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Post-impact carbonate deposition in the Chicxulub impact crater region, Yucatan Platform, Mexico

Jaime Urrutia-Fucugauchi* and Ligia Pérez-Cruz

Laboratorio de Paleomagnetismo y Paleoambientes,
Instituto de Geofisica, Universidad Nacional Autonoma de Mexico,
Ciudad Universitaria, Circuito Exterior S/N, Coyoacan,
DF 04510, Mexico

The Chicxulub crater has attracted considerable attention as one of the largest terrestrial impact structures and its association with the Cretaceous/Palaeogene boundary. Analyses of stable isotopes and magnetostratigraphic results for the Paleocene carbonate sequence in the Santa Elena borehole are used to investigate the post-impact sequence and estimate the age of basal sediments in the southern crater sector. Studies of impact ejecta and cover sediments and modelling of post-impact processes suggest erosion effects due to sea-water back surge, block slumping and partial rim collapse of post-impact crater modification. Correlation of stable isotope patterns with the global pattern for marine carbonate sediments provides a stratigraphic framework for the basal Paleocene carbonates. Magnetic polarity constrains correlation of stable isotope variations with the reference Cenozoic isotopic data suggest that the first 17 m above the breccia–carbonate contact represents about 2.5 Ma. The stable isotope data suggest a gap of less than 0.1 Ma, whereas the magnetic polarity data (absence of reverse-polarity samples above impact breccia contact) suggest a gap up to 0.25 Ma.

Keywords: Chicxulub impact crater, Cretaceous/Palaeogene boundary, stable isotope stratigraphy, magnetostratigraphy.

CHICXULUB is the youngest and best-preserved crater of only three large, multi-ring impact structures found on earth[1,2]. The Chicxulub structure was recognized from the concentric circular-pattern of gravity anomalies in the 1940s during oil exploration surveys by Pemex. The buried structure responsible for the anomalies lies in an extensive shallow-water carbonate platform. It was subsequently investigated by further geophysical surveys and drilling. Pemex drilling recovered volcanic-textured rocks towards the centre of the anomaly pattern. The structure was interpreted as an Upper Cretaceous volcanic field till the early 1980s, when an alternative interpretation in terms of an impact crater was proposed[3]. In the early 1990s Chicxulub attracted international attention when the crater was linked to the Cretaceous/Palaeogene (K/Pg) boundary[4], and considered as the long sought after impact crater proposed by Alvarez and coworkers[5]. Analyses of few remaining samples from the Pemex intermittent core recovery programme supported the inference of a K/Pg boundary age for the impact event[4,6]. Alternative interpretations were also reported for the subsurface stratigraphy of Yucatan[7,8]. With the recognition of the origin of the Chicxulub impact, volcanic-textured rocks, geophysical anomalies and age of units were reinterpreted. Ar/Ar dating on melt samples from Chicxulub-1 borehole gave an age of approximately 65 Ma, indicating a K/Pg age for the impact[6]. The reverse magnetic polarity of melt and breccia samples from Yucatan-6 borehole placed the impact within 29r chron that spans the K/Pg boundary[9].

The 200 km-diameter crater lies in the Yucatan platform in southern Gulf of Mexico, completely covered by Cenozoic carbonate sediments. The carbonate cover has protected the structure from erosion processes. Studies of crater morphology, impact melt and ejecta, cratering, post-impact processes and basin characteristics require geophysical surveys and drilling/coring. Chicxulub was identified as a potential drilling target since creation of the International Continental Scientific Drilling Programme (ICDP) in the early 1990s, and it has recently been investigated by drilling with continuous coring[10] as part of the UNAM and ICDP scientific drilling projects (Figure 1).

Analyses of core samples have examined the stratigraphy of the cover carbonate sequence, impact breccia contact and implications for the age of impact, global correlations

*For correspondence. (e-mail: juf@geofisica.unam.mx)

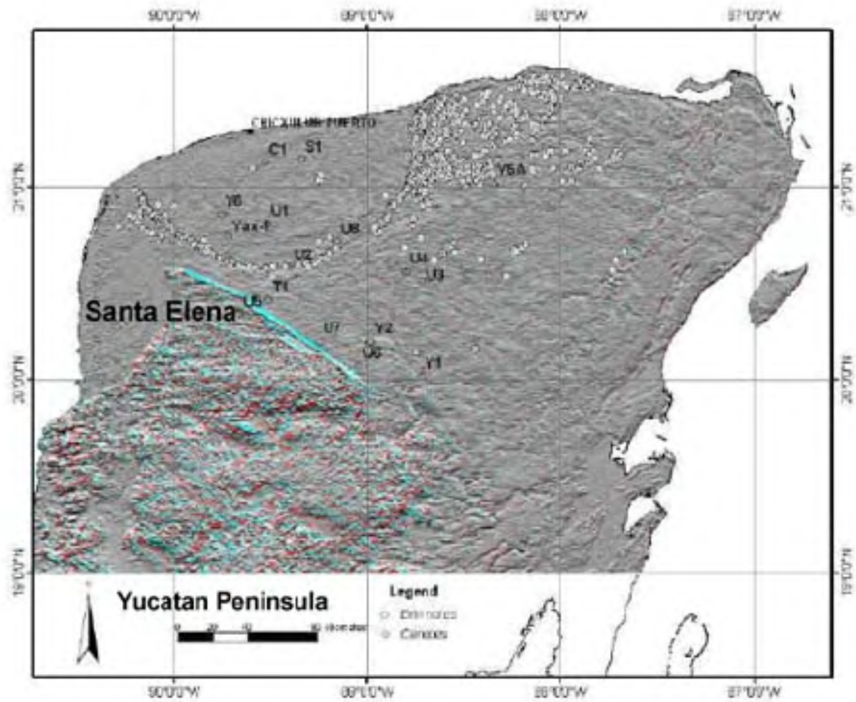

Figure 1. Location of the Santa Elena borehole (U5) and other boreholes in the Chicxulub crater and adjacent areas in the Yucatan Peninsula, Mexico. Pemex exploratory boreholes (intermittent coring programme): C1, S1, Y6, Y1, Y2, T1, and Y5A; UNAM boreholes (continuous coring programme): U1, U2, U3, U4, U5 (Santa Elena), U6 (Peto) and U7 (Tekax); and ICDP borehole (continuous coring): Yax-1. Base map is a NASA radar image. Surface projection of crater rim is approximately delineated by the surface semicircular topographic depression and the cenote (sinkholes marked by white dots) ring. Note higher density and scattered cenote distribution east of the crater area.

of the K/Pg boundary layer and palaeoenvironmental conditions following impact. Results from the ICDP drilling project[10] show that the impactite sequence in the Yaxcopoil-1 borehole located at 62 km radial distance from the crater centre is 100 m thick, thinner than that expected from lateral correlations and geophysical models. The impactite sequence has been interpreted in terms of deposits in the terrace zone and the potential role of erosive and slumping processes and asymmetric ejecta distribution related to post-cratering deformation, oblique low-angle impact and sea water backsurge processes has been highlighted. This has emphasized the need for a detailed stratigraphy of the impact breccias and basal Tertiary carbonates, which are critical to investigate the environmental and depositional conditions following the impact. The age of impact was also questioned with the proposal[11] that the Chicxulub impact occurred in the late Maastrichtian and predates the K/T boundary. While other studies of Yaxcopoil-1 cores indicate a K/Pg age for Chicxulub[12,13], the debate emphasizes the temporal resolution of current chronological methods[9,14,15], the need for further detailed analyses of the basal carbonate sections in existing boreholes and realization of additional drilling/coring projects.

The UNAM drilling programme sampled the impact breccia–carbonate contact in three boreholes, providing core material for investigating the basal sedimentary sequence. Analyses of the sections and the contact provide new insights on the impact age and evolution of the impact basin following crater formation. Results of magneto-stratigraphic[13] and stable isotope studies[14] of the Santa Elena borehole obtained are used here to discuss time resolution of isotopic and magnetic polarity stratigraphies and to address implications for the Chicxulub basal section of the post-impact carbonate sequence.

The Palaeogene carbonate sequence from the Santa Elena borehole (site coordinates: 89.6615°W, 20.3385°N; Figure 1) located at 110 km radial distance from the crater centre was selected for the stable isotope study[14] because of the high core-recovery rate, continuous coring of the Palaeogene sequence and melt-rich (upper) breccias. In parallel, results of the magnetic polarity stratigraphy were obtained[13]. In the Santa Elena borehole, the contact of impact breccias and Palaegene carbonates is at 332.0 m depth and the suevitic breccias have a minimum thickness of 146 m. The basal carbonate sequence in the first 20 m above the contact with the impact breccias presents several thin clay layers and dolomitization intervals.

The limestones show high contents of silica that decrease away from the impact breccia contact, suggesting that silica comes from reworking of the suevitic breccias.

The Santa Elena stable isotope data[14] for the carbonate sequence immediately above the impact breccia–carbonate contact are based on sixty bulk carbonate samples spaced in a 17 m thick section representing the basal sequence, from about 332 to 316 m depth (Figure 2). The $\delta^{13}C$ values vary from about 1.2 to 3.5‰, and the $\delta^{18}O$ values from about –1.4 to –4.8‰. Correlation of the isotopic records for Palaeocene bulk carbonate in marine sediment cores like DSDP Hole 577 in the North Pacific Ocean, shows similar variational trends as those documented for Santa Elena borehole (Figures 3 and 4). Correlation of $\delta^{13}C$ trends (Figure 3) suggests that the Santa Elena section spans about 2.5 Ma. The increase characterizing the K/Pg boundary is not observed in the Santa Elena record, which has been explained in terms of a short hiatus and that the 0.5 m interval above the contact has no longer been preserved for analysis. Correlation of $\delta^{18}O$ records is less clear-cut, and graphs shown are fixed from the $\delta^{13}C$ correlation (Figure 4). Assuming a K/Pg tie point for the breccia–carbonate contact, the gap is less than 0.1 Ma.

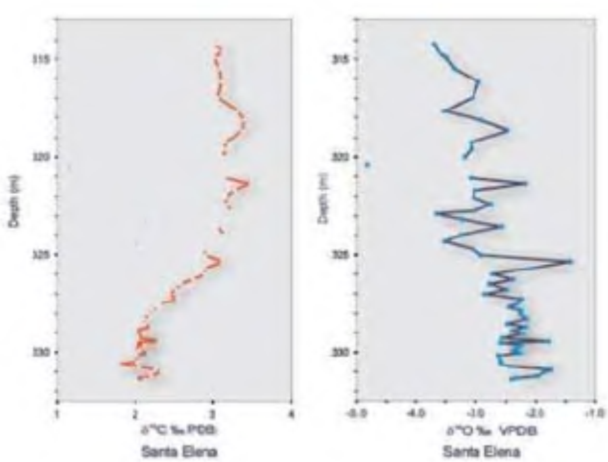

Figure 2. Stable isotope data for the Santa Elena borehole plotted as a function of depth below surface[14]. Carbon (left) and oxygen (right) isotope data are given as $\delta^{13}C$ PDB and $\delta^{18}O$ PDB. Interval analysed corresponds to basal carbonate sequence above the impact breccia–carbonate contact.

In the Santa Elena core, $\delta^{13}C$ values are slightly more positive than those in DSDP Hole 577 (Figure 3). The latter shows its highest $\delta^{13}C$ value (~2.7‰) at the boundary (65 Ma), decreasing between 65 and ~64.5 Ma. In the interval between 64.2 and 63.7 Ma, $\delta^{13}C$ values are relatively low in both holes. In the Santa Elena core, values reach ~3.5‰ at around 63 Ma, with relatively high values until the middle Palaeocene, suggesting enhanced ocean productivity in the region. This trend is seen in bulk stable isotope data[16] for DSDP Hole 577 (Figure 3). The trend of $\delta^{18}O$ values from Santa Elena core is similar to $\delta^{18}O$ DSDP Hole 577 (Figure 4)[16]. However, isotopic values in the Chicxulub Tertiary sequence are more negative, which may be related to the regional and local palaeoceanographic conditions after the K/Pg boundary. The $\delta^{13}O$ values from the Santa Elena core decrease from early Palaeocene into the middle Palaeocene (Figure 4).

Palaeomagnetic data for the Santa Elena section show a well-defined characteristic magnetization that permits documentation of five geomagnetic polarity zones for the impact breccias and the basal sedimentary sequence, which span from chron 29r to chron 27r. Rebolledo-Vieyra and Urrutia-Fucugauchi[13] combined the magnetostratigraphy with the radiometric age of the impact melt at 65 Ma within chron 29r. Reference to numerical magnetic polarity timescales[17,18] provides with tentative ages for the chron intervals, covering approximately 2.5 Ma of the basal carbonate sequence. The magnetic polarity chron boundaries can then be used to have an independent chronology for

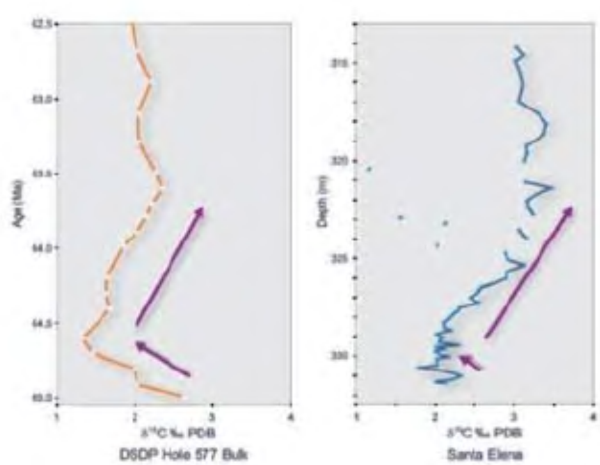

Figure 3. Carbon isotope data for the Santa Elena borehole compared with $\delta^{13}C$ PDB data[16] for DSDP Hole 577.

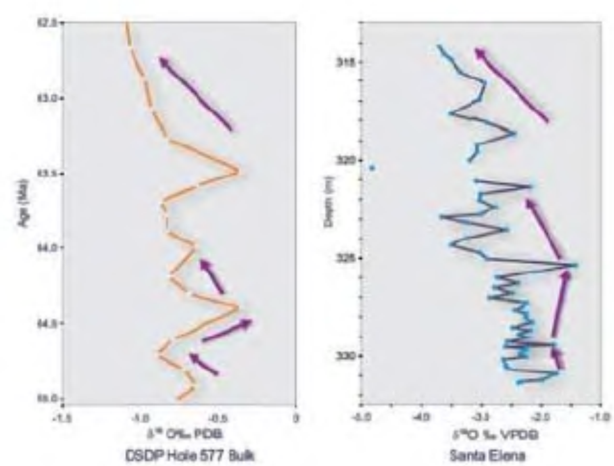

Figure 4. Oxygen isotope data for the Santa Elena borehole compared with the $\delta^{18}O$ PDB data[6] for DSDP Hole 577.

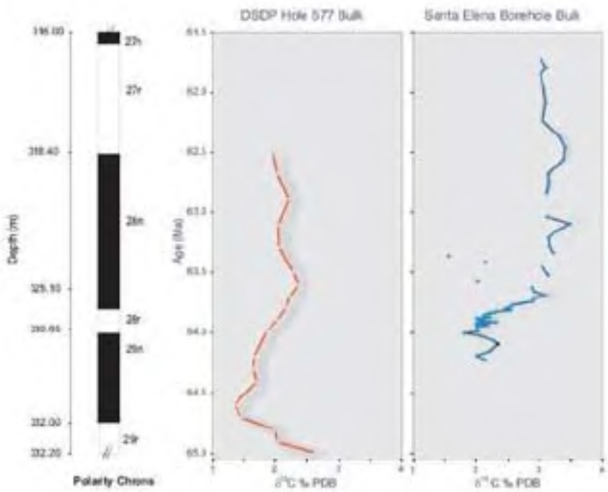

Figure 5. Carbon isotope data for the Santa Elena borehole plotted as a function of the magnetic polarity zones, and compared with $\delta^{13}C$ PDB data for DSDP Hole 577. Note the larger gap in correlating the two sequences. See Figure 3 and text for discussion.

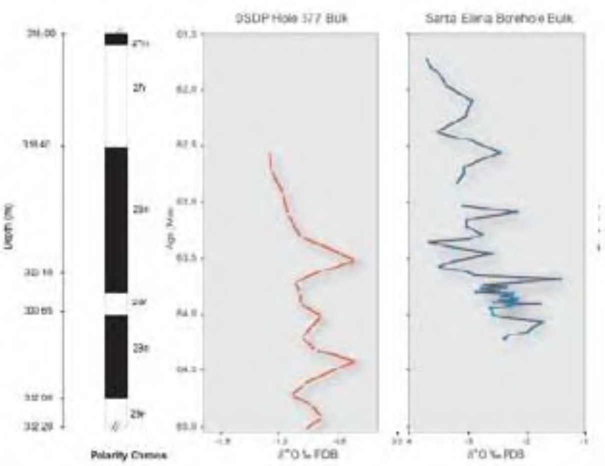

Figure 6. Oxygen isotope data for the Santa Elena borehole plotted as a function of the magnetic polarity zones, and compared with $\delta^{18}O$ PDB data for DSDP Hole 577. Note the larger gap in correlating the two sequences. See Figure 4 and text for discussion.

the carbonate section isotopic data. This is done in Figures 5 and 6 (note that for the graphs vertical depth scale is modified to fit with the magnetic polarity chron timescale, DSDP data are plotted versus age and Santa Elena data are plotted versus depth fixed by the magnetostratigraphy chron boundary points and bottom 2 m part of the graph is over-represented with respect to the rest; next interval is 5.5 m). This results in a difference of about 0.5 Ma with respect to the correlation using stable isotopes, where the low observed in the Santa Elena curve does not correspond to the low at 64.6 Ma in the DSDP curve (Figure 5). It can be noted that correlation of $\delta^{18}O$ data (Figure 6) is more problematic than that obtained earlier from the $\delta^{13}C$ curves (Figure 4). These new results suggest a larger hiatus in the basal section of Santa Elena. We note that the apparent depositional rates determined from the magnetic polarity chron correlation are variable and that for Santa Elena no reverse polarity samples are present above the breccia–carbonate contact. Reverse polarity samples are present in Peto (U6) and Tekax (U7) boreholes, suggesting that the upper part of chron 29r is missing. Within the uncertainty represented by the 0.5 m gap not available for sampling, this will give a maximum gap of 250 ka. Detailed correlation and age determination are limited by problems associated with the temporal–spatial resolution of the magnetostratigraphic data, uncertainties in reference geomagnetic polarity timescales and the incomplete nature of sedimentary sections[19,20]. These problems are also present while using the stable isotopic data for high-resolution stratigraphic reference and dating.

The Palaeocene is characterized by the most positive $\delta^{13}C$ values in Cenozoic marine carbonates. This has been interpreted as reflecting a return, at least in part, to normal, if not enhanced, global ocean productivity following the almost complete extinction of ocean plankton at the K/Pg boundary[21]. The amplitude of the $\delta^{13}C$ increase varies according to the material in which it is measured (i.e. planktonic foraminifera or bulk sediment), implying that the $\delta^{13}C$ record of surface-produced carbonate should be interpreted with caution. The Palaeocene is generally considered a time of global warmth, and low vertical and latitudinal temperatures gradients in the oceans[22], which had experienced comparatively elevated levels of atmospheric CO_2 that may have been at least partially responsible for the inferred high global temperatures[21]. $\delta^{13}C$ values increased between 3 and 4‰ (in bulk carbonate whole-rock samples) by the late Palaeocene and then decreased to values similar to those that prevailed at the K/Pg boundary. Results of the stable isotopes permit inferences about the palaeoceanographic conditions in the Chicxulub area during the Palaeocene. The increase in $\delta^{13}C$ values suggests high productivity.

The correlation of stable isotope variation patterns in the Santa Elena core with the global pattern defined for marine carbonate sediments[16,21–25] shows a reasonably good fit and provides a preliminary stratigraphy. The stable isotope data suggest a short gap of less than 0.1 Ma, whereas the magnetic polarity data (absence of reverse polarity samples above breccia contact) suggest a larger gap up to 0.25 Ma. The magnetic polarity and stable isotopes suggest that the first 17 m above the breccia–carbonate contact represents around 2.5 Ma; also marking an apparent time difference of about 0.5 Ma between the two. Erosive processes may have taken place during the initial stages after crater formation from sea water back surge and tsunamis[26], and possibly afterwards from rim collapses recorded in re-deposited breccias and Cretaceous re-worked sediments. The Santa Elena borehole combined datasets imply a hiatus following the impact, with no carbonate deposition and/or erosion. This agrees with models proposing significant effects of sea-water back surges and crater rim collapse and modification[26,27], and provides stratigraphic constraints for the duration of these processes and re-establishment of carbonate deposition in the crater region.

The isotopic and magnetic polarity data in the post-impact sediments of the Santa Elena borehole are compatible with a K/Pg age for the Chicxulub impact. The Tertiary carbonate sections sampled in the Chicxulub UNAM and ICDP drilling projects are potential archives that record the crater evolution, effects of the impact event, life recovery in the target area, development of the Yucatan carbonate platform, carbonate deposition, Cenozoic sea-level changes, and palaeoceanographic and palaeoclimatic conditions in the Gulf of Mexico–Caribbean Sea region.

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