 2. Lithologic correlation of the three boreholes. A) UNAM-5, Santa Elena, b) UNAM-7, Tekax; b) UNAM-6, Peto; (Modified from Rebolledo-Vieyra *et al.*, 2000).

the contact of the lower breccias and Tertiary carbonates is at 282.8 m deep; the thickness is 153.7 m (Fig. 2(c)). The presence of angular to sub-rounded clasts from the crystalline basement (gneiss, diorite), fragments of melt and impact glass (black and dark green) and shocked quartz grains permits correlation with the upper breccias in UNAM-5 (Fig. 2(a)) and UNAM-7 (Fig. 2(b)). The distribution of the clasts within the breccias is highly heterogeneous; this is a matrix-supported unit with the same bulk composition as the clasts (crystalline basement, melt, impact glass and occasionally carbonate clasts). Size of clasts ranges from gravel to blocks (up to 5 cm in diameter). It is important to point that the unit below the Tertiary carbonates of UNAM-5 corresponds to re-deposited sandstone. This sandstone is gray colored, fine grained and well sorted; it shows planar and cross-bedded stratification. The magnetic susceptibility log (Rebolledo-Vieyra and Urrutia-Fucugauchi, 1999) indicates that the magnetic mineralogy is similar to that of the upper breccias. The cross-bedding and sorting suggest that this unit is re-deposited. The lower unit of UNAM-5 is a matrix-supported breccia. The distribution of clasts is also highly heterogeneous, and the size of the clasts ranges from gravel to block size (up to 25 cm), the composition is mainly carbonate, crystalline limestones and anhydrite. The color is light brown to gray. Some clasts are strongly altered and the original lithology is difficult to identify. The next unit that can be correlated is a unit of dolomitized crystalline limestones, which forms the bulk of the carbonate sequence and is characterized by light cream to dark brown colors, compact appearance and a high degree of fracturing and fragmentation. Dolomitization appears in bands, replacing bivalves and corals by magnesium carbonate.

3. Time Constrains

Determining the age of the Chicxulub impact with adequate resolution to establish correlation with e.g., the K/T ejecta clay layer, marine and continental paleontological records and other volcanic and tectonic events has remained a difficult problem. Hildebrand *et al.* (1991) proposed after reviewing available geophysical, stratigraphic and borehole information for the Chicxulub impact structure (e.g., Lopez Ramos, 1973; Penfield and Camargo, 1981) that the impact had a K/T age. However, the stratigraphy for the Cretaceous

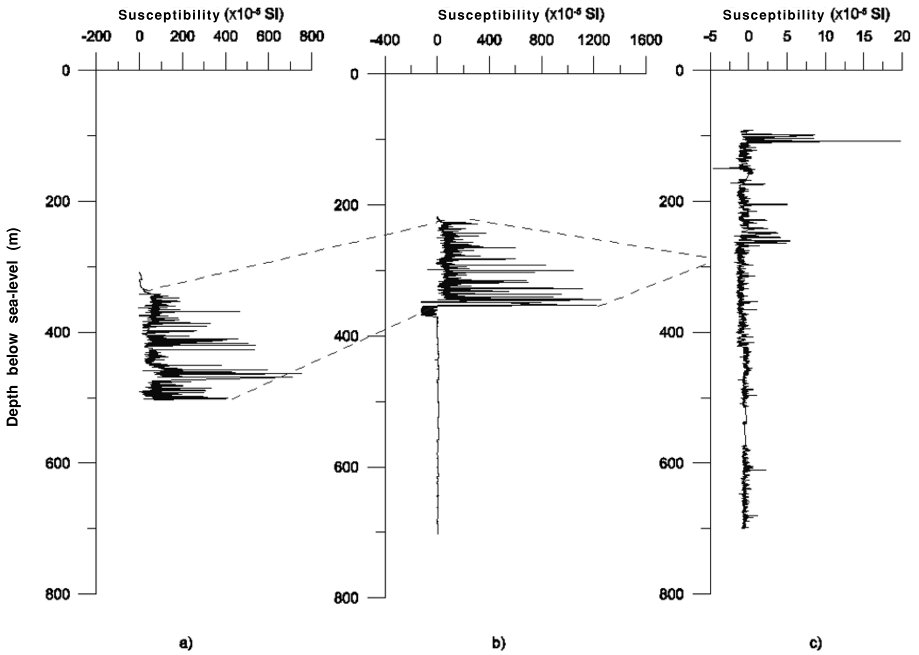

Fig. 3. Susceptibility behavior in a) UNAM-5 borehole, b) UNAM-7 borehole and c) UNAM-6 borehole. Boreholes are in radial order from the center of the crater. Units are in SI$\times 10^{-5}$. Dashed lines indicate the section corresponding to the melt-rich upper breccias.

and Tertiary carbonate sediments and the impact lithologies has been a matter of some debate (e.g., Ward *et al.*, 1995); recently, also in regarding the correlation of the impact with K/T extinction event (e.g., Keller *et al.*, 2004).

Constraints on the impact age derived directly from impact melt rocks and breccias from inside the Chicxulub crater have been reported from geochronological and magnetic polarity stratigraphy. Sharpton *et al.* (1992) and Swisher *et al.* (1996) reported ^{40}Ar/^{39}Ar ages for samples of melt rock from the Chicxulub-1 borehole of approximately 65 Ma. Urrutia-Fucugauchi *et al.* (1994) reported the reverse polarity magnetization for a sample of melt from borehole Yucatan-6, which is correlated to the 29R chron which spans the K/T boundary according to the reference geomagnetic polarity time scale (Cande and Kent, 1995).

More recently, Marin *et al.* (2001) based on analyses of carbonate sediment samples from PEMEX's borehole Y-6 concluded that the marine sediments underlying the impact rocks are Upper Cretaceous and that the K/T boundary is located in this borehole between 1000 and 1103 m (depth from ground level). This is in agreement with a K/T boundary age for the Chicxulub impact.

However, stringent constraints on impact age are required for correlation of the impact event with global ejecta layer and paleontological data in marine and continental records. Temporal resolution allowed in most studies do not permit accurate constraints within a couple of thousands years, which is the age difference proposed in Keller *et al.* (2004) for the K/T extinction and Chicxulub impact.

4. Methods

We sampled the cores from the three boreholes that recovered the impact breccia sequences (UNAM-5, UNAM-6 and UNAM-7) (Figs. 1 and 2). Details of the drilling and coring methods employed in the drilling program, including core diameters and lithological description, are given in Rebolledo-Vieyra *et al.* (2000). Cubic samples were cut from the cores every 50 cm, depending on the preservation conditions of the cores, starting at the last meter of the upper (melt and basement-rich) breccias and ending approximately 15 m above the contact between the upper breccias and the carbonate sequence, averaging 30 samples for each borehole.

Samples were analyzed in a Super Quantum Interference Device (SQUID) cryogenic magnetometer with background noise of 10^{-9} A/m, at the Paleomagnetic Laboratory of the California Institute of Technology, in Pasadena, CA. The samples were subjected to AF demagnetization from 0–100 mT in 10 mT steps, afterwards were thermally demagnetized from 0–400°C in 100°C steps, then 450°C, 500°C, 525°C and 550°C. Samples from the upper breccias had a magnetic intensity within the range of 10^{-4} A/m and about 10^{-7} A/m for carbonates and evaporites. Most of the samples were demagnetized between 300°C and 400°C (Fig. 3); these intermediate unblocking temperature spectra characteristics forced us to use the AF and the 100°C and 200°C steps to calculate the mean characteristic direction of the samples. Since our samples came from borehole cores, without azimuthal orientation, declination was not considered and we use for the final analysis to determine the magnetic polarity only the characteristic inclination. For the calculations we assumed a relative declination and used standard least-squares fit (Kirschvink, 1980) and statistics (Fisher, 1953) to determine the mean characteristic inclination and polarity (Fig. 4).

5. Magnetic Susceptibility Core Logging

Urrutia-Fucugauchi *et al.* (1996, 2004b) reported results on the behavior of the magnetic susceptibility in boreholes UNAM-6 and UNAM-7 and Yaxcopoil-1; we extended the

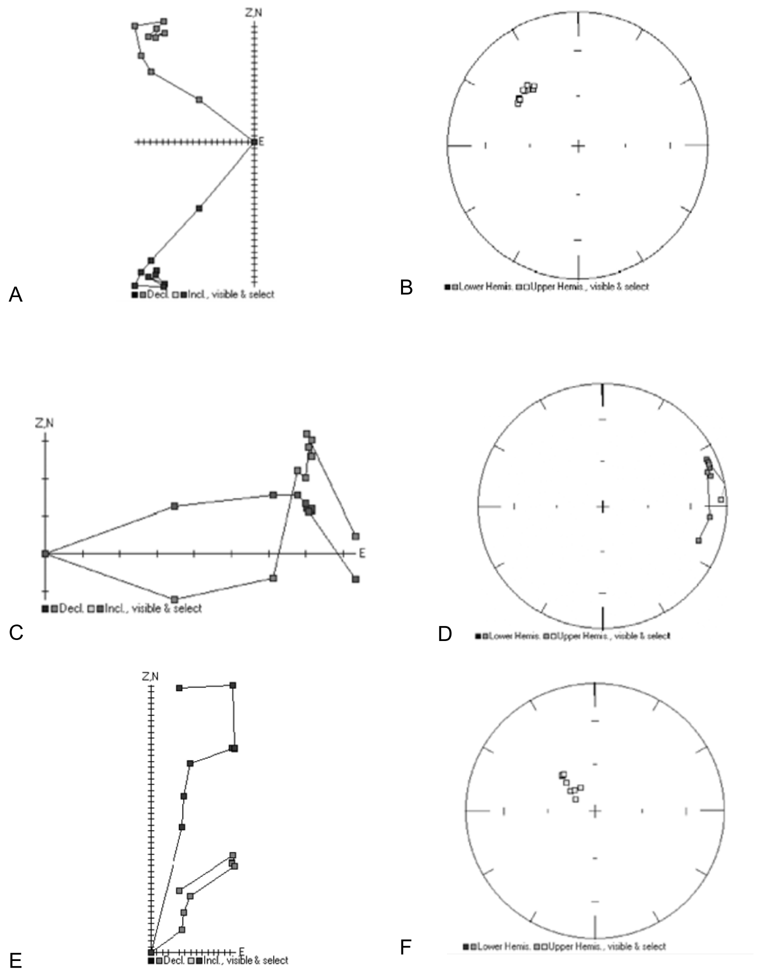

Fig. 4. Examples of Zijderveld demagnetization vector diagrams for: a) Sample of upper breccias from UNAM-7; b) Sample of lower breccias from UNAM-6; c) Sample of crystalline-limestone from UNAM-5. Least-squares fits have a maximum angular deviation of $<10^\circ$.

study on these boreholes and in addition included UNAM-5. Our aim has been to obtain high-resolution magnetic susceptibility logs to characterize the impact lithologies. Low-field magnetic susceptibility was measured with the Bartington MS2 system and a core-logging sensor. Measurements were taken at 10-cm spacing. UNAM-5 was measured between 308.00 m to 468.65 m (Fig. 3(a)), UNAM-6 was measured between 91.60 m to 700.00 m (Fig. 3(c)) and UNAM-7 was measured between 218.35 m to 702.00 m (Fig. 3(b)), in UNAM-6 we started at 91.6 m. The magnetic susceptibility contrast, between the impact lithologies and the carbonates, is high enough in UNAM-7 to establish accurately the contact between them. Susceptibility displays a simple pattern, values from, carbonates, dolomitized carbonates, marls, anhydrite and evaporitic breccias, are within the diamagnetic and paramagnetic range (Fig. 3). The upper breccias display high values, UNAM-5 highest value is 463.8×10^{-5} SI (Fig. 3(a)), and UNAM-7 (Fig. 3(b)) displays higher values, up to 1252.5×10^{-5} SI. A remarkable feature, in both boreholes, is the increment of the susceptibility towards the base of the unit. In UNAM-7, magnetic susceptibility drops from 1252.5×10^{-5} SI to the diamagnetic range, this drop marks the contact between the upper (melt-rich breccias) and lower breccias (carbonates-rich breccias) (Fig. 3(b)), that indicates the contact between the upper and lower breccias, in UNAM-7, at 346.95 m. In the measurements of UNAM-6 (Fig. 3(c)), we observed a homogeneous behavior of the susceptibility along the core, with values within the diamagnetic and paramagnetic ranges. This shows a lack of ferrimagnetic minerals in this borehole, indicating that the absence of the melt-rich breccias. Only the lower breccias are present, with composition similar to that of the carbonate target lithologies (Rebolledo-Vieyra *et al.*, 2000). UNAM-5 exhibits a similar behavior than that of UNAM-7 for the upper breccias; but we could not estimate the contact with the lower breccias, because this borehole did not reached this unit.

6. Magnetostratigraphy

Four polarity chrons were detected for the three boreholes, two reverse (29R and 28R) and two normal (29N and 28N) (Figs. 5, 6 and 7). The tie point assumed at 65 Ma was taken from the radiometric ages of the upper breccias from Y6 borehole from PEMEX (Swisher *et al.*, 1996), which correlates the breccias to the chron 29R (Urrutia-Fucugauchi *et al.*, 1994). In boreholes UNAM-5 and UNAM-7, the polarity of the samples of upper breccias is reverse, followed by carbonate sediments with normal polarity. We interpreted this polarity change as the transition from chron 29R to chron 29N (Fig. 5 and 7). In bore-

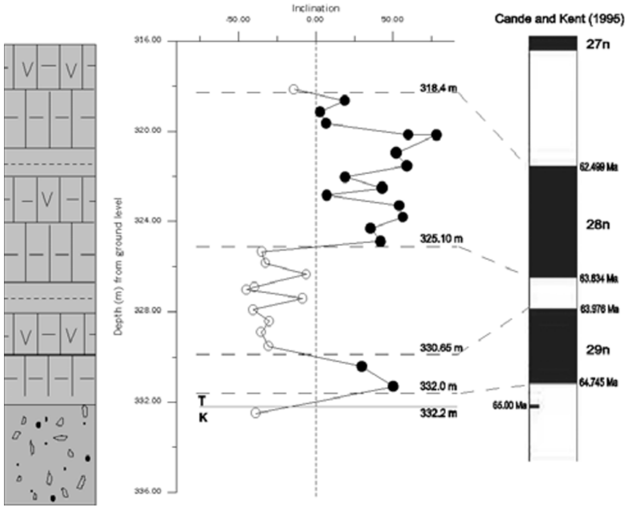

Fig. 5. Lithology, magnetostratigraphy and age constrains for borehole UNAM-5. K=Cretaceous; T=Tertiary; continuous line=K/T boundary. Lithology legend as in Fig. 2.

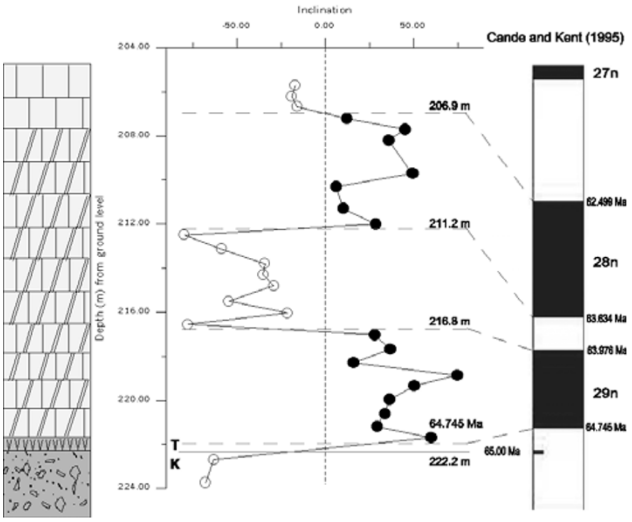

Fig. 6. Lithology, magnetostratigraphy and age constrains for borehole UNAM-7. K=Cretaceous; T=Tertiary; continuous line=K/T boundary. Lithology legend as in Fig. 2.

hole UNAM-6, we observed a long reverse polarity zone (Fig. 6), which spans from the upper breccias to the first 3–4 meters of the Tertiary carbonates, in this case, we interpreted this long reverse zone, as absence of the sedimentary sequence containing chron 29N, probably due to erosion or non-deposition of the sedimentary sequence coeval with this chron. In UNAM-6, the magnetic susceptibilities are within the diamagnetic range along the sequence of the borehole (502 m), which supports our interpretation that the melt-rich upper breccias are missing as interpreted from the magnetostratigraphy.

Once the magnetostratigraphy was established, we estimate the apparent sedimentary rate (ASR) for each borehole using the equation of Johnson and McGee (1983):

$$\Delta t = S\tau N \tag{1}$$

$$S = \frac{-\ln(1-2P)}{2} \tag{2}$$

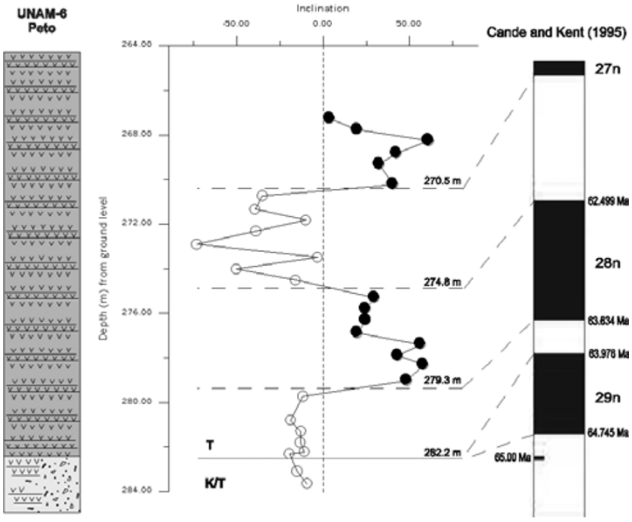

Fig. 7. Lithology, magnetostratigraphy and age constrains for borehole UNAM-6. K=Cretaceous; T=Tertiary; continuous line=K/T boundary. Lithology legend as in Fig. 2.

Table 1. Parameters and apparent sedimentary rates calculated for each borehole.

Borehole	D (m)	τ (Ma)	N	S	R	δt (Ma)	sr (m/Ma)
UNAM-5	15	0.748	26	0.137	3	2.66	5.68
UNAM-6	15	1.241	22	0.168	3	4.58	3.32
UNAM-7	15	0.748	24	0.150	3	2.69	5.65

$$P = \frac{R}{N-1} \tag{3}$$

$$sr = \frac{d}{\Delta t} \tag{4}$$

τ=arithmetic mean of the duration of the polarities within the sequence

S=Sediments accumulated

N=Number of intervals sampled

R=Number of reversals within the sequence

D=Thickness of the sequence

sr=Sedimentary rate

The sedimentary rates calculated for each borehole are summarized in Table 1. Boreholes UNAM-5 and UNAM-7 show similar ASR values, since they have the same number of polarity changes and the same number of chrons, within the approximate same thickness. These sedimentary rates are low, and may be explained in two ways. A low sedimentary depositional rate in a small shallow basin; according to Sadler (1981) accumulation rates for time spans of ~108 years, can be as low as 1 m/Ma. An alternative interpretation is in terms of erosional events that remove part of the sequence.

7. Conclusions

The magnetic susceptibility core logs exhibit an increasing trend towards the base of the upper breccias probably as a consequence of hydrothermal alteration of the magnetic minerals. Studies of the magnetic mineralogy of the impact breccias from borehole Yaxcopoil-1, indicated that magnetic carriers are mainly low-temperature magnetites formed as alteration products at temperatures under 150°C (Urrutia-Fucugauchi *et al.*, 2004b; Pilkington *et al.*, 2004).

We tied the magnetostratigraphy with the radiometric age of the impact melt at 65 Ma within chron 29R. Estimates of apparent sedimentation rates for the carbonate sequence give low values, suggesting that part of the impact breccias and the base of the Tertiary carbonate sequence have been eroded. In UNAM-6 borehole the upper breccias are not present, indicating a major hiatus. Considering a diameter of the crater between 180 and 200 km (Hildebrand *et al.*, 1991; Pope *et al.*, 1996; Urrutia-Fucugauchi *et al.*, 2004a) and the location of the boreholes from the center of the crater (UNAM-5, 110 km; UNAM-6, 152 km and UNAM-7, 127), we interpret the low apparent sedimentation rates as a consequence of a hiatus between the top of the impact breccias and the base of the Tertiary carbonates. Studies based on microfossils, stable isotopes and magnetostratigraphy from borehole Yaxcopoil-1 drilled within the crater reported a hiatus between the top of the impact breccias and the base of the Tertiary carbonate sequence (Keller *et al.*, 2004; Rebolledo-Vieyra and Urrutia-Fucugauchi, 2004). The results support that the Chicxulub crater and the surrounding region were likely subjected to post-impact erosive and re-deposition events, probably due to back-wash processes inside the basin. However, it is not clear if the three boreholes were subjected to similar erosional processes and if the magnitude of the hiatus is the same; therefore, further studies within the crater and the K/T sections to the south of the crater are important.

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