Geofísica Internacional
ISSN: 0016-7169
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Universidad Nacional Autónoma de México
México

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Geofísica Internacional, vol. 50, núm. 1, enero-marzo, 2011, pp. 99-127
Universidad Nacional Autónoma de México
Distrito Federal, México

Geofísica Internacional (2011) 50-1: 99-127

Review Article

The Chicxulub multi-ring impact crater, Yucatan carbonate platform, Gulf of Mexico

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Received: November 16, 2010; accepted: November 23, 2010; published on line: December 17, 2010

Resumen

El cráter Chicxulub, parte de un grupo selecto de rasgos geológicos, constituye un laboratorio para investigar los procesos de formación de cráteres y los efectos de impactos en el planeta. Chicxulub es uno de tres cráteres complejos multi-anillos documentados en el registro terrestre y el impacto es relacionado a los cambios ambientales y climáticos que marcan la frontera Cretácico/Paleógeno (K/Pg) y las extinciones masivas de organismos. El cráter, localizado en la porción noroeste de la península de Yucatán, está cubierto por sedimentos carbonatados y fue identificado inicialmente en los estudios dentro del programa de exploración de Petróleos Mexicanos. En la superficie, evidencias del cráter sepultado incluyen al anillo de cenotes y rasgos topográficos semi-circulares, los cuales se asocian a la compactación diferencial de los materiales fragmentados en el impacto y que forman parte del relleno de la estructura. El cráter tiene un diámetro aproximado de 200 km, esta una parte en el mar y otra en tierra y puede ser investigado usando métodos geofísicos terrestres, marinos y aéreos. Las características de la plataforma carbonatada, que no ha sido afectada por actividad tectónica o volcánica reciente, permiten tener mayor resolución en los estudios geofísicos e investigar la estructura del cráter con una alta precisión. La formación del cráter y el evento de impacto ocurren en un corto tiempo del orden de centenas de segundos, con una alta liberación de energía y la excavación de una cavidad con profundidades del orden de 25 km, afectando toda la corteza. La corteza inferior y manto superior son deformados y se tiene un levantamiento en la parte central de la excavación de varias decenas de kilómetros que forma un levantamiento de basamento que caracteriza a estos cráteres complejos. La zona de impacto es deformada y fracturada. Los estudios de la dinámica del impacto, formación del cráter, efectos globales de la liberación de energía y ondas sísmicas y los modelados del comportamiento de materiales sujetos a altas presiones y temperaturas forman parte de los problemas en estudio, representado retos interesantes en geociencias. La capa de eyecta con el material fragmentado identificada como la capa K/Pg constituye un marcador estratigráfico a escala global, permitiendo correlaciones estratigráficas y análisis de procesos en la transición del Mesozoico al Cenozoico. En los últimos 20 años las investigaciones han aportado información importante sobre el cráter Chicxulub y los eventos que marcan la frontera K/Pg, sin embargo, son las preguntas formuladas a partir de los estudios quizá la parte más relevante. Estas interrogantes incluyen temas fundamentales sobre impactos, formación de cráteres y la evolución del sistema solar.

Palabras clave: cráter Chicxulub, límite Cretácico/Paleógeno, impactos, formación de cráteres de impacto, exploración geofísica, perforación y recuperación de núcleos, plataforma carbonatada de Yucatán, golfo de México

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Abstract

The Chicxulub impact crater is part of a select group of unique geological sites, being a natural laboratory to investigate crater formation processes and global effects of large-scale impacts. Chicxulub is one of only three multi-ring craters documented in the terrestrial record and impact has been related to the global environmental/climatic effects and mass extinction that mark the Cretaceous/Paleogene (K/Pg) boundary. The crater is buried under ~1.0 km of carbonate sediments in the Yucatan peninsula. The buried structure was initially identified from geophysical surveys of the PEMEX oil exploration program in southeastern Mexico. On the surface its influence is marked by the circular ring of cenotes that have formed from differential compaction and fracturing between the impact breccias and surrounding limestone sequences. The crater is about ~200 km in rim diameter, half on-land and half off-shore with geometric center at Chicxulub Puerto, making it possible to use land, marine and aerial geophysical methods. The Yucatan carbonate platform is an ideal place to have the crater, tectonically stable with no volcanic activity, having formed by slow deposition of carbonate sediments. These characteristics permit high resolution imagery of the crater underground structure with unprecedented detail. The impact and crater formation occur instantaneously, with excavation of the crust down to ~25 km depths in fractions of a second and lower crust uplift and crater formation in the next few hundred seconds. Energy release results in intense fracturing and deformation at the target site, generating seismic waves traveling the whole Earth. Understanding the physics of impacts on planetary surfaces and modeling of crustal deformation and rheological behavior of materials at high temperatures and pressures remain major challenges in geosciences. The K/Pg ejecta layer is the only global stratigraphic marker in the geological record, allowing correlation of events worldwide. In the last 20 years much has been learned about the Chicxulub crater and the K/Pg boundary; however what is perhaps most interesting are the questions remaining, which include fundamental aspects of Chicxulub impact and its environmental effects.

Key words: Chicxulub crater, Cretaceous/Paleogene boundary, cratering, geophysical exploration methods, drilling, Yucatan platform, Gulf of Mexico

Introduction

Three decades ago Alvarez and co-workers (1980) published a paper proposing that an asteroid impact caused the extinction of organisms and the events marking the Cretaceous/Tertiary boundary (now referred as Cretaceous/Paleogene, K/Pg boundary). In their paper, they reported results from studies on pelagic carbonate sequences from Italy, Denmark and New Zealand that spanned the K/Pg boundary, which was marked by a thin clay layer. This layer was characterized by iridium enrichment, with concentrations of about 30, 160 and 20 times the background levels through the sections. The iridium and other platinum group elements and chemical and mineralogical characteristics of the clay layers were interpreted in terms of a collision of a large asteroid at the K/Pg boundary. Effects of the impact included injection into the atmosphere of large amounts of pulverized rock, resulting in blockage of solar radiation, global cooling, and interruption of photosynthesis processes. As part of the report, Álvarez *et al*. (1980) estimated the size of the bolide from different sets of assumptions, with a mean diameter of about 10 ± 4 km in diameter. They analyzed data bases available on Earth crossing objects and the terrestrial crater record. Size of resulting impact crater was estimated at ~200 km in diameter. At that time, only three craters >100 km in diameter were known, Vredefort, Sudbury and Popigai, which were not considered as possible candidates for the impact because of their formation ages. It was mentioned that the impact site may not be found, having occurred in an ocean basin, and if so, documenting it presented major obstacles for its recognition and possible disappearance as a result of plate subduction. Although probability was considered low, search for the impact site began and continued over the years, which also included studies on the distribution and characterization of the K/Pg layer and geochemical fingerprinting of bolide and target lithology. Interestingly, about a year after publication of the Álvarez *et al*. (1980) paper, results of oil exploration geophysical surveys in southeastern Mexico were presented at the Annual Meeting of the Society of Exploration Geophysicists that included the report on a buried structure in the Yucatan carbonate platform (Penfield and Camargo-Zanoguera, 1981). The structure was characterized by semi-circular patterns of gravity and aeromagnetic anomalies over a large area some ~200 km in diameter with associated rocks of andesitic composition, which were interpreted in terms of a large volcanic center or an impact crater. Although reports from the meeting were published making the association of the Yucatan crater with the K/Pg boundary impact and mass extinction, it will take a decade for additional studies on the crater and to establish its relation to the K/Pg boundary. Hildebrand *et al*. (1991) summarized the studies on the Chicxulub crater, proposing it as candidate for the K/Pg boundary impact site. Subsequent studies on impactite lithologies recovered from the drilling programs conducted by Petroleos Mexicanos (PEMEX) provided further confirmation on an impact origin for the structure and an age at the K/Pg boundary (Sharpton *et al*., 1992; Swisher *et al*., 1992; Urrutia-Fucugauchi *et al*., 1994). Chicxulub impact became linked to the worldwide distributed iridium-rich clay layer that has been the stratigraphic marker of the K/Pg boundary. The Chicxulub crater became a fundamental component for the Impact Theory, providing not only supporting evidence but opening new research avenues on impact cratering, environmental effects of impacts, killing mechanisms, biota extinctions, evolution, oil and mineral deposits and role of impacts in the solar system.

In this paper, we review the geophysical studies and drilling programs on the Chicxulub crater carried out over the past decades and briefly discuss their implications for research on a wide range of topics, from impact cratering and mass extinctions to paleoclimatic and paleoenvironmental effects of large impacts.

Chicxulub impact crater

The Chicxulub crater is located in the Yucatan carbonate platform, southern Gulf of Mexico (Figure 1). The structure lies about half offshore and half on-land covered by carbonate sediments, with the approximate geometric center at the coastline in Chicxulub Puerto. Geophysical surveys carried out as part of the oil exploration program by PEMEX documented a semi-circular gravity anomaly pattern in the northwestern sector of the Yucatan peninsula (Villagómez, 1953; Cornejo-Toledo and Hernández-Osuna, 1950; López Ramos, 1975; Penfield and Camargo-Zanoguera, 1981). The buried structure was explored with a drilling program starting in the 1950's, which provided data on the subsurface stratigraphy (López Ramos, 1975). Boreholes drilled inside the geophysical anomaly recovered samples of igneous rocks of andesitic composition, which were taken as confirmation for a volcanic origin of the structure, buried in the carbonate platform. Results from the exploration program showed no indication for oil and gas deposits in the area. Further exploration efforts included an aeromagnetic survey that showed occurrence of high amplitude magnetic anomalies located in the central zone of the semi-circular gravity anomaly, which allowed Penfield and Camargo-Zanoguera (1981) to propose an alternative impact origin

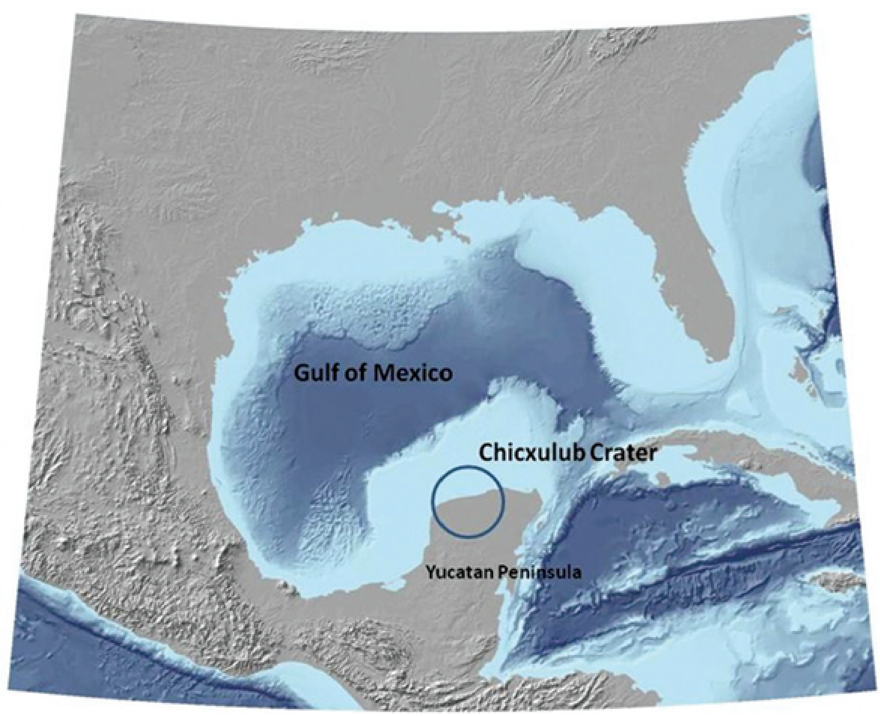

Figure 1. Location of the Chicxulub impact crater in the Yucatan peninsula, southern Gulf of Mexico (Base map is a digital terrain model of Gulf of Mexico–Caribbean Sea region, adapted from French and Schenk, 2004).

for the buried structure. Interpretation of the subsurface stratigraphy suggested a Late Cretaceous age for the andesitic body (López Ramos, 1975).

The study by Hildebrand and coworkers (1991) provided evidence in support of an impact origin for the Yucatan structure, proposing a ~180 km diameter crater characterized by high amplitude potential field anomalies. The stratigraphy derived from the Chicxulub-1, Sacapuc-1 and Yucatan-6 boreholes drilled inside the crater was interpreted in terms of a possible K/Pg boundary age. Although the geometry of the buried structure could not be adequately defined in this initial study, evidence on shock metamorphic features in the igneous-textured rocks was presented, including the petrography and chemistry of the polymictic breccias and melt and by comparing the chemistry of the melt rocks with boundary deposits in North America, Gulf of Mexico and Caribbean (Izett, 1990; Izett *et al*., 1990 Sigurdsson *et al*., 1991). Sequence was interpreted as an impact melt and breccias, with the breccia sequences drilled outside the crater correlated to the ejecta blanket. The analyses and interpretation made use of the early report and data from Penfield and Camargo-Zanoguera (1981) and internal geophysical survey and drilling data from PEMEX exploration programs.

The morphology and crater size were inferred from the gravity and magnetic data, with a -30 mGal Bouguer anomaly approximately centered near Chicxulub Puerto in the coastline (Hildebrand *et al*., 1991). Crater geometry was estimated from the gravity anomaly showing a ~20 mGal ~20 km radius central high and concentric internal lows at ~35 km and ~60 km radii, respectively (Figure 2). Two regional gravity profiles showing the negative Bouguer anomalies across the structure were compared to the gravity anomaly over the Manicoguan crater, which showed similar features. No geophysical models were reported, and analysis of subsurface stratigraphy was made with reference to borehole data and a multichannel seismic reflection line that showed a ~1.5 km deep reflector, tentatively correlated with the K/Pg boundary.

Hildebrand *et al*. (1991)'s report was followed by studies providing additional evidence on the impact origin of the structure, subsurface stratigraphy and age of impact (Sharpton *et al*., 1992; Swisher *et al*., 1992; Urrutia-Fucugauchi *et al*., 1994) and on the morphology and deep structure of the crater (Sharpton *et al*., 1993; Camargo-Zanoguera and Suárez, 1994; Pilkington *et al*., 1994). Studies addressed other major related issues such as the link of Chicxulub impact with K/Pg boundary deposits

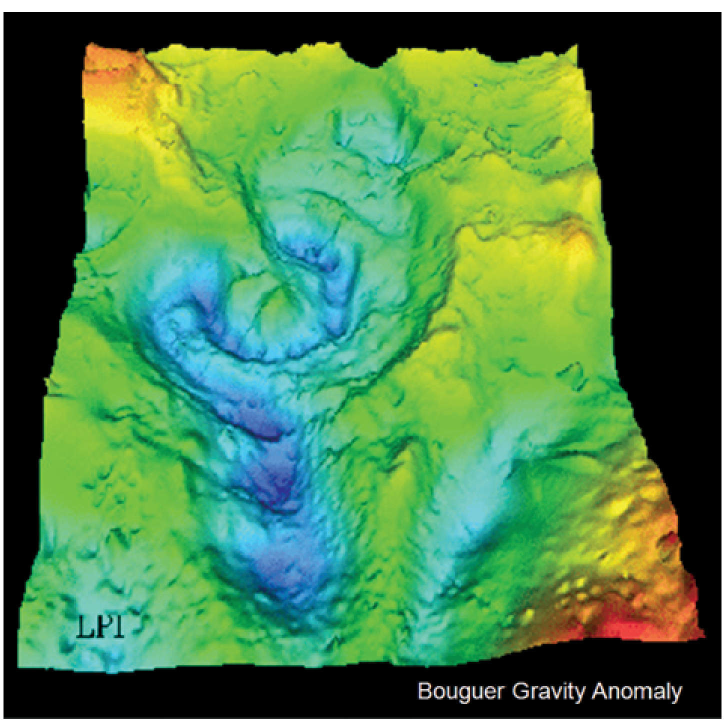

Figure 2. Oblique 3-D representation of Bouguer gravity anomaly map over the Chicxulub crater (from Sharpton *et al*., 1993). Observe the presence of a circular concentric anomaly with a high in the central zone.

in the Caribbean, southern United States and southern and northeastern Mexico, and with the global ejecta layer (Hildebrand and Boynton, 1990; Álvarez *et al*., 1992; Smit *et al*., 1992; Urrutia-Fucugauchi, 1993; Kamo and Krogh, 1995). Studies also re-examined the geology and geomorphology of the Yucatan peninsula. In the Yucatan peninsula, there are no surface outcrops of impact lithologies, and presence of the buried structure is indicated by a low-amplitude semi-circular topographic depression that can be observed in satellite images (Figure 3). This subtle topographic feature coincides with one of the most conspicuous karstic features recognized in the peninsula, the semi-circular arrangement of sinkholes referred to as the ring of "cenotes" (Pope *et al*., 1991). The buried structural rim is marked on the surface as a result of differential compaction of the impact breccias and fracturing and enhanced dissolution through fractures in the limestone terrain.

Geophysical surveys, geologic mapping and analyses of crater features provided contrasting models with different sizes and crater morphology. Crater diameters ranged from 170 km to 300 km with peak-ring and multi-ring crater morphology (Hildebrand *et al*., 1991, 1998; Pope *et al*., 1991, 1993; Sharpton *et al*., 1993; Pilkington *et al*., 1994; Urrutia-Fucugauchi *et al*., 1996; Connors *et al*., 1996; Hildebrand *et al*., 1998). At the same time, other studies questioned the stratigraphy and K/Pg impact age for Chicxulub (Meyerhoff *et al*., 1994; Ward *et al*., 1995).

The structure, size and morphology of the Chicxulub structure have been investigated in the last two decades, using gravity, magnetic, magnetotellurics and seismic reflection methods, and drilling with logging and continuous coring programs. Petrophysical properties of impact lithologies and target rocks have been determined from geophysical logs and core samples. Impact lithologies have been studied from petrological, geochemical, microprobe and isotopic analyses. The stratigraphy and age of impact have been studied from borehole information, radiometric dating, biostratigraphy, sequence stratigraphy, and magnetic polarity and stable isotope studies.

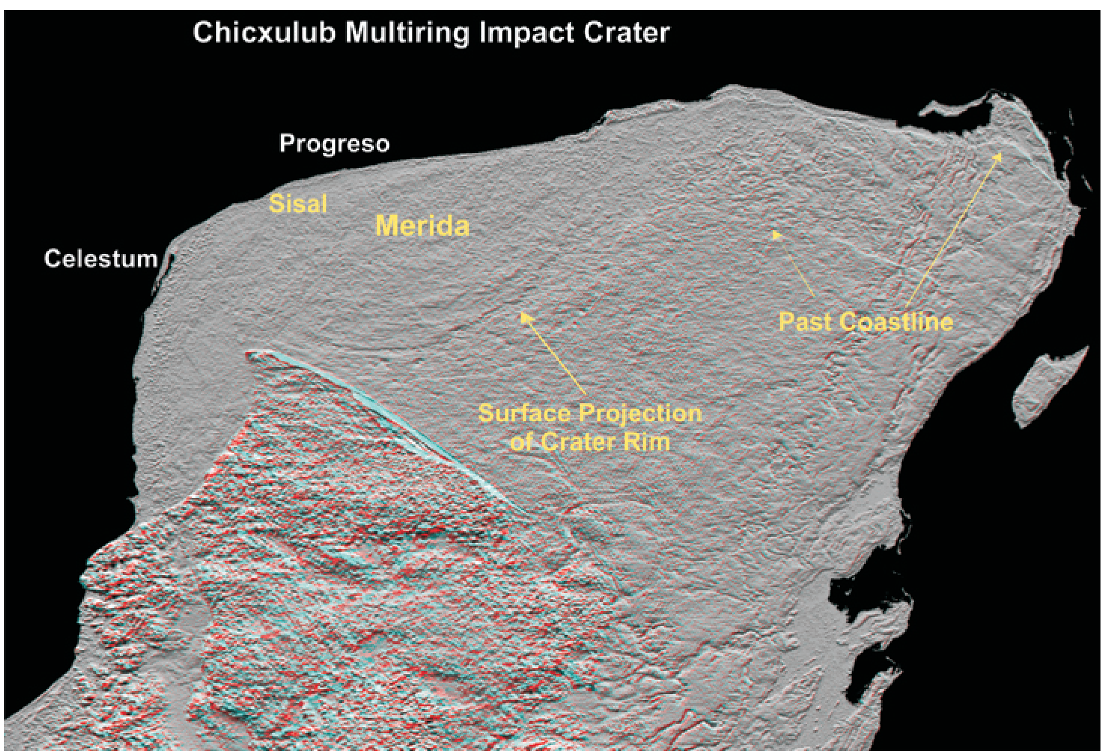

Figure 3. High-resolution interferometric radar satellite image for northern Yucatan peninsula. The surface projection of the crater rim is marked by a semi-circular topographic depression, which coincides with the cenote ring in the flat karstic terrain. The topographic depression is associated with differential compaction of impact breccias inside the crater in relation to the carbonate sequence. Note presence of fossil coastlines reflecting past sea-level changes (Urrutia-Fucugauchi *et al*., 2008). Base map from C-band interferometric radar image, Earth Shuttle Radar Topography Mission (Courtesy of NASA/JPL-Caltech).

Geophysical Models

The crater has been imaged using geophysical data from land, marine and aerial surveys. The gravity anomaly over Chicxulub is being defined from integration of surveys, including on-land surveys since the 1940's that covered a major portion of the peninsula (Penfield and Camargo-Zanoguera, 1981), marine surveys, and aerogravity surveys. Aerogravity data were collected offshore and on the western sector; processing shows survey lines artifacts oriented NNW and WSW (Hildebrand *et al*., 1998). These data have been complemented by other studies filling part of the gap areas, including the shoreline area (Connors *et al*., 1996: Hildebrand *et al*., 1998).

The Bouguer gravity anomaly shows a large well-defined semi-circular concentric anomaly pattern with amplitudes up to 30 mGals with a 40 km diameter central high and two lows at about 70 km and 120 km diameters (Figure 2). Semi-circular concentric anomalies were inferred at 52.5 ± 5 km, 77.1 ± 6.3 km, 99.6 ± 6 km and 139 ± 11 km radial distance, which define a multi-ring structure with central peak ring limited by ring 1. Rings 2 and 3 were interpreted as the inner and outer limits to transient crater wall, with a basin outer rim given by ring 4 (Sharpton *et al*., 1993). Hildebrand *et al*. (1998) and Connors *et al*. (1996) used the horizontal gradient to investigate on the concentric features, looking at zones of steeper gradients with a center at approximately 21.29º N, 89.52º W (Figure 4). The horizontal gradient map defines two concentric rings of positive anomalies, with the inner ring delineating the central uplift zone and the outer ring correlating with the cenote ring. The cenote distribution shows in some sectors deviations from circularity of up to ~3 km, and occurrence of less-developed semicircular features corresponding to partial secondary rings, particularly in the western and central sectors.

The aeromagnetic field over Chicxulub crater (Figure 5) shows high-amplitude dipolar anomalies over the central sector of the structure (Penfield and Camargo-Zanoguera, 1981; Pilkington *et al*., 1994). The anomaly field is calculated from the total magnetic field with subtraction of a regional value of 48,380 nT. Hildebrand *et al*. (1991) described the anomaly field as extending over a ~210 km zone of circular dipolar anomalies characterized by large horizontal gradients, and rough concentric patterns approximately correlating with the gravity pattern. Anomalies within the ~35 km radial distance including the central gravity high show large amplitudes (up to ~1000 nT) and short wavelengths. Magnetic anomalies of small amplitude (5 to 20 nT) short wavelengths extend over a wider area, some ~105 km radial distance. Penfield and Camargo-Zanoguera (1981) estimated the depths to magnetic sources at depths of about 1.1 km, which supported

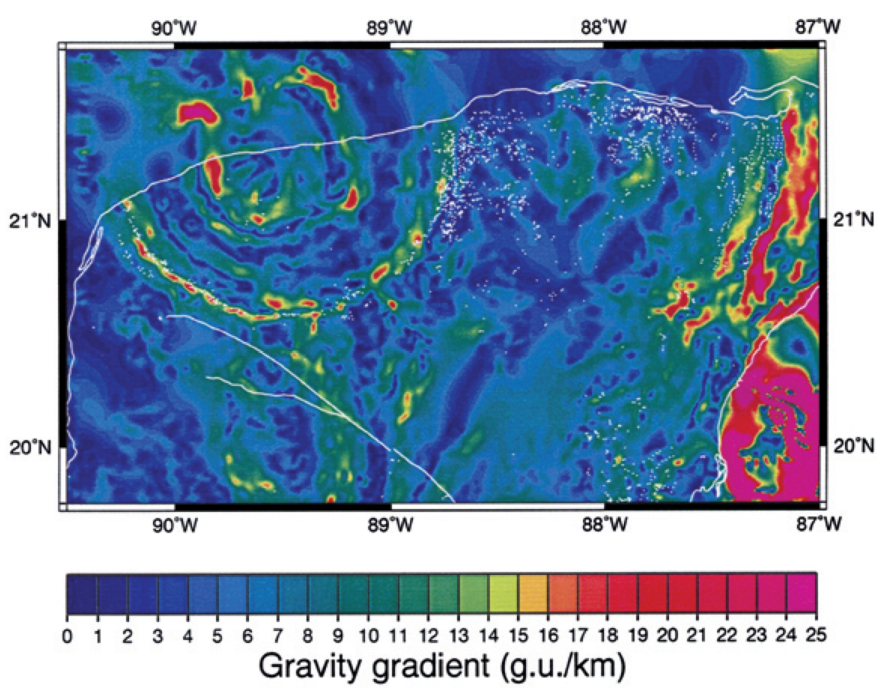

Figure 4. Horizontal gravity gradient calculated for the Bouguer gravity anomalies over the Chicxulub crater (taken from Connors *et al*., 1996). The white dots represent location of the cenotes. Observe the correlation of the cenote ring with the gravity gradient anomaly.

their association with crater structures beneath the Paleogene sedimentary cover. The inverse dipolar anomalies in the central zone suggest sources with reverse polarity magnetizations. Subsequent analyses separated the magnetic anomaly field in three broad concentric patterns, associated to crater geometry and possible source bodies. Outside these concentric zones, magnetic field is characterized by low-frequency low-amplitude anomalies probably caused by basement magnetization and/or topography variations, with NW-SE regional trends corresponding to fracture zones (Pilkington *et al*., 1994; Ortíz-Aleman *et al*., 2001). Center of concentric magnetic anomaly pattern roughly coincides with the gravity anomaly and sinkhole ring semicircular distributions (Pilkington *et al*., 1994; Hildebrand *et al*., 1998).

Although high contrasts in physical properties likely characterize the carbonates, melt, impact breccias and basement, construction of high-resolution models and use of forward and inverse methods have been limited by lack of data on physical properties. For modeling and interpretation of magnetic anomalies, limited susceptibility and remanent magnetization measurements and magnetic models suggest magnetic contrasts up to 3-4 orders of magnitude with respect to carbonates and evaporites (Hildebrand *et al*., 1991; Urrutia-Fucugauchi *et al*., 1994, 2004b). Magnetic modeling suggests that melt, breccias and central uplift are major contributors. Following Pilkington *et al*. (1994) and Pilkington and Hildebrand (2000), the isolated dipolar anomalies with large amplitudes (>100 nT) and short-wavelengths from the intermediate zone associated with reverse polarity magnetizations are related to glass-rich breccias and melt rocks. Central uplift characterized by a large high-amplitude (>500 nT) inverse dipolar anomaly has been associated to the melt, melt-rich breccias and basement (Ortiz-Aleman and Urrutia-Fucugauchi, 2010).

Interpretation of gravity and magnetic anomalies that initially drew attention to the crater was based on 2-D models. As already mentioned, studies reported structural models with contrasting geometries and crater size estimates; models predicted different geometry and morphologies for the central uplift (Figure 6). Efforts were made to develop models based on electromagnetic soundings, borehole information and seismic reflection profiles (Camargo-Zanoguera and Suárez, 1994; Urrutia-Fucugauchi *et al*., 1996; Morgan *et al*., 1997; Campos-Enríquez *et al*., 1997, 2004; Delgado-Rodríguez *et al*., 2001; Unsworth *et al*., 2002). Camargo-Zanoguera and Suárez (1994) studied the crater structure using long marine seismic profiles roughly oriented E-W along the coast. Their study permitted to image the carbonate sedimentary basin and the impactite sequence formed by breccias and melt, and the structural arrangement of the ring fractures defining the

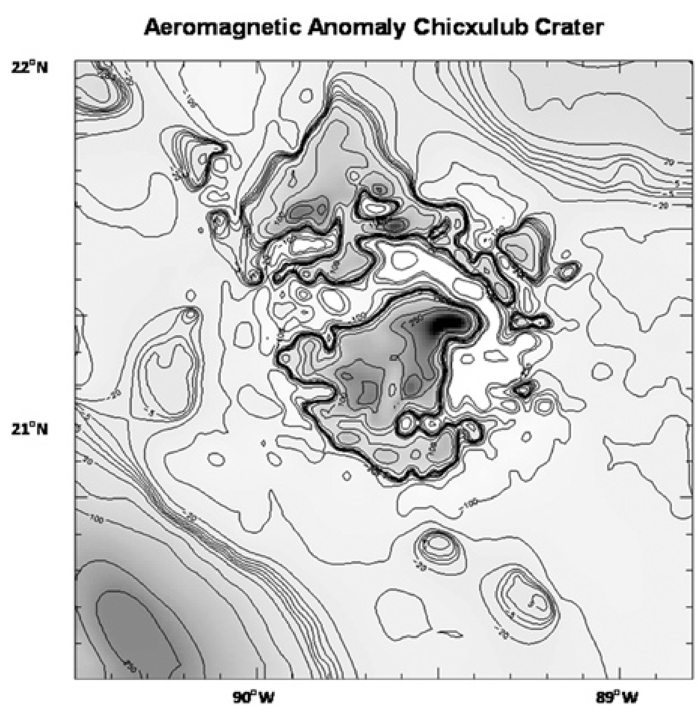

Figure 5. Contour map of the aeromagnetic anomaly field over Chicxulub impact crater, in the northwestern sector of the Yucatan peninsula. Aeromagnetic data come from the PEMEX oil exploration surveys in the Yucatan peninsula and southern Gulf of Mexico. Survey flight elevation over sea level is 500 m. Contour curves are given in nT. Observe the high-amplitude anomalies over the central sector of the Chicxulub crater (Ortiz-Aleman and Urrutia-Fucugauchi, 2010).

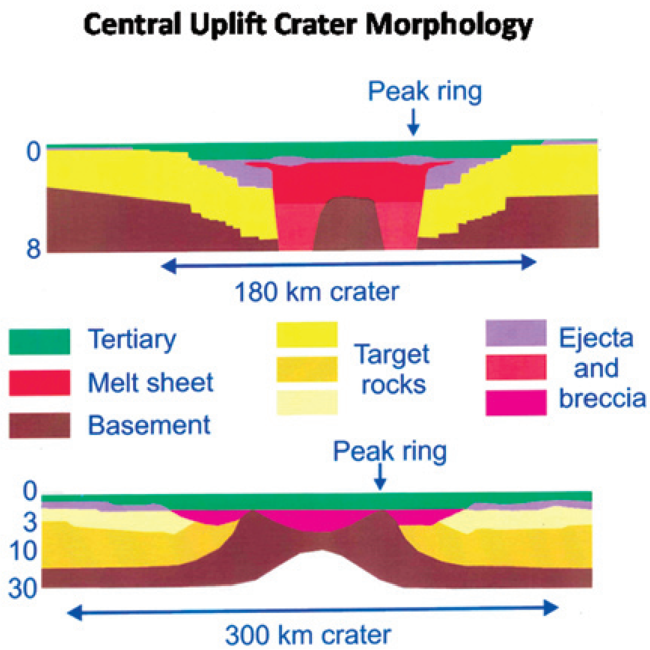

Figure 6. Schematic models of Chicxulub crater showing proposed configurations for the central uplift and deep crater structure. Model above is taken from Hildebrand *et al*. (1998) and model below is taken from Sharpton *et al*. (1993).

crater. Two marine seismic surveys (1996 and 2005 vintages) were conducted to investigate the morphology and extension of the crater. The 1996 survey, under sponsorship of the International Scientific Drilling Program, was acquired by Geco Sigma. It consists of 4 multichannel streamer lines oriented radial to the crater center. During the 2005 seismic campaign, a total of 29 additional multichannel seismic reflection profiles were acquired in various orientations. Figure 7 shows the line diagrams for the regional Chicx-A and Chicx-A1 profiles. The deformation due to the impact and excavation of transient cavity involved almost the entire crust (Morgan and Warner, 1999). The seismic profiles across the crater document deep faulting and deformation of the crust-mantle boundary, with ~35 dipping strong seismic reflectors in the intermediate and lower crust (Figure 7). The seismic data define the location of the crater rim, peak ring and outer exterior ring. The crater and peak rings may be associated with transient cavity collapse and central uplift deformation with overthrusting and overriding the terrace zone (Morgan and Warner, 1999). The processed seismic lines have been used to interpret morphologic features of the crater and its vicinities. Early interpretation work (Morgan *et al*., 1997, 2000; Snyder and Hobbs, 1999) realized the presence of normal faulting surrounding the crater impact center and the central uplift. The structure consists of tilted blocks separated by normal faulting and deformed pre-impact rocks (Mesozoic and pre-Mesozoic). Besides these structural features, the

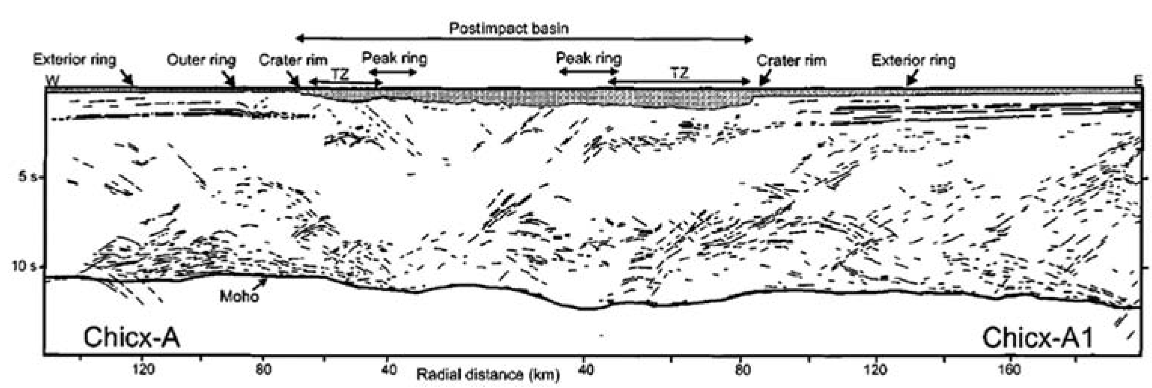

Figure 7. Chicxulub deep structure derived from composite line drawing of unmigrated seismic reflection profiles Chicx-A and Chicx-A1 (taken from Morgan and Warner, 1999).

authors identify: an outer ring at about 100 km from the crater center, a zone of terraces or tilted blocks, and a central basin filled with post-impact sediments underlain by the inner ring or peak ring at about 40 km from the crater center.

More recently, marine seismic surveys provided images of the sedimentary carbonate cover and structure of the Chicxulub crater (Morgan *et al*., 2000, 2005; Gulick *et al*., 2008). Seismic profiles delineated the terrace zone, providing evidence for a peak-ring morphology (Morgan *et al*., 1997; Snyder and Hobbs, 1999). Vermeesch and Morgan (2004) studied the central uplift shape from seismic and gravity models, investigating the central uplift with increasing depth. 3-D velocity tomography indicates that central uplift thins at depth (Morgan *et al*., 2002). Analyses of seismic profiles have also addressed the mapping of terrace zone blocks and faults and characterization of impact breccias and melt units (Vermeesch and Morgan, 2004; Gulick *et al*., 2008; Salguero *et al*., 2010; Canales, 2010). However, structure of central uplift and inner ring beneath the Paleogene sedimentary cover requires further analyses. Based on seismic interpretation and other evidences from wells, four stages of fracturing/faulting are proposed: first stage occurred at the moment of the impact forming a transit cavity; second stage occurred when the central uplift and the ejecta layer collapsed, during this stage the peak ring structure was formed. In the third stage the zone of terraces was developed; and finally, in the fourth stage subsidence and minor faulting occurred due to differential compaction.

Drilling programs

Drilling has provided information on the subsurface stratigraphy and structure and material for laboratory measurements of physical properties, shock features, impact-generated lithologies, bolide and deep basement components. Drilling programs have been conducted as part of the PEMEX oil exploration surveys (Figure 8a), the UNAM Chicxulub Program (Figure 8b), the Chicxulub Scientific Drilling Project (CSDP) (Figure 8c), and Federal Commission of Electricity exploration program (Figure 8d).

As part of the oil exploration surveys in the peninsula, PEMEX developed and carried out a drilling program starting in 1952 with the drilling of the Chicxulub-1 borehole and eventually comprising nine boreholes in the area. The PEMEX drilling program investigated the stratigraphy of the Mesozoic and Cenozoic sequences and documented the occurrence of igneous textured rocks in the area of the concentric gravity and magnetic anomalies. The paleontological and stratigraphic analyses permitted reconstruction of the subsurface sedimentary sequence and an explanation for the geophysical data in terms of a buried igneous center of probable Late Cretaceous age (López Ramos, 1975). PEMEX drilling program incorporated geophysical logging and intermittent core recovery; remaining core samples are stored in the Core Repository of Ciudad Pemex where they were recently examined (Urrutia-Fucugauchi and Pérez-Cruz, 2007). The boreholes drilled a sequence of Mesozoic and Cenozoic carbonate platform sediments with variable thickness (Figure 9). Boreholes Chicxulub-1 (1581 m total depth, t.d.), Sacapuc-1 (1530 m t.d.) and Yucatan-6 (1645 m t.d.) drilled into a unit of igneous-textured rocks corresponding to the melt and breccias sequence at depths about 1.0-1.1 km. Drilling ended into the melt unit, which presents a minimum thickness of about 250 m. The breccias section is about 250-400 m thick in these boreholes. The breccias section was also cut in boreholes outside the basin at increasing distance away from the crater center in boreholes Ticul-1 (3175 m t.d.), Yucatan-2 (3488 m t.d.), Yucatan-5A (3003 m t.d.), Yucatan-1 (3226 m t.d.) and Yucatan-4 (2425 m t.d.). The breccia sequence drilled in boreholes outside the basin present considerable thickness up to 400 to 600 m. The Cretaceous sections formed by sequences of limestones, marls and dolomites, including thick sections of evaporites and anhydrites, show variable thickness up to 2.0-2.5 km in the deepest boreholes. The Paleozoic crystalline basement is drilled in boreholes Yucatan-1 and Yucatan-4 (Figure 9).

The UNAM drilling program incorporated continuous coring in eight boreholes distributed within and immediately outside the crater rim, with three boreholes cutting the carbonate-impact breccia contact (Urrutia-Fucugauchi *et al*., 1996; Rebolledo-Vieyra *et al*., 2000). The boreholes sampled the Paleogene carbonates and impact breccias, with the carbonate-impact breccia contact lying at varying depths between 222 and 332 m (Figure 10). Impact breccias are characterized by carbonate, melt and crystalline basement clasts supported in a carbonate-rich or melt-rich matrix. Two breccia units, comparable to the suevitic and Bunte breccias in the Ries crater, have been cored in Chicxulub, where upper breccias are rich in carbonate clasts and lower breccias are rich in melt and basement clasts. Upper breccias have high magnetic susceptibilities, low seismic velocities, low density and high porosities and permeabilities. Lower breccias in contrast show low susceptibilities, variable high seismic velocities and lower porosity and permeability (Urrutia-Fucugauchi *et al*., 1996).

The stratigraphy in the boreholes drilled in the UNAM program has been analyzed in several studies, including characterization of

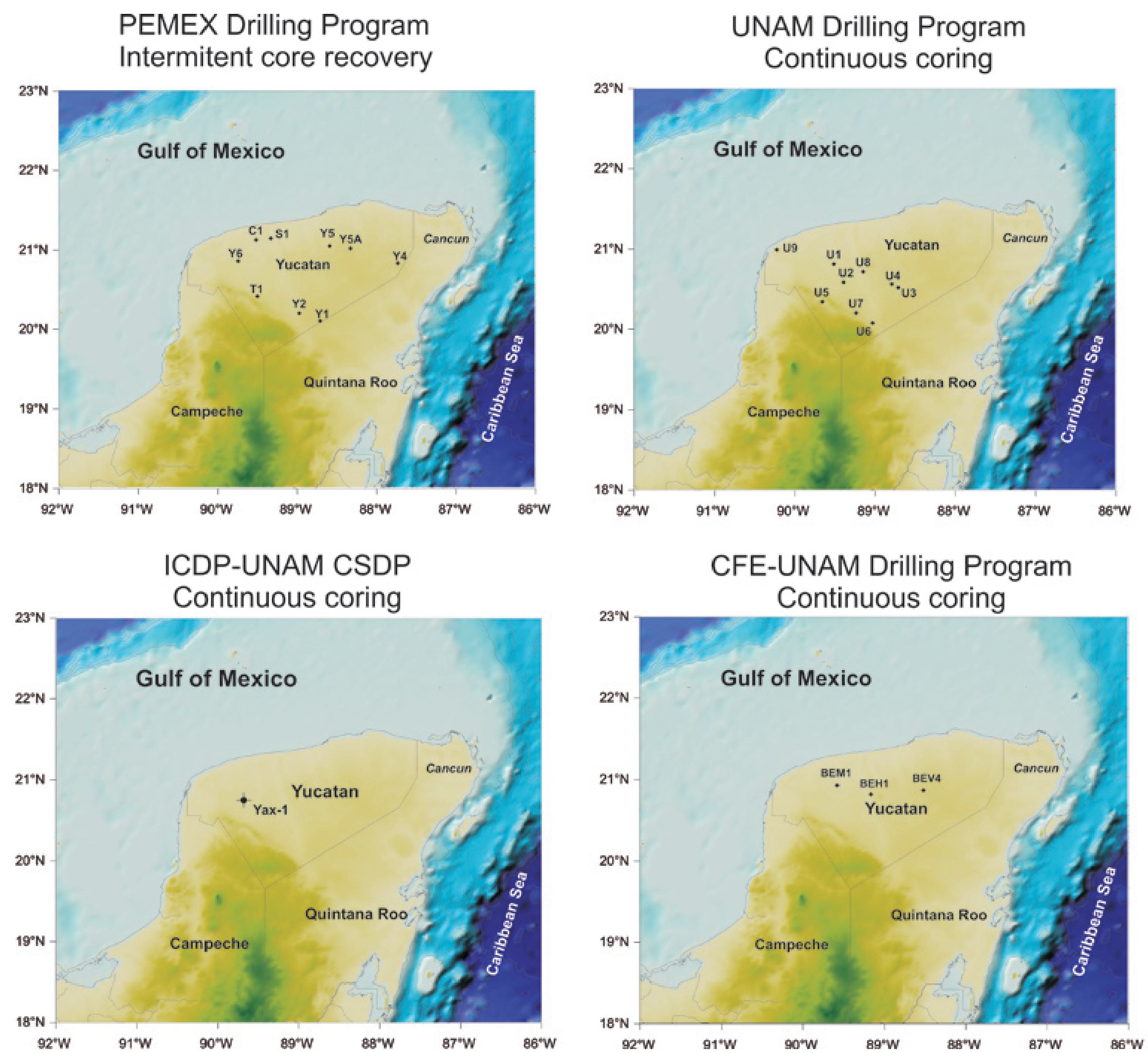

Figure 8. Location of drilling sites in the northern Yucatan peninsula. (a) PEMEX drilling program. (b) UNAM drilling program. (c) CSDP program. (d) UNAM-CFE drilling program.

the basal Paleogene sediments and breccia sections (Urrutia-Fucugauchi *et al*., 1996; Rebolledo-Vieyra *et al*., 2000). High-resolution stratigraphic studies using magnetic polarity have been completed for the Santa Elena, Peto and Tekax boreholes, and magnetostratigraphy and stable isotope analyses have been reported for the Santa Elena borehole. The impact breccias section has been characterized using geochemical and petrographic observations. The Santa Elena borehole is located ~110 km radial distance from the crater center, with site coordinates of 89.6615º W, 20.3385º N. Contact of impact breccias and Paleogene carbonates lie at ~332 m; suevitic breccias present a thickness greater than 146 m. The basal carbonates up to 30 m above the impact breccias contact are characterized by white-creamy limestones, with several thin clay layers and variable content of clay lenses. Clay contents and spherical evaporitic minerals increase within the middle section. The basal section up to 329.8 m depth is composed of gray carbonates with thin calcite lenses and dark gray lenses of apparent melted textures. This is followed by 3 m of light gray limestones <15% porosity, higher contents of clay minerals, and absence of evaporites and micro-veins. Between 325 and 315 m, the section is characterized by several clay layers and abundance of spheroidal evaporitic aggregates. Limestones show color changes, with darker tones and reduced porosity < 10 % and some micro-veins. Between 315 and 311 m, sediments show larger proportion of clay and evaporitic minerals, with numerous clay layers. Between 303 and 311 m, carbonates are formed by ~ 15 % porosity white-creamy limestones with micro-veins.

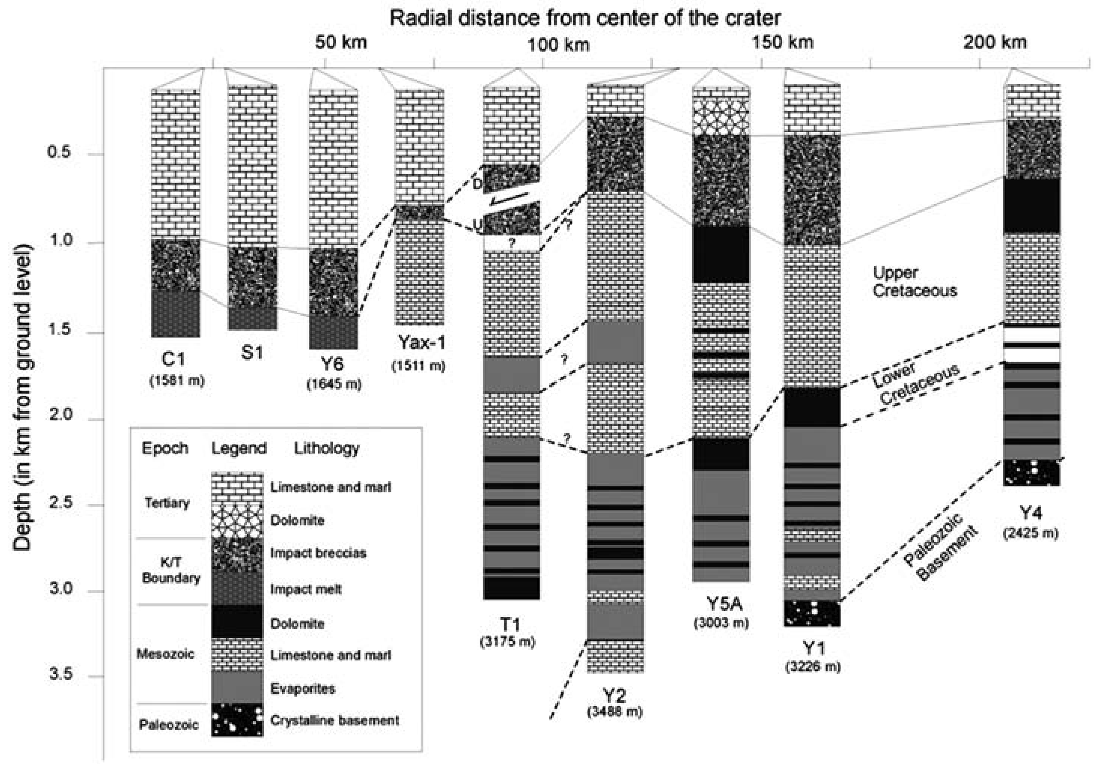

Figure 9. Schematic columns for the PEMEX boreholes, showing the main lithological divisions. The column for the Yaxcopoil-1 borehole is included (modified from López Ramos, 1975; Ward *et al*., 1995; Rebolledo-Vieyra and Urrutia-Fucugauchi, 2004).

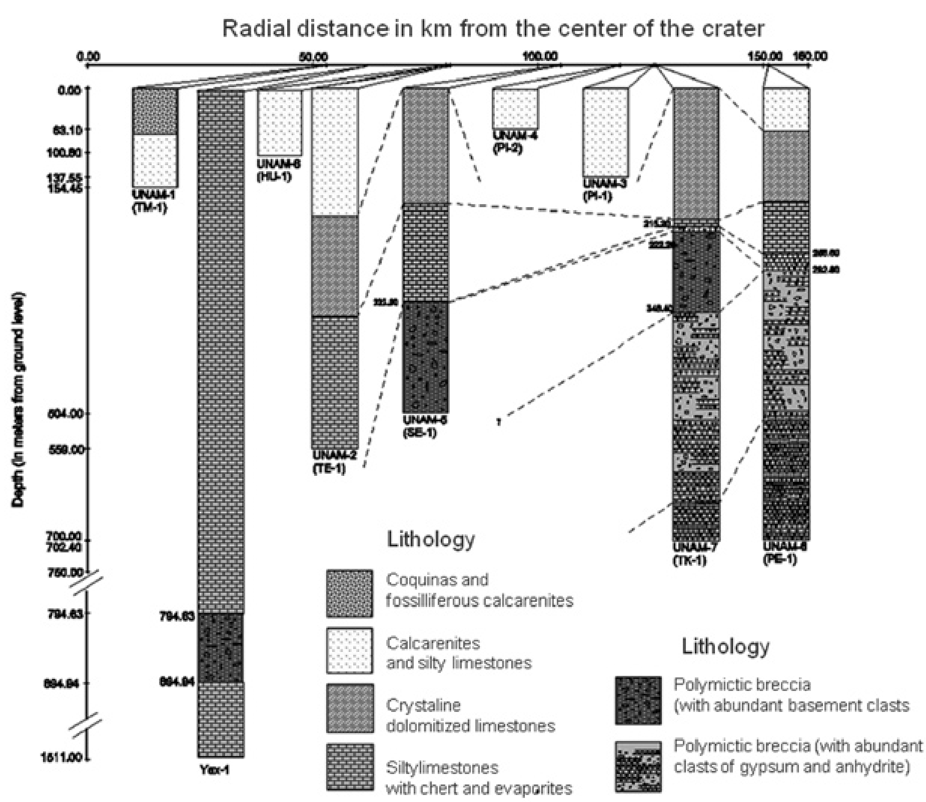

Figure 10. Schematic columns for the UNAM boreholes, showing the main lithological divisions. The column for the Yaxcopoil-1 borehole is included (modified from Rebolledo-Vieyra and Urrutia-Fucugauchi, 2004; Urrutia-Fucugauchi *et al.*, 2004).

The Yaxcopoil-1 borehole, drilled as part of the CSDP international project, investigated the stratigraphy and crater structure in the southern sector in the terrace zone (Urrutia-Fucugauchi *et al*., 2004a). Yaxcopoil-1 is located at about ~62 km away from the crater center. Continuous coring recovered cores from 404 m down to 1511 m of Paleogene sediments (~400 m), impactites (~100 m) and Cretaceous carbonates (>1000 m). Logging was carried out in two stages, from surface to 404 m before the start of the coring program and after completion at 1511 m. Data taken included measurements of hole deviation and azimuth, magnetic susceptibility, radioactive elements, electrical resistivity, acoustic velocity and borehole wall images. The 100 m thick impactite sequence is formed by six distinct units, which record variable conditions of emplacement and post-impact hydrothermal alteration (Figure 11). The Cretaceous section likely represents large displaced carbonate blocks of the megabreccia unit. In the upper part below about 895 m dikes of polymictic breccias are present. Anhydrite layers, with variable thickness from a few centimeters up to 15 m thick are included in the megablocks. Core box images of representative sections in the Paleogene carbonates, impactite sequence and Cretaceous target carbonates are illustrated in Figure 12.

The central-eastern sector of the crater extending from Merida to Valladolid has been investigated in the UNAM drilling program and recently as part of the CFE-UNAM program (Figure 8b, d). This latter program includes three boreholes drilled with continuous core recovery system, which allows investigation of the stratigraphy in this zone (Urrutia-Fucugauchi *et al*., 2008). The UNAM drilling program comprises eight boreholes drilled in the central and southern sectors of the crater. Carbonate dissolution features including large underground caves limited drilling operations. The borehole BEV-4 in the Valladolid sector, ~120 km radial distance from the crater center cored a ~34 m thick section of breccias at about 250 m deep, which is part of the proximal ejecta blanket deposits. Breccia sections were not reached inside the crater.

Chicxulub ejecta blanket may extend continuously in the peninsula region up to the Albion Island and other sites in Belize and Chetumal areas. Proximal ejecta deposits around the crater have been recovered in three boreholes in UNAM drilling program, located between 110 km and 150 km away from crater center. Ejecta outcrops found along the Rio Hondo of Belize and Quintana Roo have been interpreted as gravity

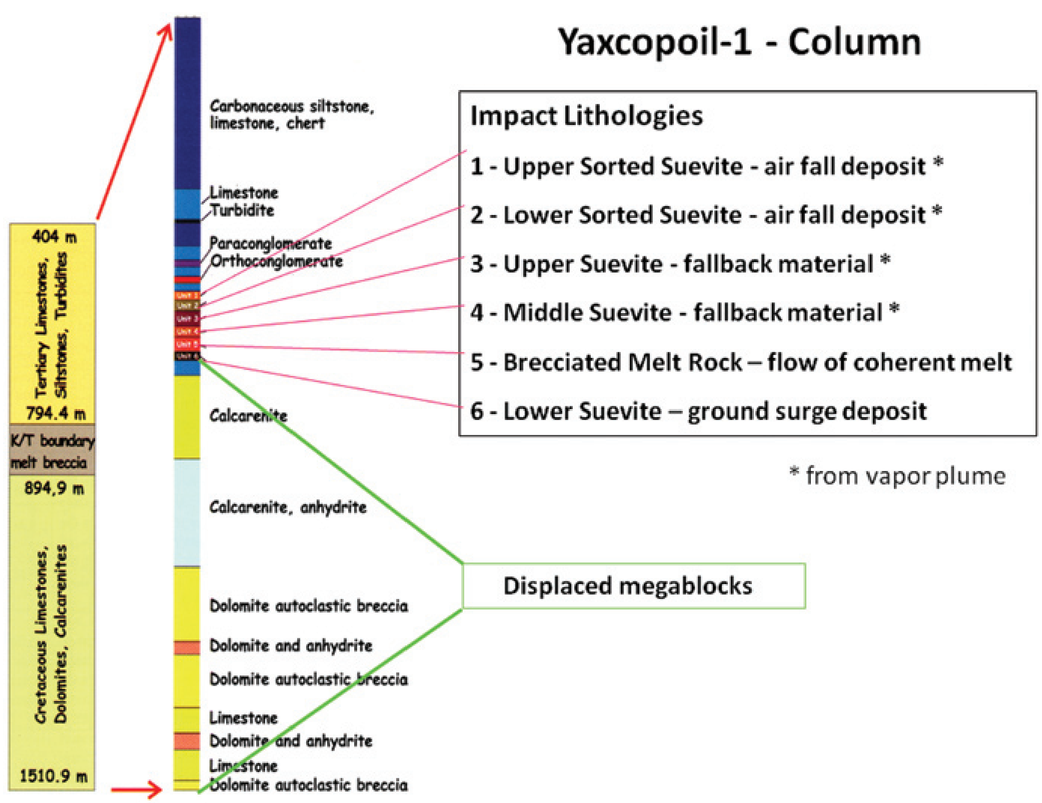

Figure 11. Schematic column for the Yaxcopoil-1 borehole, showing the main lithological divisions. The impactite sequence is ~100 m thick and is formed by six distinct breccia units (Stoeffler *et al*., 2004; Kring *et al*., 2004).

Figure 12. Yaxcopoil-1 core box images of representative sections in the Paleogene carbonates, impactite sequence and Cretaceous target carbonates.

or secondary flows. Outcrops located 360 km away from the crater center are grouped into the Albion Formation composed of 1 m thick clay and dolomite spheroid basal layer and a 15 m thick coarse diamictite bed. Pope *et al*. (2005) 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.

There are no surface outcrops of ejecta deposits and melt inside the crater and the adjacent area. Carbonate breccias in boreholes Yucatan-1 and Yucatan-2, about 135 km and 160 km from crater center, and in Yucatan-5A and Yucatan-4 ~138 km and ~205 km away in the eastern sector indicate a continuous ejecta blanket in the peninsula. Thickness of the carbonate-rich breccia in the Valladolid area is small compared to thickness 200-400 m in Yucatan-5A borehole 400-900 m and in UNAM boreholes of the southern sector. The thin Valladolid BEV-4 breccia section may suggest erosion, removing basement and melt-rich breccias and portions of lower carbonate breccias. Studies suggest that back surge of the sea into the crater resulted in re-working and erosion of the breccia deposits, possibly also affecting rim morphology. If rim stood above sea level, it may have been subjected to erosion and slope collapses. Conditions after cratering and ejecta emplacement and re-establishment of carbonate sedimentation have been poorly constrained. Occurrence of erosive processes is indicated by presence of thinner units in Peto borehole with re-worked basement and melt-rich breccias in Valladolid BEV-4 borehole, and re-worked breccias upper unit in Yaxcopoil-1.

The proximal ejecta sequence has been documented in nearby areas in the Gulf of Mexico, in outcrops (Guayal, Tabasco and Bochil, Chiapas) and on samples from Pemex exploratory wells in the Cantarell oil field. Grajales-Nishimura *et al*. (2000), based on detailed biostratigraphic, sedimentologic and diagenetic studies of outcrop and well samples, found that the clastic carbonate sequence overlies Middle-Late Maastrichtian hemipelagic limestones and underlies Lower Danian marls and shaly limestones. An outer platform, deepwater depositional environment is interpreted for the sequence in the Cantarell wells.

Deposits of proximal ejecta or continuous ejecta blanket from large impact craters are relatively rare. Other possible analogue is the Sudbury Onaping Formation, which has been compared to the diamictite unit from the Albion Formation, representing the outer portion of a continuous ejecta blanket. The Chicxulub ejecta blanket was emplaced following deposition of ballistic deposits of the basal spheroid bed. Ries Bunte breccias and Chicxulub carbonate breccias, drilled close to the rim may represent proximal ejecta deposits emplaced in the early stages of cratering from surface lateral ejecta curtains and ejecta cloud collapse prior to emplacement of suevitic basement and melt-rich breccias.

Petrography and Geochemistry

One of the initial tasks for investigation was the evaluation of an impact origin for the structure. This involved identification of mineralogical indicators of shock metamorphism and occurrence of impact breccias and melt forming an impactite sequence. Early evaluation of an impact origin for the Chicxulub structure as mentioned before was made on core samples from the PEMEX boreholes Chicxulub-1, Sacapuc-1 and Yucatan-6, which provided critical evidence for shock deformation and planar elements on quartz grains. Analyses also confirmed occurrence of polymictic breccias with melt and basement clasts (Hildebrand *et al*., 1991).

Breccia and melt from Yucatan-6 well, core sections N13, N14, N16, N17 and N19, and from the Chicxulub-1 well, core section N10 have been analyzed. Yucatan-6 N9, N13, N14, N16, N17 and N19 came from: 700-703 m, 1,100-1,103, 1,208-1,211 m, 1,295.5-1,299 m, and 1,393-1,394 m, respectively. Chicxulub-1 N10 melt samples come from interval 1,393-1,394 m and show fine-to-medium grained coherent microcrystalline groundmass of augite, alkali feldspar, plaglioclase feldspar and interstitial cryptocrystalline phases of magnetite, apatite and ulvospinel. Breccias contain fine-grained altered melt clasts dispersed in a medium-to-coarse grained matrix of pyroxene and feldspar with little or no macroscopic alteration. Clasts contain 0.2 to 0.1 cm fragments of basement silicate material with variable degrees of digestion. Melt and breccias in Yucatan-6 extend from about 1,100 m to more than 1,400 m; sequence is well-sorted with an apparent gradation. Sharpton *et al*. (1992) reported analyses of quartz and feldspar grains, which showed one or more sets of planar deformation features with distinct crystallographic orientations, characteristic of shock-induced lamellae deformation. Breccia samples analyzed indicate mixtures of target materials affected by different shock pressures, suggesting different relative distance of impact zonation. They also reported observations on shock mosaicism and diaplectic glasses. Samples from Chicxulub-1 N10 and Yucatan-6 N19 were analyzed for iridium contents. Iridium abundances were relatively high with variable contents, suggesting a heterogeneous distribution within the melt, which might be related to non-uniform mixing of bolide material, fractionation during extended melt cooling and crystallization and post-impact hydrous or hydrothermal alteration. These processes are also evidenced in the radiometric dating and magnetic mineralogy studies. Samples of melt clasts, glasses, melt rocks and melt matrix separates were analyzed for major oxides. Bulk compositions are similar to those determined in Haitian tektites (Sharpton *et al*., 1992; Sigurdsson *et al*., 1991; Izett *et al*., 1990).

The impact breccias and melt have been further investigated on samples recovered in the UNAM and CSDP drilling programs. The impact breccias and melt have been characterized based on geochemical analyses of major and trace elements, scanning and transmission electron microscopy and measurements of physical properties. Studies have also included analyses of platinum group elements and isotope studies, directed to investigate emplacement processes, hydrothermal alteration and the nature of the bolide (e.g., Kring *et al*., 2004; Zurcher and Kring, 2004; Gelinas *et al*., 2004; Stoeffler *et al*., 2004; Escobar-Sánchez and Urrutia-Fucugauchi, 2010).

The impactite sequence in the Yaxcopoil-1 borehole was cored from about 795 m to 895 m (Figure 11). The section is formed by six distinct units (Stoeffler *et al*., 2004; Kring *et al*., 2004), which have been named, from top to bottom, as: (1) USS Upper Sorted Suevite (794-808 m), (2) LSS Lower Sorted Suevite (808-823 m), (3) US Upper Suevite (823-846 m), (4) MS Middle Suevite ((846-861 m), (5) BMR Brecciated Impact Melt Rock (861-885 m), and (6) LS Lower Suevite (885-895 m). Core images obtained with the CSDP Core Scan system of sections of the breccias, illustrating the different textures and composition are given in Figure 13. Paleomagnetic measurements have been completed on samples cut and drilled from the breccia units. Results indicate that breccias carry remanent magnetizations acquired at the time of emplacement, but were affected to distinct degrees by hydrothermal post-impact alteration (Urrutia-Fucugauchi *et al*., 2004b). Study of emplacement mode in the breccias units has been used to reconstruct the ejecta plume and collapse processes during cratering (Wittmann *et al*., 2007; Velasco-Villareal *et al*., 2010).

Stratigraphy and impact age

Stratigraphic analyses of exploratory boreholes in northwestern Yucatan peninsula documented the age of the igneous-textured rock unit, corresponding to the breccias and melt rocks, found in boreholes Chicxulub-1, Sacapuc-1 and Yucatan-6 as Late Cretaceous (López Ramos, 1975). The interpretation assigned a Late Cretaceous age for the 60 to 170 m of limestones and marls on top of the impactites, which was supported by correlation of resistivity logs between the Yucatan-6 and Yucatan-1 boreholes. Hildebrand *et al*. (1991) in their report re-analyzed the borehole stratigraphy and proposed an age coinciding with the K/Pg boundary. The boundary age correlation was challenged, based on stratigraphic and log correlation analyses (Meyerhoff *et al*., 1994; Ward *et al*., 1995).

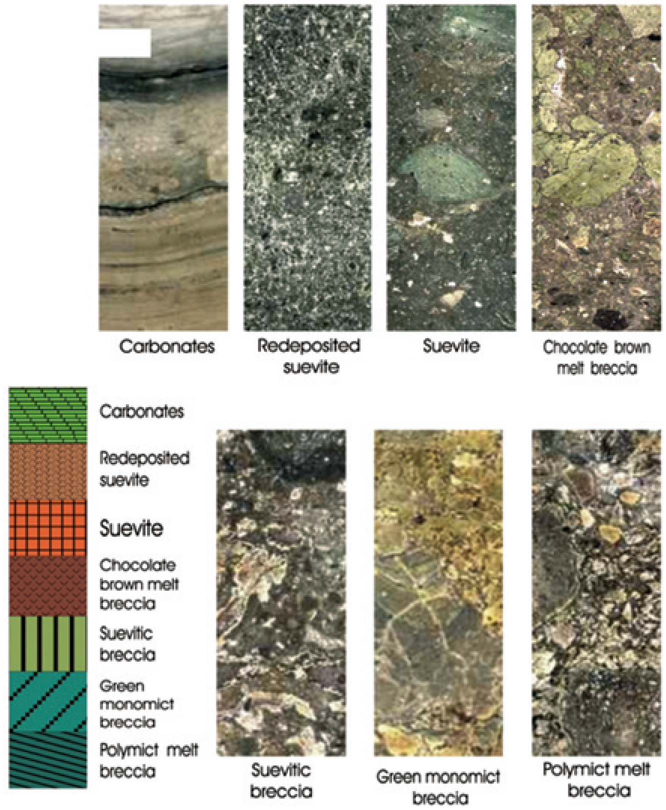

Figure 13. Breccia sequence in Yaxcopoil-1 borehole. Core images obtained with the CSDP Core Scan system of sections of the breccias, illustrating the different textures and composition.

Samples from the melt unit in boreholes Chicxulub-1 (N10 interval, depth 1393-1394 m) and Yucatan-6 (N19 interval, depth 1377-1379 m) were dated using the Ar/Ar incremental heating method. Sharpton *et al*. (1992) reported an age of ~65.2 ± 0.4 Ma for the Chicxulub-1 melt, confirming the K/Pg boundary assignment. Swisher *et al*. (1992) reported an age of 64.98 ± 0.05 Ma, and also provided ages for the K/Pg layer in El Mimbral sedimentary section of 65.07 ± 0.10 Ma. These ages correlate well with those reported for Haitian tektites of 64.05 ± 0.1 Ma (Izett *et al*., 1990), further supporting the correlation to the K/Pg boundary ejecta layer. The Ar/Ar dates have been re-analyzed and additional constraints on the K/Pg boundary age have been reported by Kuiper *et al*. (2008). They have proposed a revised age for the boundary of about ~65.5 ma. Paleomagnetic studies of samples from the melt and breccias in Yucatan-6 (interval N17, depth 1295.5 to 1299 m) documented a reverse polarity magnetization, which was correlated to reverse polarity chron C29r that encompasses the K/Pg boundary (Urrutia-Fucugauchi *et al*., 1994). The characteristic remanence inclination of -43º gives a paleolatitude in the southern Gulf of Mexico, in agreement with Late Cretaceous paleoreconstructions for the Yucatan Block.

The stratigraphy was revisited by Marin *et al*. (2001) who studied samples from the limestone interval N12 (depth 1000-1003 m) of Yucatan-6 borehole. The N12 and N13 (depth 1200-1203 m) intervals both lie within the Upper Cretaceous carbonate section interpreted in the Pemex reports and used to question the K/Pg age for Chicxulub. Study of the planktic foraminifera assemblage in the N12 interval identified species from the genera *Globigerina* and *Globorotalia*, with *Globorotalia pseudobulloides*, *Globorotalia trinidadenses* (or *Globorotalia uncinata*) and *Globorotalia triloculinoides*. The stratigraphic ranges for these species cover from the Lower Danian to most of the Lower Thanetian (represented by *G. trinidadenses*). Marin *et al*. (2001) assign a depositional interval from the Middle to the Lower Danian and base of Lower Thanetian, represented by zones P1 through middle P2 or lower P2 through lower P3, within the Lower to Middle Paleocene.

Magnetic polarity stratigraphic studies have been completed in several boreholes, which provide additional constraints for the age of the impactite sequence and basal Paleogene carbonates. Rebolledo-Vieyra and Urrutia-Fucugauchi (2004) reported data for the upper most section of the impact breccias and cover carbonates comprising about 1 m thick section between about 793.75 m and 794.75 m. The section with the re-worked suevites and dolomitic limestones is characterized by two polarity zones with reverse polarity in the breccias and basal finely laminated dolomitic limestones up to ~794.03-794.07 m and normal polarity in the rest of the section. The magnetic polarity zones are correlated with chrons C29r and C29n, respectively, with the polarity change at ~794.03-794.07 m. Arz *et al*. (2004) reported biostratigraphic data for the carbonate section and identified the K/Pg boundary at ~794.11 m within the reverse polarity chron. The carbonates above the impact breccias and below the K/Pg boundary show cross-bedding structures and interbedded greenish fine sandy layers of re-worked breccias. Above the K/Pg boundary, the sequence is composed by laminated dolomitic limestones. Magnetic polarity studies have also been completed for the Santa Elena, Peto and Tekax boreholes. The study documents that the breccias carry a reverse polarity, which correlates with chron C29r. The carbonates above the contact with the impact breccias present reverse polarity in the Peto borehole and normal polarity in the Santa Elena and Tekax boreholes, which suggest a hiatus at the base of the Danian section (Rebolledo-Vieyra and Urrutia-Fucugauchi, 2006). The study documents a sequence of normal and reverse polarities in the basal carbonate section, which has been correlated to chrons C29r to C27n (Figure 14). Stable isotope studies have been carried out in the basal carbonate section in the Santa Elena borehole, which document characteristic trends in oxygen and carbon isotopes that correlate with the pattern observed in marine carbonates in the Paleocene (Figure 15) (Urrutia-Fucugauchi and Pérez-Cruz, 2008).

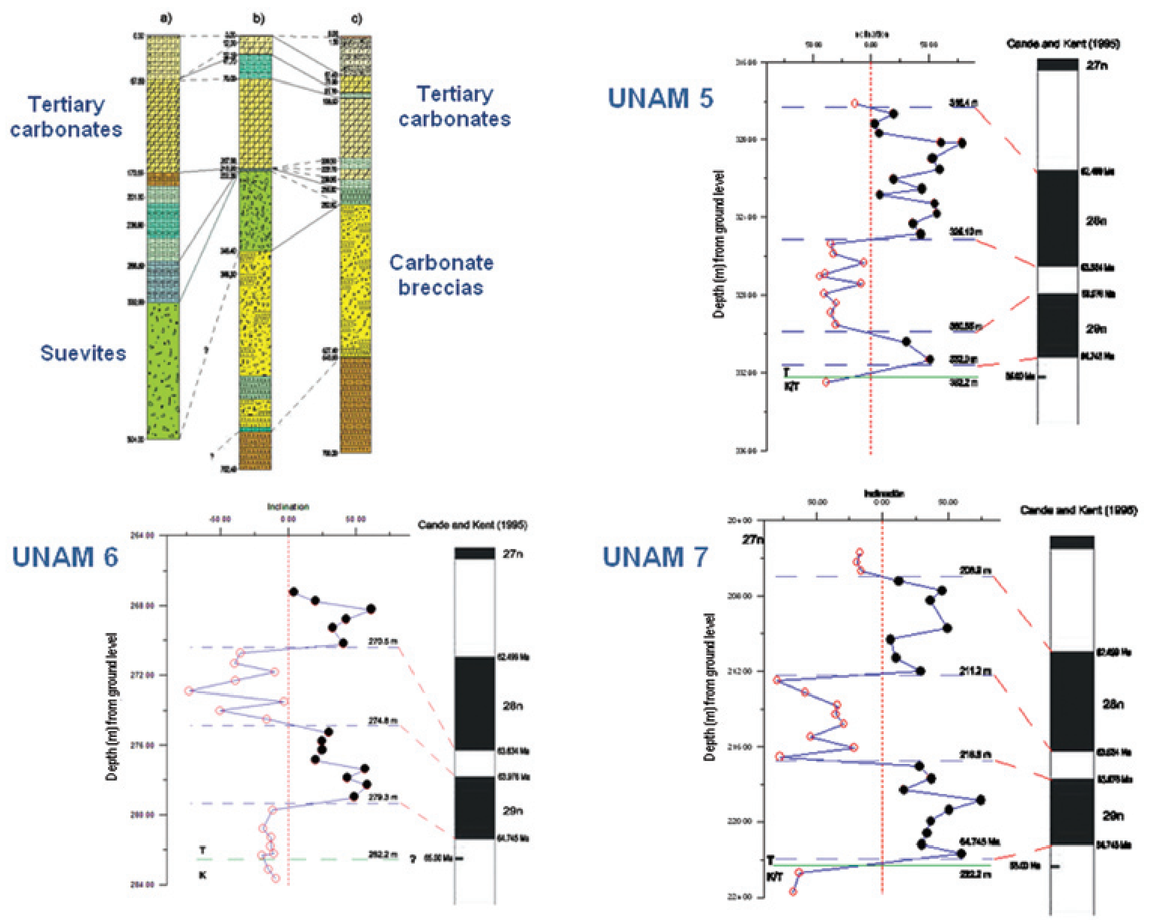

Figure 14. Magnetic polarity stratigraphy for the Santa Elena, Peto and Tekax boreholes. Impact breccias carry a reverse polarity, which correlates with chron C29r. Carbonates above the contact with the impact breccias present reverse polarity in the Peto borehole and normal polarity in the Santa Elena and Tekax boreholes (Rebolledo-Vieyra and Urrutia-Fucugauchi, 2006). Study documents a sequence of normal and reverse polarities in the basal carbonate section, correlating to chrons C29r to C27n.

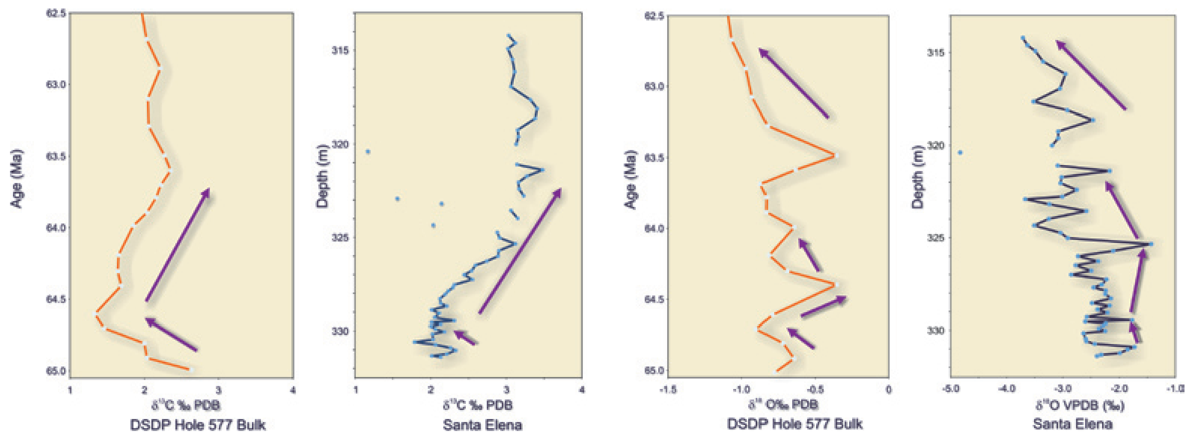

Figure 15. Stable oxygen and carbon isotope stratigraphy for the Santa Elena basal carbonate section. The stable isotope trends correlate with pattern observed in Paleocene marine carbonates (Urrutia-Fucugauchi and Perez-Cruz, 2008).

Age constraints for the Chicxulub impact have been provided from studies of proximal K/Pg boundary sections. For instance, Arenillas *et al*. (2007) reported biostratigraphic studies on the Bochil and Guayal sections in southern Mexico and correlated the clastic unit representing the boundary with the K/Pg ejecta layer and extinction level of marine microorganisms in El Kef and Caravaca sections. Their study documented the occurrence of the lowermost Danian PO biozone in the thin dark clay layer above the clastic unit, linking it to the K/Pg boundary clay in El Kef reference section.

Discussion

Geophysical surveys have allowed characterization and imaging of the crater structure. The crater is characterized by patterns of semi-circular concentric gravity and magnetic anomalies associated with the buried basin and high contrasts in physical properties between the platform carbonates and the impact-generated lithologies and central uplift. The gravity anomaly is characterized by a regional low corresponding to the large basin within the platform marked by concentric rings related to basin structure and a central high (Figures 2 and 4). The central gravity high likely arises from high density uplifted intermediate and lower crustal rocks forming the central uplift. The magnetic anomaly show a central zone roughly corresponding to the central gravity anomaly with high amplitude inversely polarized dipolar anomalies, which are surrounded by higher frequency low amplitude anomalies that extend over a large area some ~200 km in diameter (Figure 5). Data processing and modeling of the aeromagnetic anomalies using the reduction to the pole, analytical signal, first and second derivatives and upward and downward analytical continuations permit characterization of location and depth to sources, revealing the symmetric and asymmetric distributions at depth (Figure 16). The potential field anomalies permit characterization of crater structure and main crater elements such as deep broad basin, central peak ring, basement uplift, basin rim, fracture ring, impact breccias, melt, Paleogene carbonate infilling and Mesozoic target carbonate sequences (Rebolledo-Vieyra *et al*., 2010; Ortíz-Aleman and Urrutia-Fucugauchi, 2010). Models based on potential field data are however non-unique and distinct family models fit the observed data and solutions require additional constraints. This and other considerations on the anomaly data and modeling have resulted in contrasting models being proposed for crater structure, with a wide range of crater sizes, geometry, source bodies and morphology. Models based on surface geologic and geomorphologic observations such as faults, karstic features and cenote ring, similarly result in different geometries (e.g., Pope *et al*., 1993; Perry *et al*., 1995). Marine seismic reflection profiles have helped constraining crater morphology, demonstrating the peak-ring multi-ring nature of the crater, and constraining transient excavation cavity to about 100 km and crater diameter to about 195-200 km (Morgan *et al*., 1997; Gulick *et al*., 2008).

Asymmetries in the potential field anomaly pattern, particularly in the offshore sectors, have been used to infer impact angle and trajectory. The gravity anomalies have been interpreted in terms of a shallow oblique impact, with SW-NE or SE-NW trajectories (e.g., Hildebrand *et al*., 1998). Impact angle and trajectory are critical parameters in estimating energy released, ejecta distribution and environmental perturbations (e.g., Pierazzo and Melosh, 2000). A NW directed oblique impact has been related to environmental effects and distribution of ejecta and shock quartz

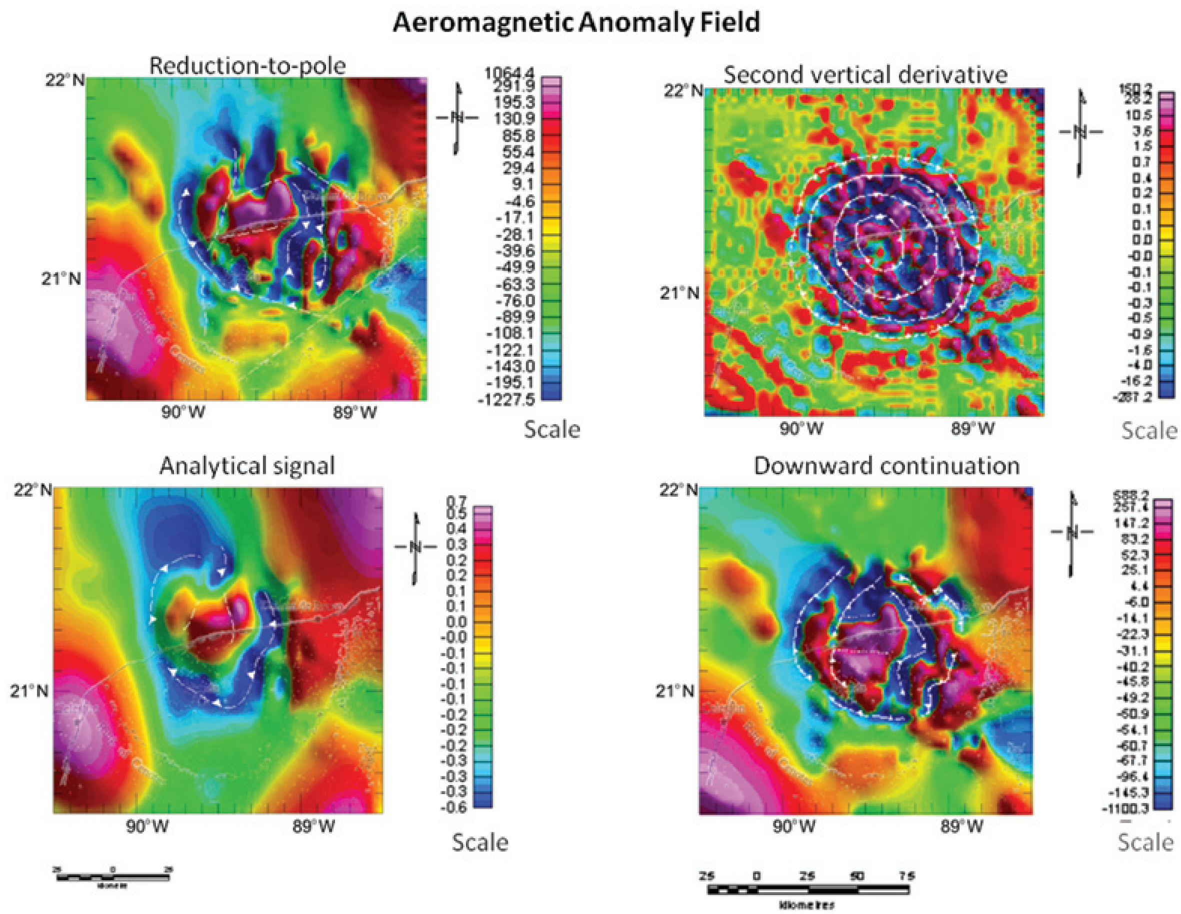

Figure 16. Aeromagnetic anomaly over the Chicxulub crater in the Yucatan platform (taken from Rebolledo-Vieyra *et al*., 2010). (a) Reduced to the pole aeromagnetic anomaly field. Local geomagnetic field inclination is 45º and declination is 5º. (b) Second derivative of the aeromagnetic anomaly field. (c) Analytical signal of aeromagnetic anomaly field. Density contrast is 1.8 g/cm3. (d) Downward analytical continuation to a reference surface of 450 m.

in interior North America sections (e.g., Claeys *et al*., 2002). Analyses of marine seismic reflection profiles document the extensional ring faults, terrace zone and peak ring, with down-dropped and up-thrust blocks and scale-wide asymmetries (Gulick *et al*., 2008; Collins *et al*., 2008). Profiles document significant variation in faulting and structure in the crater (Figure 17). For instance, ring and terrace faults change spacing, tilt and distribution with position around the crater. The peak ring lies some 400 m shallower in the western sector than in the eastern sector, with the main dipping reflector also being about 1 km greater in the west. Terrace zone is deeper in the west, with slump blocks 2 km deeper in the northwestern sector. Structural asymmetries in the central uplift, peak ring, melt sheet, breccias sequence, Cretaceous sediments and faulting are documented in the potential field models. Gulick *et al*. (2008) proposed that the crater asymmetries result from target pre-impact crustal structure. In particular, crustal structure and water depth along the Cretaceous platform varied, getting deeper in the northeastern sector with the base of Mesozoic sequence lying 3-3.5 km deep and water depth 1.5 km deeper. Magnetic models in Rebolledo-Vieyra *et al*. (2010) show an asymmetric structure in radial profiles (Figure 18), which supports inferences from the seismic models. The magnetic anomaly models show marked changes in the central uplift, which suggest that response of lower crust to the transient crater excavation was asymmetric, suggesting a complex process involving crustal heterogeneities and impact dynamics. Further constraints are being provided from computer modeling. For instance, models derived from hydrocode simulations provide constraints on cratering processes and crater structure, including formation of peak ring. Collins *et al*. (2008) used the iSALE hydrocode to simulate peak ring and terrace zone formation and investigate on target controls on cratering. Models assuming target sections with 3 km carbonate sediments and no water layer and

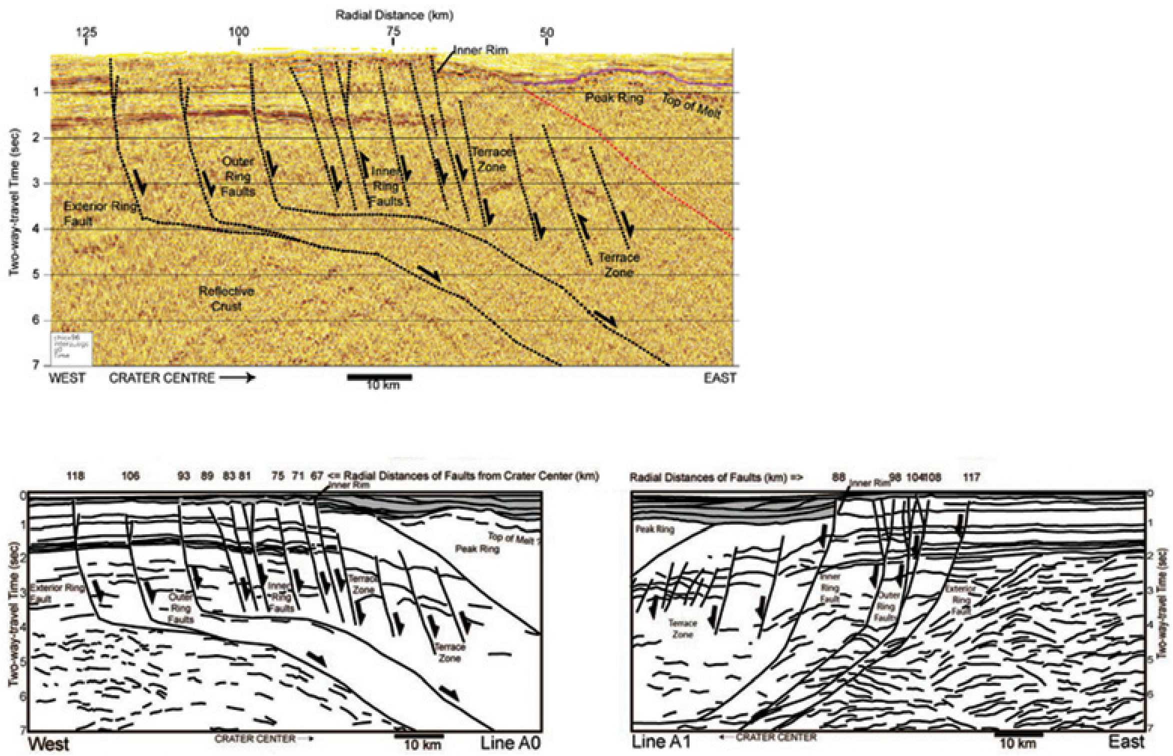

Figure 17. Structural analysis of Chicxulub crater showing location of faults in interpreted line drawings for lines Chicx-A and Chicx-A1 (taken from Gulick *et al*., 2008). Sections illustrate the asymmetric configuration in the crater. Figure above gives the seismic profile for line Chicx-A, with structural interpretation added.

sections with 4 km carbonate sediments and 2 km water layer resulted in different terrace zone geometries, indicating that target heterogeneities can influence crater structure. Model results are compatible with observations derived from the seismic reflection data.

A major contending issue in studies of Chicxulub crater has been the impact age and relation to the mass extinction and K/Pg boundary events. Following the initial stratigraphic, radiometric Ar/Ar dating and paleomagnetic studies, studies on multiple impacts and an age for Chicxulub earlier than the K/Pg boundary have been reported. Keller *et al*. (2004, 2009) based on studies of the impactites and Paleocene carbonates in the Yaxcopoil-1 borehole and proximal K/Pg sections in the Gulf of Mexico have argued that Chicxulub impact occurred ~300 ka earlier than the extinction levels of marine microorganisms. This interpretation has been challenged, with studies based on foraminiferal biostratigraphy and analyses of K/Pg sections concluding that the Chicxulub impact occurred at the K/Pg boundary (Arenillas *et al*., 2007; Schulte *et al*., 2010). The stratigraphy, sedimentary features and depositional mode for the critical section in the Yaxcopoil-1 borehole has been examined by different groups. Arz *et al*. (2004) analyzed the foraminiferal biostratigraphy of the carbonate deposits in southern Mexico and concluded that the section spanned the K/Pg boundary, with the Chicxulub impact occurring at the boundary and correlating with the extinction level. Rebolledo-Vieyra and Urrutia-Fucugauchi (2004) used paleomagnetic measurements to provide magnetostratigraphic constraints, documenting reverse polarity in the upper re-worked breccias and first centimeters of carbonate sediments and normal polarity in the upper carbonate sediments, with the polarity change being compatible with the K/Pg boundary horizon within the reverse polarity carbonate section.

Magnetostratigraphic studies of sections with the breccias-carbonate contact recovered in boreholes drilled in the southern crater sector also indicate that impact occurred at the K/Pg boundary (Rebolledo-Vieyra and Urrutia-Fucugauchi, 2006). A critical aspect in the studies is related to completeness of the sections and presence of hiatus. High-energy processes may have acted in crater area, including generation of tsunamis associated with re-surge and back-wash processes. Mass flows and tsunami deposits are recorded in proximal sites in the Caribbean Sea

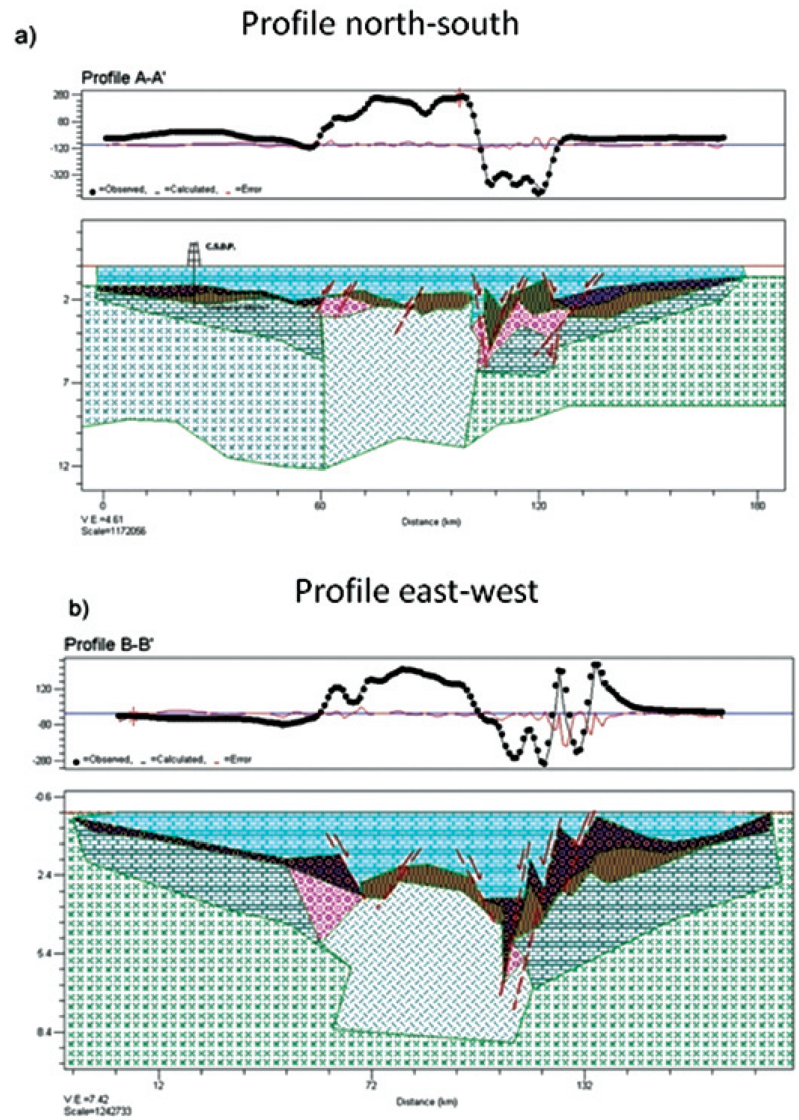

Figure 18. Magnetic models for Chicxulub crater (taken from Rebolledo-Vieyra *et al*., 2010). (a) Model for north-south profile A-A′. (b) Model for east-west profile B-B′. Observe the asymmetric crater structure documented in the models with respect of the central uplift and fault pattern.

and Gulf of Mexico (Bourgeois *et al*., 1998). Thick carbonate debris deposits occur in nearby areas of the Gulf, resulting from deformation affecting the carbonate platform (Álvarez *et al*., 1992; Smit *et al*., 1992; Smit, 1999). Stable oxygen and carbon isotope stratigraphic studies have been used to examine the completeness of the basal Paleocene section, which document the occurrence of a hiatus. Urrutia-Fucugauchi and Pérez-Cruz (2008) analyzed the stable isotope and magnetic polarity stratigraphy and proposed that the Santa Elena borehole section records a hiatus at the base, possibly representing less than ~100 ka.

Global ejecta distribution depends on a number of variables, including single or multiple impacts, impact angle and trajectory, low or high latitude sites, atmospheric conditions, depositional environment and preservation. Thickness and characteristics of the global clay layer have been analyzed since the early studies by Álvarez *et al*. (1980) which showed that the iridium anomaly and clay layer characteristics had no apparent simple connection to impact geographic position. Global distribution of shock quartz may carry geographic information related to impact site position and impact dynamics. Claeys *et al*. (2002) suggested that emplacement of shock quartz and effects recorded in North American sections relate to a NW-directed impact trajectory. A re-analysis by Morgan *et al*. (2006) concluded that global distribution of shock quartz supports a single high-angle impact.

Álvarez *et al*. (1980) proposed that impact injected large amounts of fragmented material into the atmosphere, with the very fine-grained dust staying in the stratosphere for several years, causing environmental perturbations and suppressing photosynthetic processes. The environmental and climatic effects of a large impact have been intensively studied in the following years, including the effects related to an impact on a carbonate platform (e.g., Brett, 1992; Pierazzo and Melosh, 2000; Pope, 2002; Robertson *et al*., 2004). The fossil record and biotic turnover have been examined and discussed in relation to the impact. The impact on a thick carbonate section with anhydrites and evaporites would have released large amounts of climatically sensitive gases, including sulfur compounds, water vapor and other greenhouse gases into the atmosphere, adding to the global environmental consequences. Campos-Enríquez *et al*. (1998) estimated, based on potential field data, the amount of material relased to the atmosphere. Potential effects on the continental and marine environments have been assessed. Studies on environmental consequences and relation to the biological turnover have been recently reviewed by Schulte *et al*. (2010). Studies have addressed the role of dust, darkness, photosynthesis shut-down, greenhouse gases, sulfur compounds and acid rain, global wildfires, biomass combustion, global pulse of thermal radiation at the ground due to ejecta material reentry and ocean acidification.

Characteristics of K/Pg boundary sections world-wide are also important in studies of the climatic and environmental perturbations generated by the impact and in evaluating effects in the biosphere. Initial studies were carried out in distal sections from Europe (Álvarez *et al*., 1980), and only later analyses of sections in proximal sites were completed. Studies demonstrated the global distribution of the ejecta layer, with K/Pg boundary sections in all continental areas and ocean basins (Figures 19 and 20). Marine and continental deposits were characterized by the iridium anomaly, and shock minerals. Studies in the Gulf of Mexico-Caribbean Sea areas showed that sections were more complex and thicker as compared with distal sites, with presence of high-energy sedimentary deposits and fireball layer, and also indicating that iridium enrichment

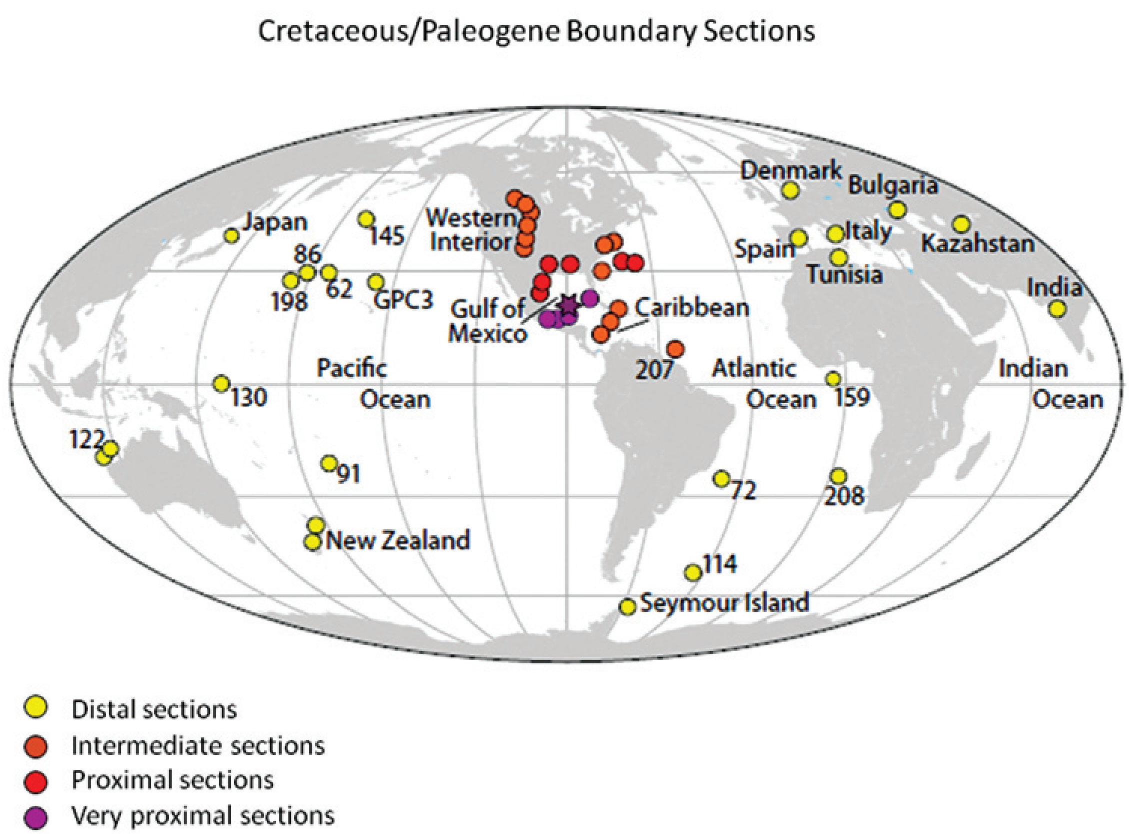

Figure 19. Location of K/Pg boundary sites, separated into distal, intermediate, proximal and very proximal sections (taken from Schulte *et al*., 2010). Location of Chicxulub crater is indicated by the asterisk. The numbers in marine sections correspond to the Deep Sea Drilling Project and Ocean drilling Project Leg identifications.

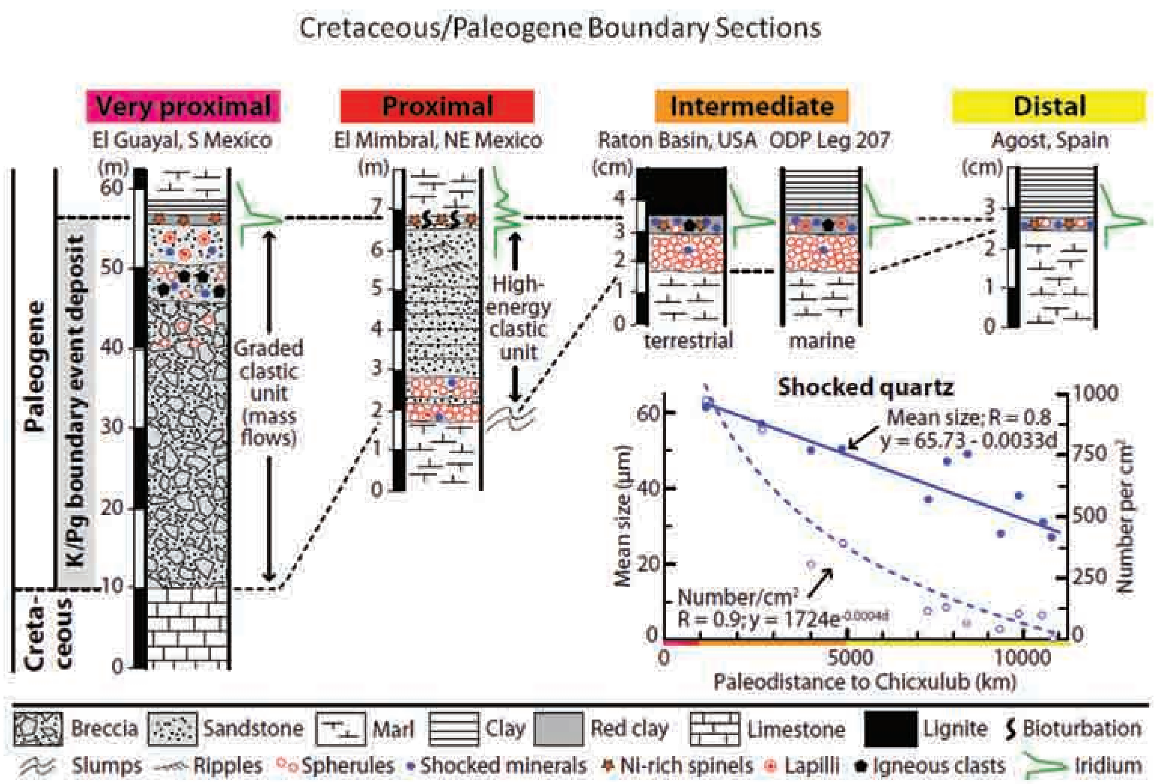

Figure 20. Schematic stratigraphic columns for representative K/Pg sections at distal, intermediate, proximal and very proximal locations. The spatial distribution of shocked quartz mean sizes as a function of paleodistance to Chicxulub crater is shown in the inset (taken from Schulte *et al*., 2010).

patterns varied with relative location to impact site (Bourgeois *et al*., 1988; Smit *et al*., 1992; Álvarez *et al*., 1992; Urrutia-Fucugauchi, 1993). The K/Pg boundary layer in distal and proximal sections is characterized by a magnetic anomaly, with increased magnetic susceptibility and remanent magnetization (Figure 21) (Villasante *et al*., 2007). The nature of the magnetic anomaly in distal sections suggest presence of a distinctive ferrimagnetic phase associated to Mg- and Ni-rich, highly oxidized spinels associated with the bolide (Urrutia-Fucugauchi, 1992). In proximal sections magnetic properties show different patterns, which may be related to ejecta emplacement conditions and diagenetic and alteration effects (Villasante *et al*., 2007; Ortega-Nieto *et al*., 2009). In the proximal sections, the magnetic anomaly observed in teh spherule laye appears dominated by mixutures of iron oxyhydrates, in particular fine-grained goethite. Villasante *et al*. (2007) interpreted the goethite-rich layer as a product of diagenetic remobilization and iron precipitation. Further studies are needed to investigate the magnetic anomalies in proximal and very proximal sections. Schulte *et al*. (2010) have recently analyzed the K/Pg boundary sections at varying distance from the impact site (Figure 20) and their relation to global effects.

Ejecta deposits around the crater have been investigated by drilling, in particular studies on the Santa Elena, Peto and Tekax boreholes recovered cores from the ejecta in the southern crater sector, showing >200 m thick sections of carbonate-rich and melt and basement-rich breccias, with an inverted stratigraphy correlating to the Ries crater suevite and Bunte breccias (Urrutia-Fucugauchi *et al*., 1996). Sections in Belize and Chetumal areas record thick ejecta deposits, including the basal spherule layer and diamictite unit (Pope *et al*., 2005). Sites in southern Mexico and Central America record thick ejecta sections, with 1 m and up to 80 m thick deposits. Sections in Cuba and the Caribbean Sea show presence of massive mass flow deposits several hundred meters thick. Proximal sites in Gulf areas located ~500 km to ~1000 km away are formed by basal spherule layer, high-energy transport sandstone deposits, fine-grained fireball layer and the clay layer. The fireball layer is characterized by enrichment of iridium and platinum group elements and shocked minerals, showing evidence of heating to temperatures several hundred degrees high.

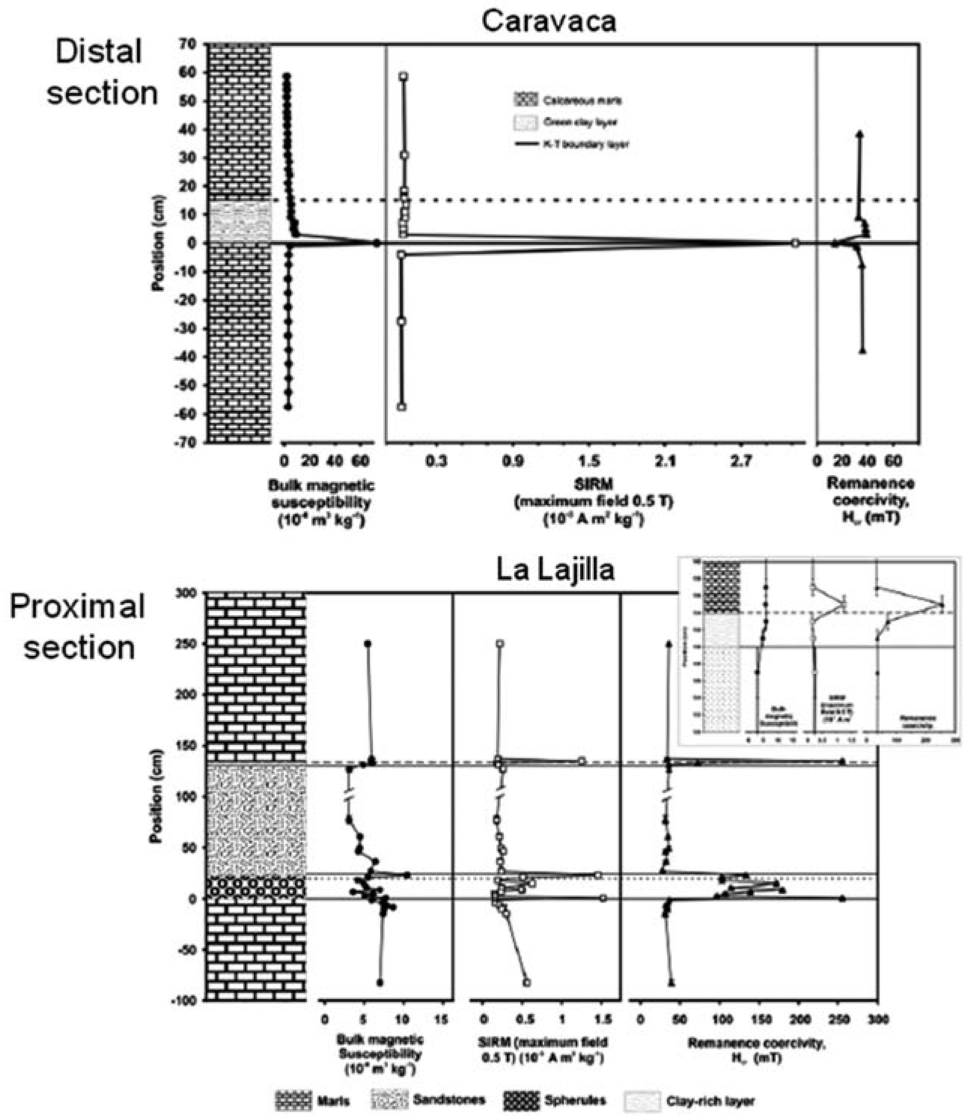

Figure 21. Magnetic anomalies at K/Pg boundary sections in distal (Caravaca, Spain) and proximal (La Lajilla, NE Mexico) sites, showing increased magnetic susceptibility, saturation isothermal remanent magnetization and remanence coercivity (taken from Villasante *et al*., 2007). High values of magnetic parameters are observed at the basel in the spherule layer and at the top in the transition with the Velasco marls (see inset). In the distal sections, the magnetic anomaly is observed at the basal spherule layer, which is usually represented by a sharp increase, also corresponding to the iridium anomaly (Figure 20).

Intermediate sites located some 1000 to 5000 km away record deposits with ~10-2 cm thick basal spherule layer and ~0.5-0.2 cm thick layer with shocked minerals, Ni-rich spinels and granitic clasts. Distal sections more than 5000 to 7000 km away are formed by occurrence of a basal spherule-rich layer and ~0.5-0.2 cm clay layer enriched in iridium and platinum group elements and Ni-rich spinels. Schulte *et al*. (2010) show that the thickness of the ejecta layer decreases with increasing distance from Chicxulub. This is consistent with a single source for the K/Pg global ejecta layer (Figure 20). Further, characteristics, composition, ejecta emplacement, depositional mode, occurrence of shocked minerals, clasts and grain sizes are compatible with Chicxulub as the source of the ejecta, matching the characteristics of target site in the Yucatan platform.

In recent decades, interest in investigating the role of impacts in the evolution of planetary surfaces has increased, as a result of planetary exploration missions. Surveys on the Moon and Mars have provided high resolution multispectral data on a range of impact craters ranging from simple bowl-shaped to large peak-ring and multi-ring basins. The geophysical surveys and drilling/coring programs on the Chicxulub crater have contributed to our understanding of the dynamics of impact and cratering processes, particularly about formation of large multi-ring structures (Figures 22 and 23). At the same time, studies have posed further questions concerning main crater components, which include for instance determining the characteristics and shape of the melt sheet (e.g., Kring, 1995; Morgan *et al*., 2002; Collins *et al*., 2008). The schematic models for formation of large complex structures (e.g., Figure 22) are being refined as further constraints from experiments and computer modeling are incorporated. These studies are providing insight on the various cratering stages from initial contact, excavation of transient cavity and fragmentation of target rocks, central uplift, plume and ejecta curtain collapse, melting, and formation of crater rings, terrace zone and post-impact deformation. Studies begin to address the role of target heterogeneities and pre-existing structures, as well as rheological properties of materials at high-energy regimes involving high temperatures and pressures.

Conclusions

Geophysical, geochemical and geologic studies on the Chicxulub crater have confirmed an impact origin for the structure and an age at the K/Pg boundary. The Chicxulub impact is linked to the worldwide distributed iridium-rich clay layer that is the stratigraphic marker of the K/Pg boundary. Study of Chicxulub crater has involved inter- and multidisciplinary approaches, with researchers from diverse fields from geosciences to astronomy, physics, chemistry, biology, ecology, ocean, atmospheric and planetary sciences. The geological and geomorphological characteristics

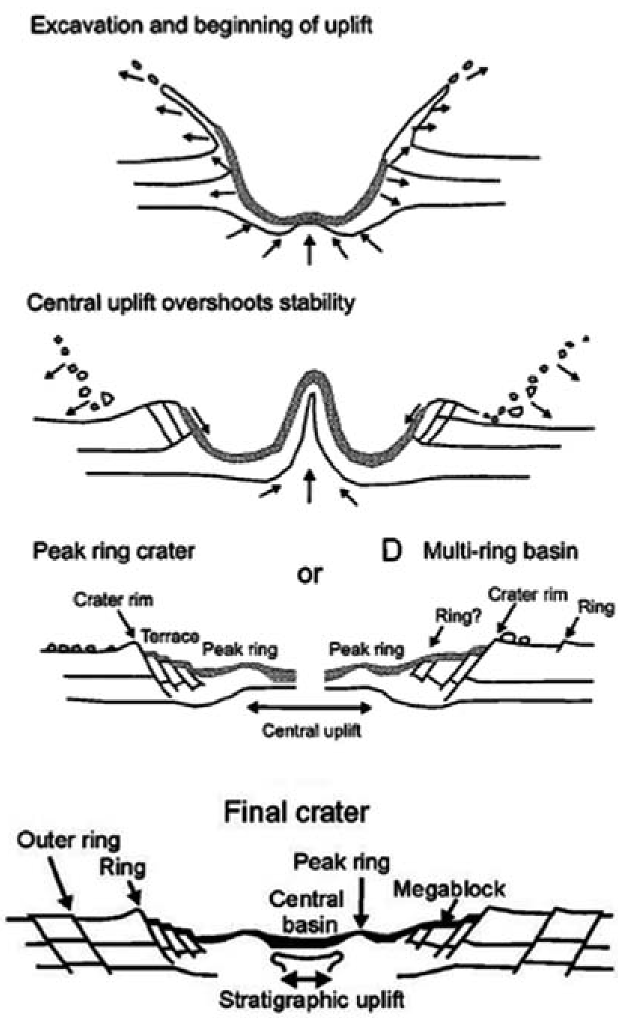

Figure 22. Schematic model for crater formation processes in large multi-ring structures (adapted from Melosh, 1989; Gulick *et al*., 2008; Urrutia-Fucugauchi and Pérez-Cruz, 2009). Crater formation of large complex structures inveves several stages, from initial contact, compression, excavation of transient cavity, basement aplift and modification. Crater formation is a highly-energetic rapid process, involving ligh temperatures and pressures. Large volumes of fragmented material are ejected, forming an ejecta plume and ejecta curtain, with grand surges. Model illustrates formation of peak-ring and multi-ring structures.

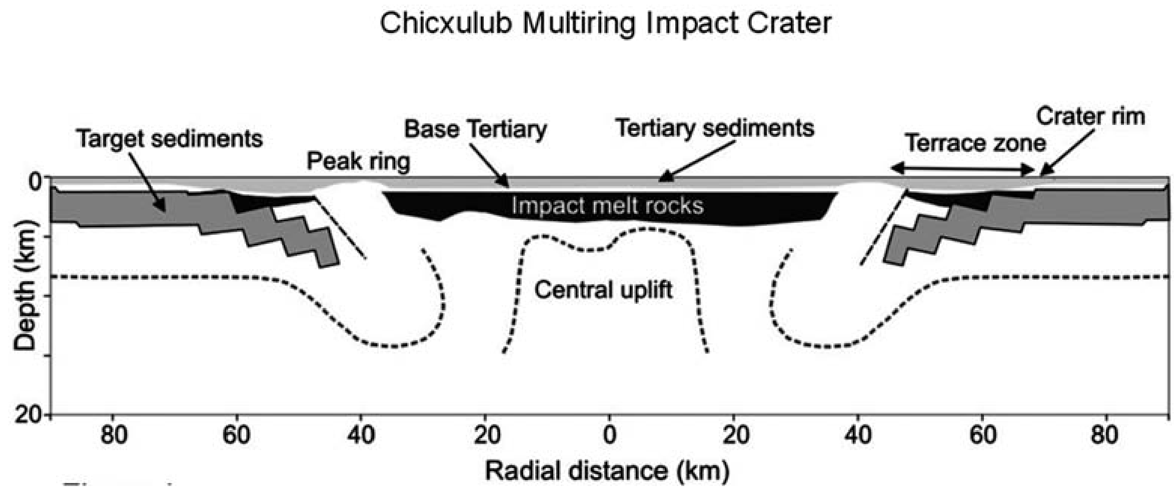

Figure 23. Schematic model for Chicxulub deep structure (taken from Collins *et al*., 2008).

of the Yucatan carbonate platform formed by slow deposition of carbonate sediments, tectonically stable with no volcanic activity, allow high-resolution imagery of the crater underground structure with unprecedented detail. Among major questions remaining are the dynamics of the impact event, global effects on life-supporting systems and understanding the physics of impacts on planetary surfaces. In particular, modeling of crustal deformation and rheological behavior of materials at high temperatures and pressures remain major challenges in geosciences (Melosh, 1989; Pierazzo and Melosh, 2000; Urrutia-Fucugauchi and Perez-Cruz, 2009). The impact and crater formation occur instantaneously, with crustal excavation down to ~25 km depths in fractions of a second, and lower crust uplift and crater formation in the next hundred seconds. Energy release and crustal deformation generates seismic waves traveling the whole Earth, resulting in intense fracturing and deformation at the target site. In the past two decades much has been learned about Chicxulub and the K/Pg boundary; however what is perhaps most interesting are the questions remaining, which include many fundamental aspects of Chicxulub impact and its effects.

Acknowledgments

We acknowledge the support and data provided by PEMEX on the oil exploration surveys and drilling program. Studies have been carried out within the Cooperation Agreement between PEMEX and UNAM. Geophysical surveys and drilling projects have been carried out as part of several projects and programs, including international collaboration programs. Space limitations have not permitted to include more references to the extensive literature on the Chicxulub crater and the Cretaceous/Paleogene boundary studies. Collaboration with numerous colleagues over the years has been important in developing the studies of Chicxulub impact crater and the K/Pg boundary. Important contributions have been provided by students participating in the Chicxulub Research Program, their assistance is gratefully acknowledged. Partial economic support during the preparation of this review has been provided by CONACYT grant 60520 and PAPIIT project IN114709.

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