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Chicxulub Asteroid Impact: An Extreme Event at the Cretaceous/Paleogene Boundary

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ABSTRACT

Crater-forming impacts represent a class of extreme events involving high-energy release and short time scales. Impacts constitute major geological processes shaping the surfaces and evolution of planetary bodies. The formation of large craters involves high pressures and temperatures resulting in intense deformation, fracturing, and melting. Impacts produce deep transient cavities, with excavation to deep levels in the crust, fragmentation, and removal of large volumes of rock. In this chapter, we analyze the Chicxulub impact and its effects on the Earth's climate, environment and life-support systems, in relation to the Cretaceous/Paleogene boundary. The boundary represents one of the major extinction events in the Phanerozoic, which affected about 75% of species. Effects of the impact have been intensely investigated, where the affectation in the evolution patterns was profound and long lasting. The disappearance of large numbers of species including complete groups severely affected the biodiversity and ecosystem composition in the marine and continental realms. There are several aspects involved in addressing the Chicxulub impact as an extreme event. First, we examine the impact event and cratering, time scales involved, and energy released. Next, we assess the impact's regional and global effects, which involve major perturbations in the ocean and atmosphere. From here, we discuss how and to what extent life-support systems are affected by large impacts, and what the fossil record tells about the extinction event and biotic turnover. In particular, how sudden or extended are the processes, extinction event and recovery temporal records.

8.1. INTRODUCTION

Over the past decades, study of extreme events has emerged as a major area in Earth sciences, across a wide range of disciplines with a strong inter- and multidisciplinary character and with implications into the social and economic sciences. A major component is focused on studies of geological and geophysical processes with capacity to generate disasters [*Meyers*, 2010]. Examples of extreme events within this context include large earthquakes, explosive volcanic eruptions, crater-forming meteorite impacts, tsunamis, catastrophic landslides, and floods, which involve processes delivering large amounts of energy on short time scales at their extreme ends of process range [*Ghil et al*., 2011].

In this chapter, we discuss the Chicxulub asteroid impact and the events at the Cretaceous/Paleogene (K/Pg) boundary in terms of a "geological extreme event." Large crater-forming events with capacity to

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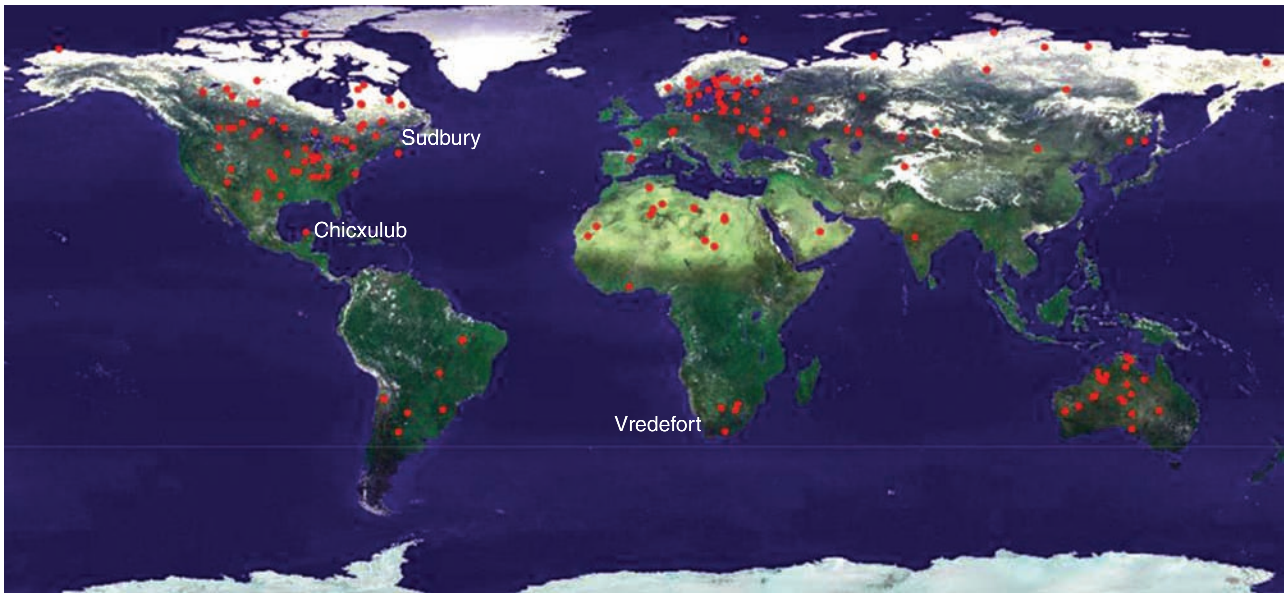
Terrestrial impact crater record (~170–180 craters)



Three large complex multiring structures

Figure 8.1 Impact craters documented in the terrestrial record (Earth Impact Database, University of New Brunswick, http:www.unb.ca/passc/ImpactDatabase). The uneven distribution of craters (shown by red dots) correlates with the distribution of the most intensely mapped areas and Precambrian terrains. The three largest structures with multiring morphology are Vredefort, Sudbury, and Chicxulub.

produce severe regional and global effects, profoundly affecting the life-support systems on both short and long spatial and temporal scales represent a different type of extreme events—at the end of process range. Impact produced a large, ~200 km diameter structure with peak ring and multiring morphology. Chicxulub is the youngest and best preserved crater of only three multiring structures identified in the terrestrial record (Figure 8.1). Multiring craters are common features on the Moon and other bodies of the solar system. In contrast, on Earth the tectonic, magmatic, and erosional processes have erased the record of past large impacts. Crater-forming events deliver large amounts of energy in "seconds" time scales, resulting in deep excavation, fracturing, and deformation of the crust [*Melosh*, 1989]. In contrast, plate motions, sea-floor spreading, plate subduction, and mountain-building processes which involve intense deformation of Earth's lithosphere occur on longer time scales.

The K/Pg impact caused severe effects on the climate and environment on a global scale, which have been related to the mass extinction of organisms marking the K/Pg boundary [*Alvarez et al.*, 1980; *Schulte et al.*, 2010]. The end-Cretaceous extinction is one of the five major mass extinction events in the Phanerozoic, which affected about 40% of genera and 75% of species. The effects on life evolution are long lasting, affecting species on the marine and continental realms.

There are several different aspects involved in addressing the Chicxulub impact as an extreme event. First, we examine the impact and cratering process, with the energy release, deep excavation, mass removal, ejection of large amounts of fragmented rock, widespread crustal deformation, and crater formation. Time scales involved in the impact and cratering are short in seconds to thousands of seconds, with a large amount of energy released [*Melosh*, 1989; *Kenkemann*, 2002; *Collins et al.*, 2008]. Next, we assess the target deformation and local, regional, and global effects of the impact, cratering, and ejecta deposition, which involve crustal deformation and major perturbations in the ocean and atmosphere. From here, we discuss how and to what extent life-support systems are affected by large impacts, and what the fossil record tells about the extinction event and biotic turnover. Of particular interest is how sudden or extended are the processes and extinction records.

The study of *Alvarez et al.* [1980] introduced a sudden catastrophic explanation for the mass extinction of organisms involving the effects of an impact of a large asteroid or comet. *Alvarez et al.* [1980] presented geochemical data for the K/Pg boundary layer in the pelagic carbonate sequences from Italy, Denmark, and New Zealand. The boundary layer is enriched in iridium and other platinum group elements (PGEs) with

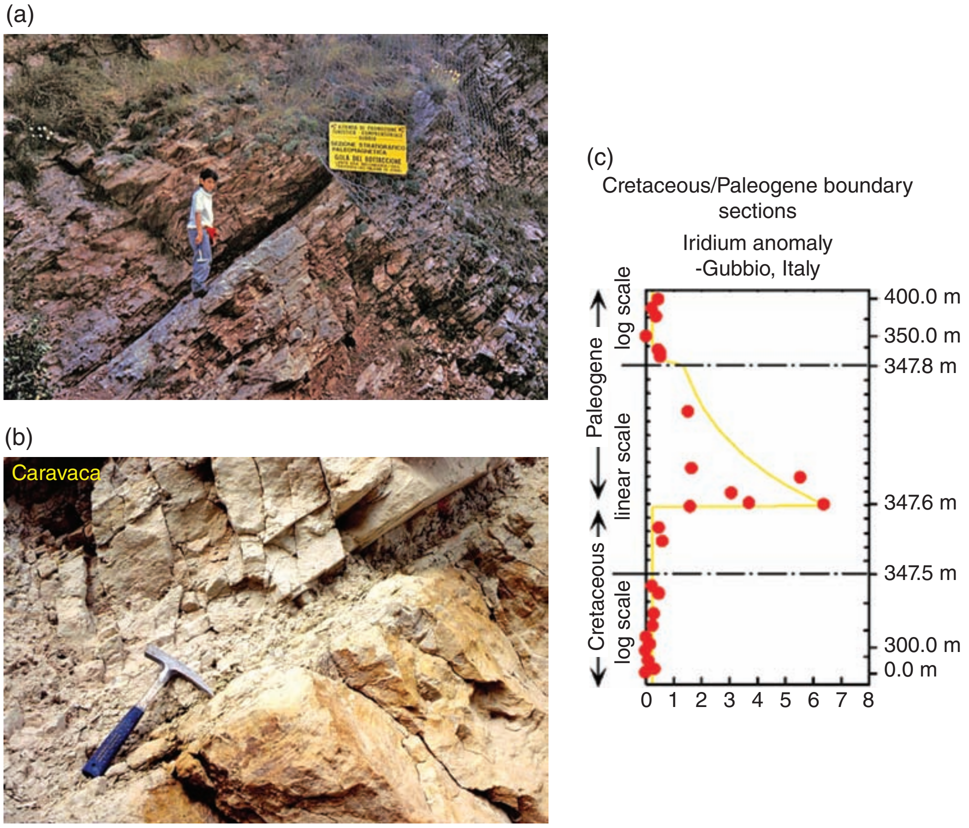


Figure 8.2 Distal Cretaceous/Paleogene boundary sections and K/Pg iridium anomaly. Views of the (a) Gubbio, Italy and (b) Caravaca, Spain Cretaceous/Paleogene (K/Pg) boundary sections, and (c) an example of the iridium anomaly for the Gubbio section.

concentrations of about 30, 160, and 20 times, respectively the background levels through the sections (e.g., Figure 8.2). The enrichments were associated with collision of an asteroid or a comet that injected large amounts of pulverized debris into the atmosphere, resulting in blockage of solar radiation, global cooling, and shut down of photosynthesis. The sizes of the bolide and resulting crater, estimated from various sets of assumptions, were in the range of 10 ± 4 km and ~200 km, respectively.

The impact hypothesis for the K/Pg boundary was met with opposition, mainly from within the paleontological community that considered the mass extinction occurring over an extended period. In the following years, evidence for an impact from analyses of the K/Pg boundary clay layer was confirmed by data from numerous marine boundary sections and eventually on continental sections [*Schulte et al.*, 2010]. The PGE anomaly is globally distributed, with K/Pg boundary sections showing a characteristic pattern with distance to the impact site (Figure 8.3). Studies have uncovered further impact indicators in the K/Pg boundary layer, in addition to the anomalous enrichment in iridium and PGEs, such as shocked quartz, spinels, magnesioferrites, and cromites [e.g., *Claeys et al.*, 2002; *Morgan et al.*, 2006; *Villasante-Marcos et al.*, 2007].

Recognition of the ~200 km diameter Chicxulub crater as the K/Pg impact site in the Yucatan carbonate platform, southern Gulf of Mexico (Figure 8.4), provided strong support for the impact hypothesis [*Hildebrand et al.*, 1991; *Sharpton et al.*, 1992; *Schulte et al.*, 2010; *Urrutia-Fucugauchi et al.*, 2011a, 2011b]. The impact is the largest documented in the past 600 Ma, since multicellular organisms evolved. The two other multiring craters, Sudbury (Canada) and Vredefort (South Africa), were formed at 2000 and 1850 Ma in the Precambrian [*Grieve and Therriault*, 2000].

The nature and suddenness of the mass extinction of organisms and the impact of cause/effect relations and its role as the main sole extinction cause continue to be debated. This is largely due to the incompleteness and temporal resolution of the geological and fossil records, which even for the marine realm have limitations that hamper and preclude analyses of sharp discrete events. In the past three decades, studies have contributed to unravel the role of impacts in the evolution of Earth and other bodies of the solar system.

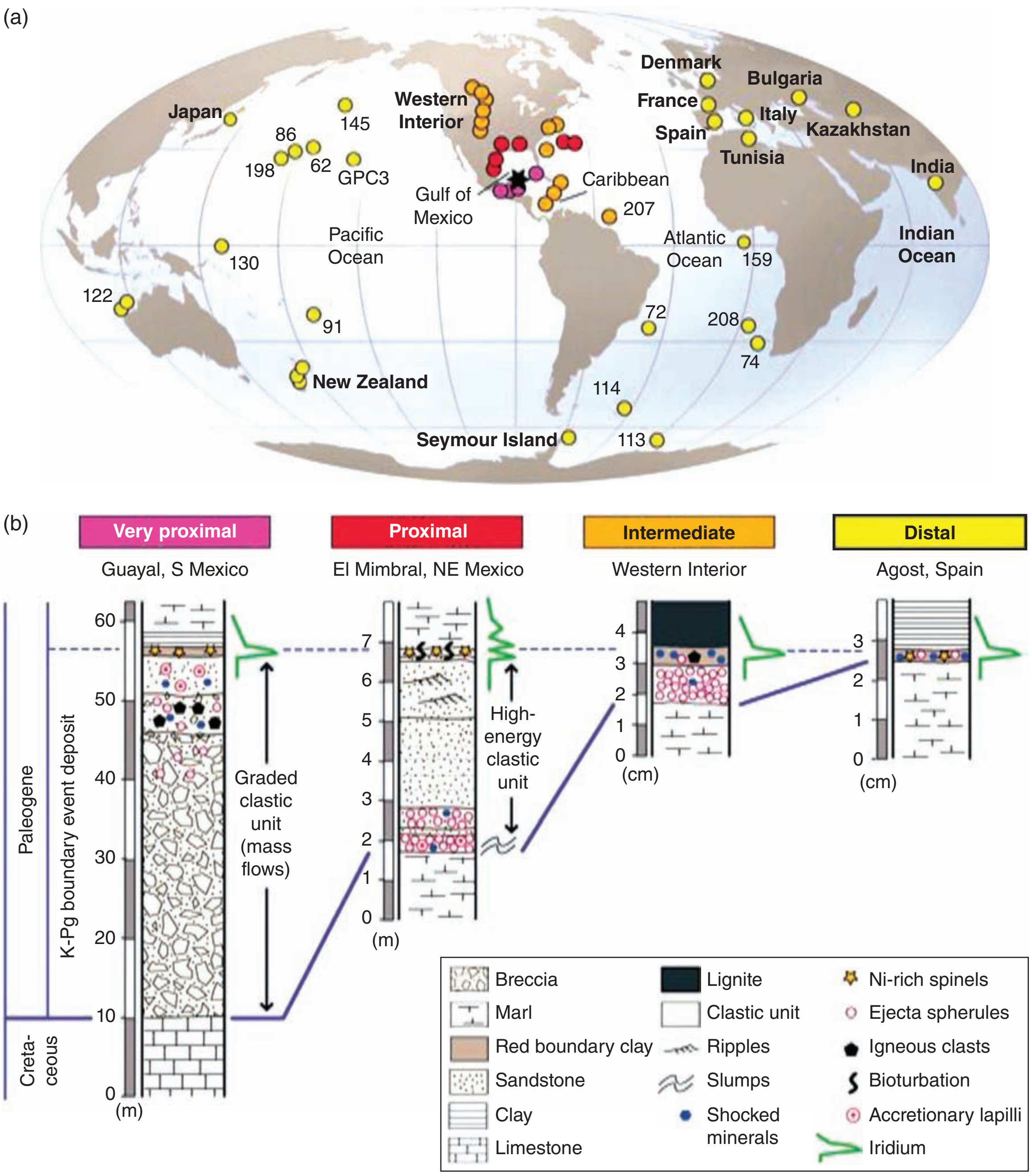


Figure 8.3 (a) Location of K/Pg boundary sites, separated into distal, intermediate, proximal, and very proximal sections [*Schulte et al.*, 2010]. Location of Chicxulub crater is indicated by the asterisk. Colors identify the distal, intermediate, proximal, and very proximal sections relative to distance from Chicxulub crater. Numbers in marine sections correspond to the Deep Sea Drilling Project and Ocean drilling Project Leg identifications. (b) Schematic stratigraphical columns for representative K/Pg sections at distal, intermediate, proximal, and very proximal locations [*Schulte et al.*, 2010].

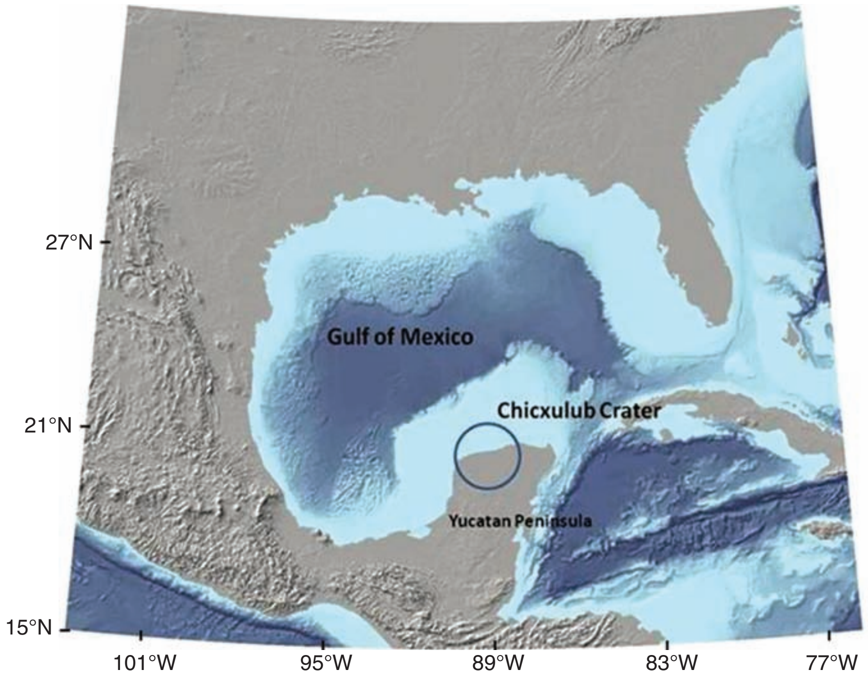


Figure 8.4 Location of the Chicxulub impact crater in the Yucatan Peninsula, southern Gulf of Mexico (base map is a digital terrain model of Gulf of Mexico-Caribbean Sea region). Note the extent of Yucatan carbonate platform shown in light blue.

8.2. EXTREME EVENTS IN THE GEOLOGICAL PAST

Study of extreme events in the geological records in the past has become more complex due to problems related to stratigraphical incompleteness and dating resolution of events. Analysis of the K/Pg boundary offers the possibility of exploring criteria for evaluating the geological record of an extreme event associated with a sudden catastrophic asteroidal impact, with reference to the K/Pg clay layer as a global stratigraphical marker of the Chicxulub impact.

The catastrophic nature of an impact explanation as cause of the K/Pg events and mass extinction was perceived as in contradiction to the uniformitarian view of geological processes. The impact theory posed a catastrophic explanation for one of the three major geological transitions in the geological time scale between the Mesozoic and Cenozoic eras. As such, the impact theory emerged central stage in a renewed debate about the role of catastrophism in the Earth's evolution.

Early on in the development and formulation of geological concepts and theories, a long-term debate occurred over what were considered competing frameworks or scientific paradigms. In the 18th and 19th centuries, debate was framed into the catastrophist and uniformitarian theories, with apparently opposite views of nature and geological processes. Eventually, uniformitarianism emerged to provide a framework for development of geological sciences, where present-day processes were held as key to understand the past. Stratigraphical principles such as the law of superposition provided the foundations for geological research.

Many geological processes were considered to occur in small incremental steps over relatively long time scales. Examples include erosion, sedimentation, mountain building, and motion of tectonic plates. Deep canyon systems are formed by removal of large amounts of material, usually by slow incremental erosion and transport processes. The formation of thick sedimentary sequences in large river deltas involves deposition of sediments for extended periods. Construction of mountain chains involves tectonic deformation with uplifting, folding, thrusting and faulting, and/or magmatic and volcanic activity. Opening and closing of ocean basins and formation and break up and drift of continental landmasses and supercontinents occur by plate motions at rates of a few centimeters per year. Their study has been partly based on observations of current processes and inferences and modeling of conceptual theories.

8.3. CHICXULUB IMPACT

The Chicxulub structure was first identified from oil exploration surveys, which discovered a large semicircular gravity anomaly in the northern sector of the Yucatan Peninsula (Figure 8.5). The anomaly pattern was interpreted as a buried volcanic center, which was apparently

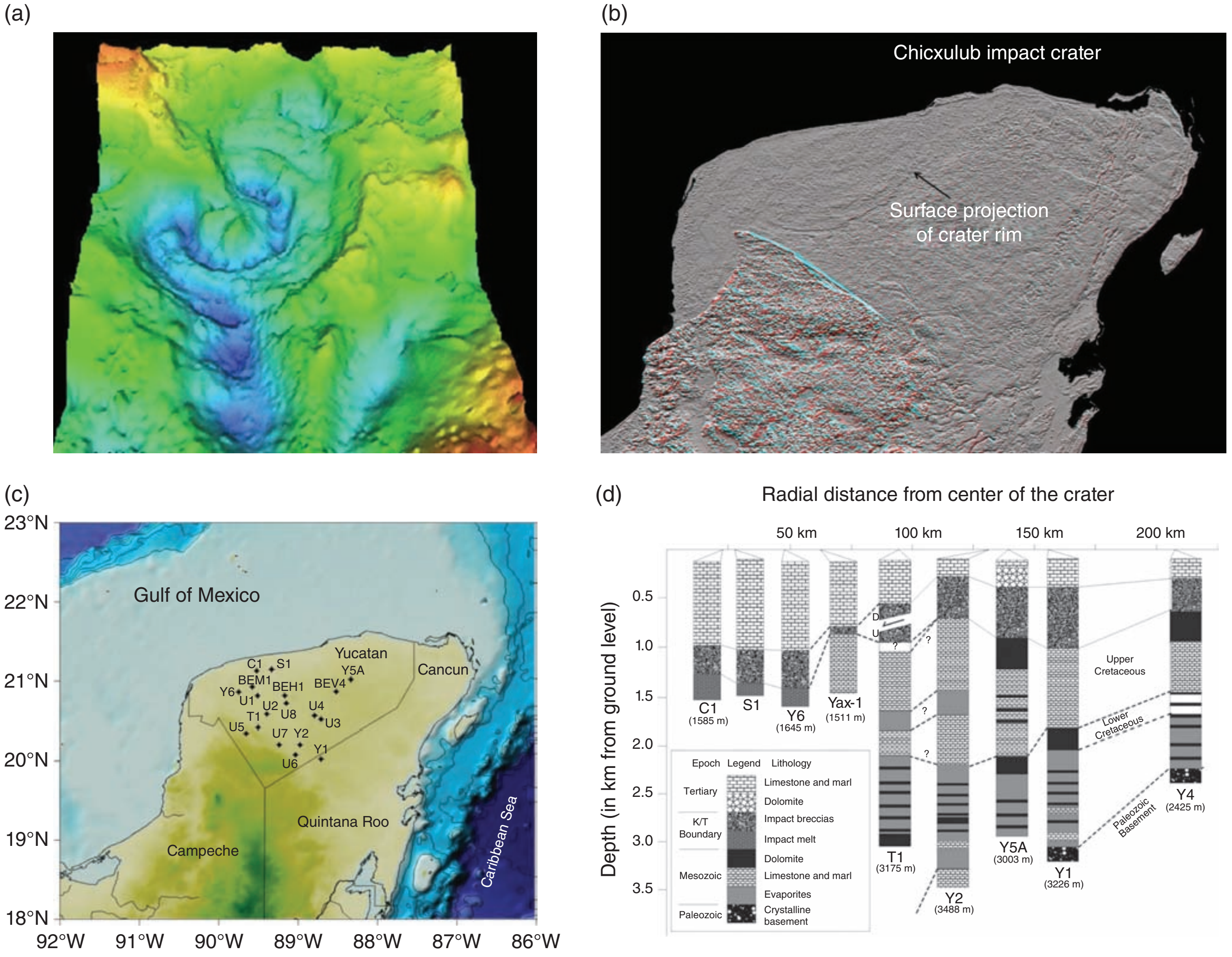


Figure 8.5 (a) Oblique three-dimensional view of Bouguer gravity anomaly map over the Chicxulub crater [from *Sharpton et al.*, 1993]. Observe the presence of a circular concentric anomaly with a semi-circular concentric anomaly that characterizes the multiring structure, with the gravity high in the central crater zone. (b) Interferometric radar satellite image for northern Yucatan Peninsula. The surface projection of the crater rim is marked by a semicircular topographic depression, which coincides with the cenote ring in the flat karstic terrain. Topographic depression is associated with differential compaction of impact breccias in side 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). (c) Location of drilling sites in the northern Yucatan Peninsula from the PEMEX, UNAM, CSDP, and UNAM-CFE drilling programs [*Urrutia-Fucugauchi et al.*, 2011a, 2011b]. Schematic columns of the PEMEX boreholes, showing the major lithological units. The column for the Yaxcopoil-1 borehole is included.

confirmed by drilling within the central zone and recovering of andesitic rocks. In the late 1970s, aeromagnetic surveys documented a large magnetic anomaly pattern within the central zone of gravity anomalies (Figure 8.6). In 1981, the anomalies were alternatively interpreted in terms of an impact crater [*Penfield and Camargo-Zanoguera*, 1981]. In 1991, it was proposed that the crater was a possible K/Pg boundary impact [*Hildebrand et al.*, 1991], which was confirmed by radiometric dating and magnetic polarity stratigraphy [*Sharpton et al.*, 1992; *Urrutia-Fucugauchi et al.*, 1994].

In the last two decades, geophysical studies and drilling projects have investigated the structure and stratigraphy of the crater (Figure 8.5) [*Sharpton et al.*, 1993; *Kring*, 1995; *Hildebrand et al.*, 1998; *Morgan et al.*, 1997; *Morgan and Warner*, 1999; *Urrutia-Fucugauchi et al.*, 1996, 2004, 2008; *Gulick et al.*, 2008]. The geometric center of the geophysical anomalies lies at Chicxulub Puerto in the present coastline. The crater is part on land and part offshore. The Chicxulub crater is buried under about 1 km of Paleogene carbonate sediments. The flat relief of Yucatan permits to integrate the marine and terrestrial

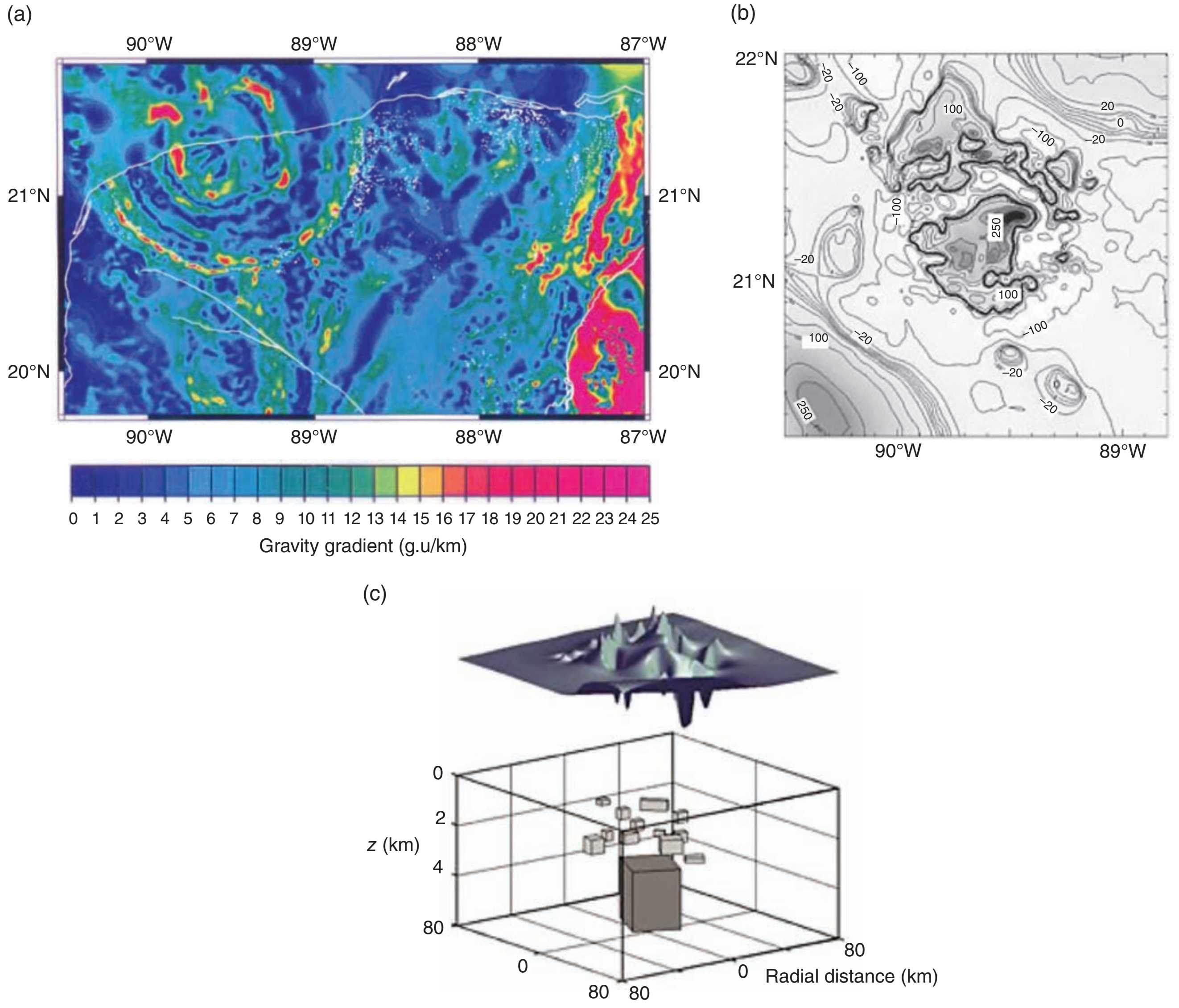


Figure 8.6 (a) Horizontal gravity gradient calculated for the Bouguer gravity anomalies over the Chicxulub crater [taken from *Connors et al.*, 1996]. The white dots represent location of the cenotes. Observe the correlation of the cenote ring with the gravity gradient anomaly. (b) Contour map of the aeromagnetic anomaly field over Chicxulub impact crater, in the northwestern sector of the Yucatan peninsula. Survey flight high 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. (c) 3D inversion model of magnetized source bodies [*Ortiz-Aleman and Urrutia-Fucugauchi*, 2010].

surveys with high resolution. Structural models derived from modeling the potential field anomalies, electromagnetic and seismic data define major crater features, including a central zone with the basement uplift, breccias and melt deposits, and terrace zones with radial faulting (Figure 8.7). Seismic reflection surveys have allowed mapping and imaging of crater morphology, Paleogene basin, and deep crustal deformation features [*Morgan et al.*, 1997; *Morgan and Warner*, 1999; *Gulick et al.*, 2008]. Joint modeling of geophysical and drilling data, particularly lithological columns and well-logging information result in improved spatial resolution and structural characterization [*Hildebrand et al.*, 1998; *Urrutia-Fucugauchi and Pérez-Cruz*, 2008; *Urrutia-Fucugauchi et al.*, 2008, 2011a]. A marine seismic reflection survey provides a three-dimensional imaging of the structure with the peak ring, terrace zones, fractures, postimpact carbonates, impactites, and target Mesozoic sequence [*Gulick et al.*, 2008].

Aeromagnetic data show high-amplitude short wavelength anomalies in the central sector delimitated by the central gravity anomaly (Figure 8.6), which are associated with the basement uplift, breccias, and melt [*Pilkington*

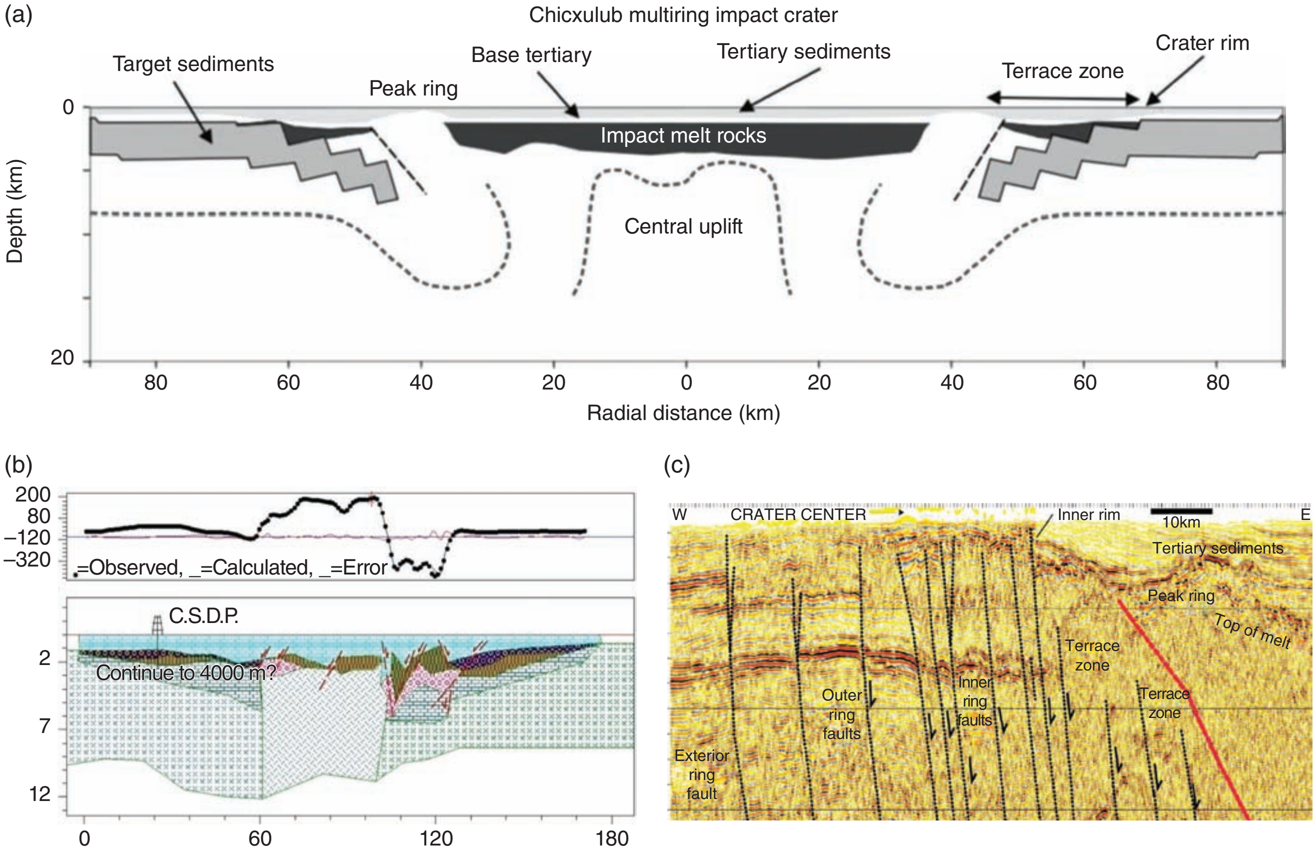


Figure 8.7 (a) Schematic model for Chicxulub deep structure (taken from *Collins et al*. [2008]). (b) Magnetic model for Chicxulub crater; observe the asymmetric crater structure documented in the models with respect to the central uplift and fault pattern [*Rebolledo-Vieyra et al.*, 2010]. (c) Marine seismic reflection Chicx-A profile of the western sector of the Chicxulub structure with structural interpretation added. Note the distribution and extent of the fault pattern [*Gulick et al.*, 2008].

and Hildebrand, 2000; *Ortiz-Aleman and Urrutia-Fucugauchi*, 2010; *Batista et al*., 2013]. Aeromagnetic anomalies show three strong, well-defined concentric patterns, with a central high-amplitude 40 km diameter zone. Magnetic properties associated with the melt sheet, upper breccias, and central uplift present three to four orders of magnitude contrasts with the surrounding carbonate units. Models suggest sources extending to radial distances ~45 km from crater center, with average depths ranging between 2 and 4 km. Magnetic sources in central zone are located at about 3.5–8 km depth, with dominant contributions from the structural uplift [*Ortiz-Aleman and Urrutia-Fucugauchi*, 2010]. Low-amplitude magnetic anomalies associated with the impact breccias likely reflect effects of hydrothermal activity, with formation of secondary iron-titanium oxides [*Pilkington and Hildebrand*, 2000; *Urrutia-Fucugauchi et al*., 2004: *Velasco-Villarreal et al*., 2011]. Impact breccias show effects of hydrothermal activity related to fluid circulation in the fractured-porous formations [*Kring et al*., 2004]. The hydrothermal system remained active for a long period in the Paleocene [*Abramov and Kring*, 2007; *Escobar-Sanchez and Urrutia-Fucugauchi*, 2010].

Drilling projects conducted by Pemex, UNAM, UNAM-CFE, and CSDP have provided samples for laboratory analyses (Figure 8.5c and d). Pemex drilling incorporated intermittent core recovery, and there was need for detailed sampling through the lithological column [*Lopez Ramos*, 1976; *Urrutia-Fucugauchi et al*., 2004, 2008]. 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]. Three boreholes in the southern sector at different radial distances from the crater center sampled the Paleogene carbonates and the impact breccia sequence, with the carbonate–breccia contact lying at varying depths between 222 and 332 m, below the surface. Impact breccias are characterized by clasts of carbonates, melt, and crystalline basement in a matrix characterized by carbonate-rich and melt-rich components. The breccia units, compared to the suevitic

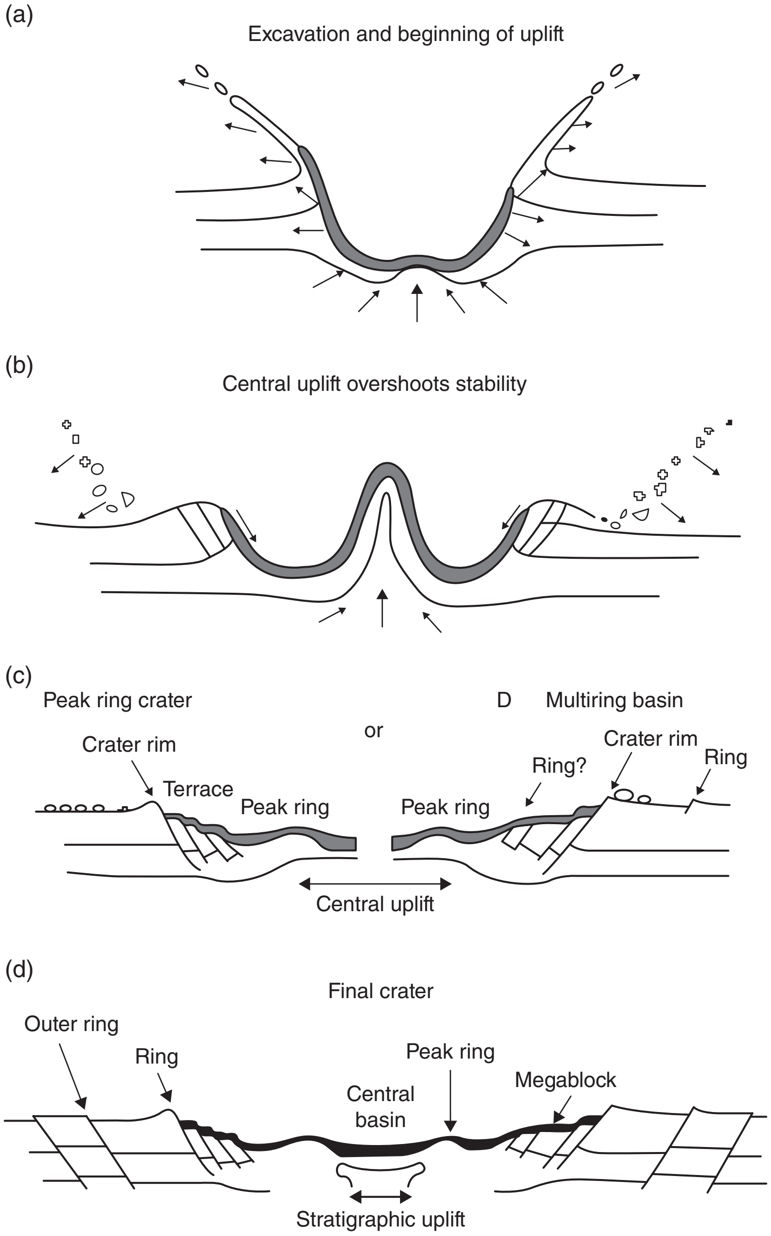


Figure 8.8 Schematic model for crater formation processes in large multiring structures (adapted from *Melosh* [1989]; *Collins et al.* [2008] and *Gulick et al.* [2008]). (a) Excavation of transient cavity and uplift. (b) Central uplift, ejecta emplacement with ejecta plume and lateral curtains, and crater modification. (c) Formation of peak ring and multiring basin morphologies. (d) Final crater morphology delimited by the crater ring and outer ring, with a central basin, basement uplift, melt sheet, megablock breccias, peak ring, and terrace zone.

and Bunte breccias in the Ries crater, have been cored in Chicxulub, with upper breccias rich in carbonate clasts and lower breccias rich in melt and basement clasts [*Urrutia-Fucugauchi et al.*, 1996]. Ejecta deposits are documented in these boreholes and in drilling in the eastern Merida-Valladolid area [*Urrutia-Fucugauchi et al.*, 2008]. Proximal deposits are exposed in areas to the south in Belize, Chetumal, and Campeche, which are part of the ejecta blanket covering the Yucatan Peninsula.

The geophysical and drilling data on Chicxulub have been reviewed in *Urrutia-Fucugauchi et al.* [2011a, 2011b], where additional details on the structure are discussed. A schematic model for the crater, showing the major elements of the crater rim, Tertiary basin, central uplift, terrace zone, melt sheet, and breccias is shown in Figure 8.7a. Models for the formation of large complex structures are being refined as further constraints from experiments and computer modeling are incorporated

(Figure 8.8). Final structure for complex craters forms in stages [*Melosh*, 1989; *Melosh and Ivanov*, 1999; *Pierazzo and Melosh*, 2000]. The structure develops after initial contact: excavation of a deep transient cavity, fragmentation of large volume of target rocks and formation of ejecta plume, uplift of lower crust basement and collapse. During this stage, the peak-ring structure formed. After crater formation, subsidence and faulting occurred due to differential compaction. The studies are providing insight on the various cratering stages from initial contact, excavation of transient cavity, fragmentation of target rocks, central uplift, plume and ejecta curtain collapse, melting, and formation of crater rings, terrace zone and postimpact deformation. The nature of the bolide has been investigated from geochemical and isotope analyses of the ejecta, which support an asteroid impact [*Mukhopadhyay et al*., 2001; *Gelinas et al*., 2004].

8.4. CHICXULUB IMPACT AND K/Pg BOUNDARY LAYER

One of the central issues in the impact hypothesis for the end-Cretaceous extinction of organisms has been the dating and correlation of events [*Kuiper et al*., 2008; *Tohver et al*., 2012]. This was addressed in the initial studies and has remained at the forefront of the discussions ever since. Crater-forming impacts deliver huge amounts of energy in very short time scales. Although they leave characteristic marks in the geological record, including the crater structure and ejecta deposits, resolving the spatial and temporal processes from the geological record and in particular the impact effects and relation to other induced or independent events presents a complex daunting problem. For the K/Pg boundary, problems relate to nature of the mass extinction, boundary events, fine-tuning connection of impact effects, and biotic recovery.

Studies have addressed the problem along different paths, examining the crater stratigraphy, ejecta deposits at proximal, intermediate and distal sections, and high-resolution stratigraphical correlations (Figure 8.3). Evidence on a causal relation comes from (1) coeval dates on Chicxulub impact melt and K/Pg tektites and glasses, (2) chemical fingerprinting of boundary layers and Yucatan target rocks, (3) dating of boundary-layer zircons in intermediate and distal sections, (4) distribution and characteristics of K/Pg sections in Gulf of Mexico-Caribbean Sea region, (5) distribution of shock quartz and other impact indicators, and (6) correlation of paleontological and stratigraphical records for the Maastrichtian and Danian sections. The studies provide strong support linking the K/Pg boundary clay with the Chicxulub impact [*Claeys et al*., 2002; *Morgan et al*., 2006; *Schulte et al*., 2010; *Kamo et al*., 2011].

Following the proposal that Chicxulub crater was the K/Pg impact site, several studies examined the links between the K/Pg layer and Chicxulub breccias and melt. Geochemical, mineralogical, and isotopic studies in different sections have documented the genetic links. Chemical compositions of impact glasses from Beloc, Haiti, and El Mimbral Mexico correlate with analyses for the Chicxulub melt and melt-rich breccias. 40Ar/39Ar dates for the Beloc impact glasses gave dates of 65.07 ± 0.1 Ma, similar to the dates on the Chicxulub melt rocks. U-Pb dates for shocked zircons from sections in Canada constrained the link to Chicxulub crater [*Krogh et al*., 1993; *Kamo et al*., 2011].

In proximal sections in the Gulf of Mexico and Caribbean, the ejecta are represented by a characteristic impact material-rich complex clastic unit. *Arenillas et al.* [2007] reported a detailed planktonic foraminifera record for the proximal sections of Bochil and Guayal in southern Mexico. The lowest Danian biozone P0 is documented in sediments on top of the complex clastic unit, consistent with a K/Pg boundary age. *Schulte et al*. [2010] analyzed the K/Pg boundary sections at varying distance from impact site (Figure 8.3) and relation to global effects. Very proximal ejecta deposits have been investigated by drilling, with boreholes in the southern crater sector showing >200 m thick sections of carbonate-rich and melt and basement-rich breccias, with an inverted stratigraphy [*Urrutia-Fucugauchi et al*., 1996, 2011a, 2011b]. Sections in Belize and Chetumal areas record thick ejecta deposits with the basal spherule layer and diamictite unit [*Pope et al*., 2005]. Proximal sites in southern Mexico and northern Central America show 1−80 m thick deposits. Sections in Cuba and the Caribbean Sea show occurrence of massive mass flow deposits hundred meters thick. Proximal sites in Gulf areas located ~500 to ~1000 km away show a basal spherule layer, high-energy sandstone deposits, fine-grained fireball, and clay layers. The fireball layer is characterized by enrichment of iridium and PGEs, shocked minerals, and showing evidence of heating to temperatures several hundred degrees high. Intermediate sites located some 1000−5000 km away record deposits with ~2–10 cm thick basal spherule layer and ~0.2−0.5 cm thick layer with shocked minerals, Ni-rich spinels, and granitic clasts. Distal sections more than 5000−7000 km away are characterized by basal spherule-rich and ~0.2–0.5 cm clay layers enriched in PGEs and Ni-rich spinels. *Schulte et al*. [2010] show that thickness of the ejecta layer decreases with increasing distance from Chicxulub, which is consistent with a single source of the K/Pg global ejecta layer.

Studies have investigated the strontium isotope anomaly at the K/Pg boundary sections [*Martin and MacDougall*, 1991; *Vonhof and Smit*, 1997]. Strontium isotope data have been related to the impact, including enhanced continental weathering by acid rain precipitation, impact ejecta, and soot from impact-induced fires [*MacDougall*, 1988]. Alternatively, sources such as the

Deccan Traps volcanic activity phases have been considered [*Vonhof and Smit*, 1997].

8.5. END-CRETACEOUS MASS EXTINCTION

Most of the species in the fossil record are extinct, with an estimate of 99%, which indicates that extinction is the norm in the evolution process. Extinction rates appear to vary, with times characterized by higher rates when the apparent ratios between extinction and speciation differ. From analyses of the fossil data, five periods of extinction known as the five mass extinction events are recognized. These extinctions occurred at Late Devonian, Late Ordovician, Permo-Triassic, Triassic and end-Cretaceous [*Raup and Sepkoski*, 1982; *Bambach*, 2006]. Estimates of the percentages of genera and species going extinct are difficult to estimate, but they may have affected about 75% of the species at the time.

The paleontological record has been examined searching for taxonomical, temporal and geographic patterns, numbers of groups and subgroups, and biodiversity [*Raup and Sepkoski*, 1982; *Straus and Sadler*, 1989; *Raup and Jablonski*, 1993]. Statistical analyses of fossil databases are used to defining trends and patterns of extinction and speciation. Records of continental organisms are less complete than marine records that allow greater resolution for analyzing trends and patterns of extinction and speciation. On the continents, one of the major groups going extinct was the non-avian dinosaurs. Dinosaurs arose in the Late Triassic and diversified reaching large sizes at a time when the major landmasses drifted apart after the supercontinent Pangea breakup [*Sereno*, 1999]. During the Cretaceous, major evolutionary changes took place, including the appearance of flowering plants.

An area that has been intensely surveyed for vertebrate fossil remains is the North American interior. Several studies on the dinosaur fossil record in the Hell Creek Formation in Montana and North Dakota have provided a fairly detailed record in the last stages of the Cretaceous. The K/Pg boundary layer is well exposed in the continental sedimentary exposures, which provides a stratigraphical marker. Studies in the 1970s identified a zone in the last meters of the Cretaceous with few fossil remains. This zone was later known as the 3 m gap and discussed in terms of the extinction of dinosaurs at the K/Pg [*Archibald*, 1996; *Sheehan et al*., 2000]. The sedimentary sections continue to attract attention and recent surveys have uncovered dinosaur fossils within the zone below the K/Pg layer [*Lyson et al*., 2011]. Discussions on the stratigraphical and fossil record and implications for gradual or sudden extinction at the boundary also highlight the issues of diversity of dinosaurs in the Cretaceous.

Recent studies have reexamined the diversity of dinosaur taxa during the Late Cretaceous. *Wang and Dodson* [2006] examined the diversity of non-avian dinosaurs, concluding that the genera documented for a small part of the diversity. They examined the decline in diversity for the last stages of the Cretaceous and concluded that diversity was steady, with no decline for the last 10 Ma of the Cretaceous. In contrast, *Barrett et al*. [2009] report based on the sauropodomorph record that dinosaur genus diversity declined during the last stages of the Cretaceous. *Brusalte et al*. [2012] analyzed the geographic and clade-specific patterns, finding a more heterogeneous distribution. They found that, while ceratopsids and hadrosaurs, and some North American groups reduced diversity in the two final stages of the Cretaceous, predator dinosaurs, mid-sized herbivores, and some groups in Asia showed stable diversity.

The K/Pg mass extinction had been associated to several different gradual incremental causes, including sea-level changes, climate change, ocean anoxia, and volcanic-induced environmental and climatic changes [*Hallam*, 1987; *Keller*, 2008]. In particular the association with the intense volcanic activity of the Deccan Traps in India has been investigated and proposed as a major cause of environmental changes. The chronology of Deccan Traps activity has been investigated in increasing detail [e.g., *Ravissa and Peuker-Ehrenbrink*, 2003; *Chenet et al*., 2008; *Keller*, 2008], with emphasis on the correlation to K/Pg boundary events. The proposal by *Alvarez et al*. [1980] of the global effects of a large bolide impact introduced a cause involving short time scales. Distinguishing sudden from gradual extinction scenarios remains a difficult problem, mainly because of the incompleteness of the stratigraphical and paleontological records and the resolution of the dating and correlation methods [*Straus and Sadler*, 1989; *Springer*, 1990; *Marshall*, 1995; *Marshall and Ward*, 1996; *Payne*, 2003]. *Signor and Lipps* [1982] showed that due to the incomplete nature, stratigraphical distributions of last fossil appearances appear gradual even if the species became extinct at a given stratigraphical level. Several statistical methods have been developed to test sudden from gradual extinctions, which permit to place significance levels to the extinction patterns [*Wang et al*., 2012].

The global environmental and climatic effects of the bolide impact have been examined in terms of effects on life-support systems. *Alvarez et al*. [1980] and studies that followed discussed impact effects related to the extinction of organisms. The impact-induced processes involve different time scales, from very short to long lasting [*Gilmour and Anders*, 1989; *Mukhopadhyay et al*., 2001; *Keller et al*., 2004, *Robertson et al*., 2004; *Keller*, 2008]. Processes initially proposed include disruption of photosynthesis due to the fine-grained dust particles and sulfate aerosols in the upper atmosphere [*Alvarez et al*., 1980]. The reduction of solar radiation resulted in freezing temperatures in continental regions and shut down of photosynthesis affecting the base of the global food chain in the marine and on land realms. Several studies have investigated the environmental effects of fine-grained ejecta particles and aerosols [*Toon et al*., 1982, 1997; *Covey et al*., 1990, 1994; *Pierazzo et al*., 2003]. *Pope* [2002] analyzed the effects of dust and shutdown of photosynthesis, arguing that the dust-loading threshold for photosynthesis lies in the mass and distribution of the submicron-size dust. From theoretical calculations and coarse-dust fraction observations on the K/Pg boundary clay, *Pope* [2002] concluded that dust was not sufficient for globally blocking solar radiation and photosynthesis shutdown.

Robertson et al. [2004] proposed that the thermal pulse resulting from reentry of ejecta into the atmosphere was a major factor in the extinction event. They proposed that the intense infrared radiation affected organisms and ignited fires on a global scale. In their study, they analyzed the differential pattern of survival among nonmarine vertebrates, showing that the selectivity pattern was compatible with a sudden-killing mechanism. The effects of the infrared radiation pulse had been examined [*Melosh et al*., 1990; *Toon et al*., 1997], and associated with global wildfires [*Wolbach et al*., 1988]. The magnitude of a thermal pulse propagating through the atmosphere associated with reentering ejecta was reexamined by *Goldin and Melosh* [2009], reassessing the self-shielding effects of infrared radiation.

Global wildfires ignited by the impact might have added to the environmental perturbation, injecting large amounts of smoke and carbon dioxide into the atmosphere. Studies on continental K/Pg boundary sections in interior North America identified occurrence of soot, interpreted as the remains of massive wildfires ignited by the thermal pulse generated by reentry of ejecta into the upper atmosphere [*Wolbach et al*., 1988]. The global wildfire scenario has been challenged by *Belcher et al.* [2003] from studies of charcoal, soot, and pyrosynthetic polycyclic aromatic hydrocarbons, which show that they were not produced by vegetation fires but were the result of hydrocarbon combustion. *Belcher et al*. [2003, 2009] report that K/Pg boundary sections in interior North America contain less charcoal than the sequences above and below. The K/Pg layer is characterized by the lack of charred remains and instead shows abundance of non-charred plant material at interior North America sites. The soot morphological characteristics in marine sections appear inconsistent with biomass sources, supporting an origin from partial hydrocarbon combustion. Reports of carbon cenospheres formed from hydrocarbon combustion in marine and continental sections support observations against widespread global wildfires. The new evidence indicates combustion of organic material and hydrocarbons from the impact site in the Yucatan carbonate platform. Rough estimates of Gulf carbonate sequences suggest that organic matter may have been above global mean values. Study by *Harvey et al*. [2008] shows that target carbonates with average abundances of organic matter appear compatible with concentrations estimated for carbon cenospheres and soot.

Impact was on the shallow Yucatan carbonate platform, as evidenced by the tsunami deposits in the areas around the Gulf of Mexico and elsewhere [*Bourgoise et al*., 1988]. Impact affected the Yucatan sequence composed of limestones, evaporatites and dolomites, with release of large amounts of CO_2 and sulfur compounds in the atmosphere [*Brett*, 1992; *Pope et al*., 1997]. Sulfur compounds may have resulted in acid rain, adding to the environmental perturbation. The injection of large quantities of CO_2 may have resulted in a greenhouse effect following the initial cooling episode [*Emiliani et al*., 1981]. The deposition of silicate dust particles in the oceans affected the seawater chemistry causing a disruption in the carbonate-compensation level. Scenarios include the "Strangelove ocean" with primary productivity disrupted for a long time and suppression of flux of organic matter from the surface to the bottom. The effects on different parts of the oceans may have varied widely. The mass extinction affected groups of vertebrates, invertebrates, phytoplankton, and zooplankton, with entire groups disappearing. For instance, the planktonic foraminifera experienced losses of 90% of the species [*D'Hondt et al*., 1996]. Estimates of recovery intervals for pelagic ecosystems involve several millions of years to be reestablished [*D'Hondt et al*., 1996, 1998]. In contrast, continental margin ecosystems recovered relatively fast in short time scales.

Estimating the time represented by the K/Pg boundary layer, which was the initial motivation for the PGE geochemical study by *Alvarez et al* [1980], has been investigated using isotope studies. The boundary clay associated with the Chicxulub impact is globally distributed and relatively thin in distal sections. *Mukhopadhyay et al*. [2001] used helium-3 as a flux proxy of sedimentation rate in the clay layer and constrained the duration in less than about 10 kyr. In the study, they analyzed the Gubbio and Monte Conero sections in Italy and the Ain Settara section near El Kef in Tunisia. They report a near-constant flux of helium-3, which they use to rule out a comet shower and for the estimate of sedimentation rate. They conclude that there is not a long hiatus at the boundary, and that faunal turnover was relatively rapid. *Sepulveda et al*. [2009] examined the resurgence of marine primary productivity at the K/Pg boundary, which has been difficult to determine due to the lack of paleontological records tracing primary producers with no skeletons. They used stable carbon and nitrogen isotopes and abundances of algal steranes and bacterial hopanes in the K/Pg boundary Fish Clay in Denmark to quantify algal primary productivity. They conclude that there was a rapid resurgence of marine productivity with carbon fixation and ecological reorganization, after a short interval of possibly less than a century.

8.6. DISCUSSION

The formation of large complex craters involve high pressures and deformation, high temperatures and melting, excavation to deep crustal levels with fragmentation, and removal of large volumes of rock [*Melosh*, 1989]. Impacts constitute major geological processes shaping the surfaces of planetary bodies with implications for the composition and evolution of the crusts [*Neumann et al.*, 1996; *Mungall et al.*, 2004; *Urrutia-Fucugauchi and Pérez-Cruz*, 2009, 2011]. Large bolide impacts have deeper and long-lasting effects in planetary evolution [*Mohit and Phillips*, 2007]. Collisions of planetesimals and large asteroids were numerous in the early stages of evolution of the solar system. Remnants of such period are represented by the iron and differentiated meteorites which were once parts of differentiated bodies. Meteorite impacts spanning a wide range of compositions and sizes continue falling on Earth, most of them of small sizes, which provide unique and rich information on the early evolution of the Solar System, dynamic processes, effects on Earth systems and on potential hazards [e.g., *Covey et al.*, 1994; *Toon et al.*, 1997; *Lauretta and McSween*, 2006; *Urrutia-Fucugauchi et al.*, 2014]. An example of large collisions is the formation of the Earth-Moon system, with collision of a Mars-sized body with the early Earth, which resulted in partial melting of the Earth and formation of the Moon with bolide and Earth's components [*Canup and Asphaug*, 2001]. The ages for the Moon and Mars large impact basins record a period of heavy bombardment, which is documented in the inner solar system [*Frey*, 2006, 2008].

Mars is characterized by a hemispheric dichotomy, with the southern hemisphere with higher and abrupt topography and a northern hemisphere of lowlands and smooth relief [*McGill and Dimitriou*, 1990; *Watters et al.*, 2007]. The southern hemisphere is heavily cratered and includes the large impact basins [*Frey et al.*, 2002]. In contrast, the northern hemisphere has fewer craters and no large basins. The lowlands of the northern hemisphere present a thinner crust compared to the southern highlands that are 25 km thicker. Studies have proposed that the dichotomy was formed by a large impact, with the northern hemisphere being a very large impact basin [*Wilhelms and Squyres*, 1984; *Andrews-Hanna et al.*, 2008; *Marinova et al.*, 2008]. Impact may have occurred early in the solar system formation more than 4 Ga, producing a long-lasting effect on the evolution of Mars lithosphere with the hemispheric dichotomy.

Large crater-forming impacts occur in short time scales. The intense deformation at short time scales differs markedly from low stress rates that characterize geological processes of deformation and fracturing, which involve long time scales in a series of incremental steps [*Kenkemann*, 2002; *Lana et al.*, 2010]. Depending on pressure, rocks deform or fracture when a pressure limit is exceeded. In impact events the sudden large energy release with generation of shock waves on the target rocks imposing intense stresses, result in fracturing of a large rock volume. Transient pressures are large, producing high temperatures and strain rates, resulting in fracturing, shock mineral deformation, and melting [*Melosh*, 1989; *Cintala and Grieve*, 1998; *Pierazzo and Melosh*, 2000].

The end-Cretaceous mass extinction is part of the five big events documented in the fossil record for the Phanerozoic, being the second largest after the Permo-Triassic extinction [*Raup and Sepkoski*, 1982; *Bambach*, 2006]. The percentages of genera and species going extinct at any given time and extinction rates have been difficult to determine. The chronological control available does not permit to constraint adequately the duration of the extinction events. Detailed studies of stratigraphical sections provide better control on the timing, pattern, and synchronicity of extinctions, but even then sections are affected by hiatus and incompleteness problems. The duration of extinction events had been estimated in hundreds of thousands or millions of years [*Hallam*, 1987; *Archibald*, 1996]. The causation for the extinctions involves a range of mechanisms such as marine regressions and transgressions, global cooling or warming, ocean acidification, warming-induced calcification, ocean anoxia, and volcanic-induced climate perturbations [*Hallam*, 1987; *Archibald*, 1996; *Keller*, 2008]. These mechanisms affect the environment and climate at different spatial and temporal ranges, resulting in disappearing of genera and species. In this context, large bolide impacts introduced a drastically distinct scenario, involving an intense very short-lived perturbation with capacity for producing global changes and catastrophic affectation of organisms.

Mass extinctions are recognized from higher extinction rates as compared with background extinction patterns. Mass extinctions appear to involve and/or trigger additional processes, bringing qualitative and quantitative changes in extinction selectivity [*Jablonski*, 1994, 2005]. Mass extinctions result in macro-evolutionary changes, with empty ecological niches being filled involving complex dynamics in biota turnover. Studies of taxa extinction and survivorship, within the limitations on the incompleteness of fossil record, provide insight on inner structure and response for perturbations. Recovery patterns and trends of ecosystems portrait a complex dynamics with distinct spatial and temporal scales, which are beginning to be deciphered [*Jablonski*, 2008].

The effects of Chicxulub impact on the ecosystems extended for a long period of several millions of years.

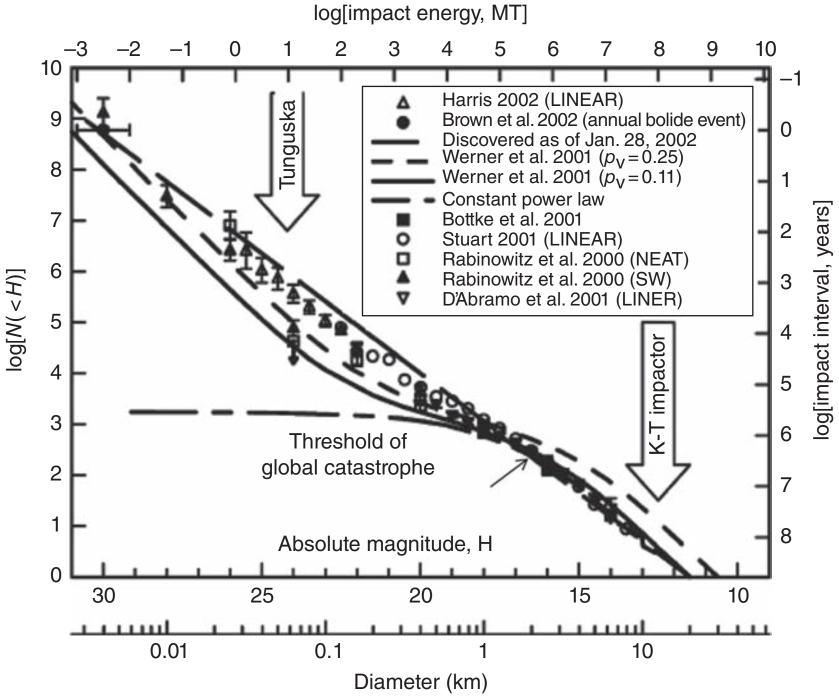


Figure 8.9 Logarithmic relationships among estimated impact interval (in years) and size distribution of cumulative number of NEAs as a function of impact energy release (in megatons MT), absolute magnitude of NEAs (H) and bolide diameter (in km) (taken from *Chapman* [2004]). The stellar magnitude H of an asteroid is estimated at 1 astronomical unit distance from Sun and Earth. Large impacts like Chicxulub with energy release of around 10 MT are characterized by long recurrence intervals, larger than 100 million years.

Disappearance of large numbers of species including complete groups severely affected the biodiversity and ecosystem composition in the marine and continental realms during the following periods. In the oceans, the K/Pg mass extinction affected groups of vertebrates, invertebrates, phytoplankton, and zooplankton, with entire groups disappearing, and long-term recovery time scales of several millions of years [*Sepkoski*, 1998; *Coxall et al.*, 2006]. The extinction was associated with a sharp decline in the flux of organic matter to the ocean deeps, with the suppression of pelagic marine productivity [*Zachos et al.*, 2008]. Recovery of the planktonic foraminifera involved diversification of new taxa during the Paleocene. The diversification patterns appear linked to recovery of the marine carbon cycle, with two stages recognized by *Coxall et al.* [2006] involving an extended period. Their study documents that time for reestablishment of integrated ecosystems in the deep ocean took several million years, following the collapse at the mass extinction event.

Effects of impacts in the environment and climate of the Earth have been intensely investigated, mainly in relation to the K/Pg boundary impact, where the affectation was profound and long lasting [*Pope et al.*, 1997; *Pierazzo et al.*, 2003; *Robertson et al.*, 2004]. The local and global environmental effects depend on a number of factors, including the energy released, impact angle, latitude, oceanic or continental target, amount of dust and climate-active gases, etc. [*Toon et al.*, 1982, 1997; *Covey et al.*, 1990, 1994; *Wünnemann et al.*, 2010; *Schulte et al.*, 2010]. The energy released depends on the impactor mass and velocity, which permits to estimate the magnitude of the impact event. Approximate estimates of the energy released have been related to diameter of impactors. Large impacts like Chicxulub with energy release of around 10 MT are characterized by long recurrence intervals, larger than 100 million years, while smaller impacts tend to occur with short recurrence intervals. The frequency of impacts has also been related to the impactor size, giving a logarithmic plot that has been analyzed in terms of the hazard associated with impacts [*Chapman*, 2004; *Pierazzo and Artemieva*, 2012]. Hazard analyses posed by impacts have incorporated the size distribution of near-Earth asteroids (NEAs), which have been mapped in recent years (http://neo.jpl.nasa.gov/stats/). The relationships among estimated impact interval and size distribution for cumulative number of NEAs as a function of impact energy release and bolide diameter are plotted in Figure 8.9 (taken from *Chapman* [2004]). Large impacts have the capacity for global disruption of the ocean and atmosphere and affectation of the climate and life-support systems, with >10 km diameter impactors resulting on extinction events [*Schulte et al*., 2010; *Pierazzo and Artemieva*, 2012].

8.7. CONCLUSIONS

In this chapter, we review the crater-forming impacts and their effects on the Earth's climate, environment, and life-supporting systems focusing on the K/Pg boundary and end-Cretaceous mass extinction of organisms. K/Pg boundary is marked by one of the major mass extinction events in the Phanerozoic, which affected about 40% of genera and 75% of species with whole groups disappearing, including the non-avian dinosaurs and ammonites.

Crater-forming impacts might be considered as a special class of extreme events with respect to other geological events, which are characterized by high energy release in "seconds" time scales. Impacts constitute major geological processes shaping the surfaces and evolution of planetary bodies. The formation of large complex craters with peak ring and multiring morphologies involves high pressures and temperatures resulting in intense deformation, fracturing and melting. Impacts produce deep transient cavities, with excavation to deep crustal levels, fragmentation, and removal of large volumes of rock.

The K/Pg boundary is marked by a clay layer globally distributed, which is characterized by anomalous contents of iridium, PGEs, and shocked minerals. The boundary clay marks the occurrence of a large bolide impact, which is traced by the Chicxulub crater. Chicxulub, located in the Yucatan Peninsula, southern Gulf of Mexico, is one of only three multiring basins in the terrestrial record. It is the only one with the ejecta preserved and the only multiring crater in the Phanerozoic. Studies examining the age, stratigraphical correlations, and composition of the K/Pg boundary layer have documented the genetic links to the Chicxulub crater. Impact resulted in deformation and shaking, which is recorded in the breccias and debris flow deposits in the Gulf of Mexico and Caribbean Sea area. Impact was on a shallow carbonate platform and resulted in huge tsunamis and in injection of carbon dioxide and sulfur components into the atmosphere.

Effects of impacts in the Earth's environment and climate are better understood, thanks mainly to studies of the K/Pg boundary impact. The affectation in the biota was profound and long lasting. Effects of the impact on the ecosystems extended for a long period of several millions of years. Disappearance of large numbers of species including complete groups severely affected the biodiversity and ecosystem composition in the marine and continental realms.

There are different aspects involved in addressing the Chicxulub impact as an extreme event. They include, examining the impact event and cratering, time scales involved and energy released and, assessing the local, regional and global effects, which involve major perturbations in the ocean and atmosphere modifying the climate and environment. We discuss how and to what extent life-support systems are affected by large impacts; and what the fossil record reveals about the extinction event and biotic turnover and how sudden or extended are the processes and extinction temporal records.

Studies of the K/Pg boundary events and mass extinction of organisms have focused increasing attention on the nature of sudden discrete events in the stratigraphical record. The impact hypothesis for the end-Cretaceous mass extinction reintroduced catastrophic scenarios for a discrete extreme event with long-lasting consequences. The impact produced a large crater in hundred of seconds time scales, generating severe effects on the Earth's atmosphere, oceans, and climate affecting life-support systems globally, causing a mass extinction.

Research on extreme events has over the past decades emerged as a major area in Earth and planetary sciences, across a wide range of disciplines, with a strong inter- and multidisciplinary character and with implications into the social and economical sciences. Extreme events within this context include large earthquakes, explosive volcanic eruptions, crater-forming impacts, tsunamis, catastrophic landslides and floods, which involve processes delivering huge amounts of energy on short time scales at their extreme ends of process range. Recognition and study of extreme events in the past geological records become more complex, due to problems related to stratigraphical and dating resolution of events. Stratigraphical analyses and recognition of sudden versus gradual processes remains a complex task, due to the incompleteness of the records, sampling resolution, biases, correlation, and dating. Analysis of the K/Pg boundary offers the possibility of exploring criteria for evaluating the geological record of an extreme event associated with a sudden catastrophic asteroidal impact.

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