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# Built From the Crater Up – Site Museums in Geosciences Communication and Outreach

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## Abstract

What is the role of site museums and geological sites in geosciences communication, education and outreach? Natural history and site museums contribute to learning, outreach and educational programs, with geological sites in National Parks, GeoParks and UNESCO heritage sites attracting large numbers of visitors, as well as scholars and students. Here, we examine the role and potential of a museum and research center in Yucatan, Mexico built around studies of the Chicxulub asteroid impact and the Cretaceous/Paleogene boundary mass extinction. The impact ranks among major single events shaping Earth's history, triggering global climatic change and wiping out ~76% of species. The crater, with a ~200 km rim diameter, is the best preserved of the three large terrestrial multi-ring impact structures, being a natural laboratory for investigating impact dynamics, crater formation and planetary evolution. The crater and impact deposits are not exposed at the surface, being covered by carbonate sediments after its formation, which presents a challenge for outreach and educational programs. The Chicxulub museum and center have a core mission to serve as a hub for multi-disciplinary research on the impact, planetary sciences, climate change and life evolution, as well as educational, outreach and science communication programs. It fulfills a recognized task for dissemination and communication of geosciences. After decades of studies, the Chicxulub impact and mass extinction remain under intense scrutiny and the new facilities built inside the crater, play a major role in expanding those efforts.

## 1 Introduction

Here, we address the potential of site museums with research capabilities, referring to a museum and research center in Yucatan, Mexico dedicated to the Chicxulub asteroid impact and the Cretaceous/Paleogene (K/Pg) boundary mass extinction. The impact and mass extinction of organisms, which includes the dinosaurs, ammonites, marine and flying reptiles among many other species, provide interesting attractive contexts for education, outreach and science communication.

Natural history and geological museums have a long rich tradition, housing important collections of rocks, minerals, fossils and animals and plants. They play an important role in non-formal education, with high learning potential for school students, museum-school synergies, science engagement, and teachers' professional development (Mujtaba et al., 2018). Museums with research departments allow integrating up to date science advances, expanding their capabilities. Modern museums take advantage of exhibits, interactive displays and virtual experiences, opening new opportunities (Collins and Lee, 2006; Louw and Crowley, 2013). Site museums and geological sites play major roles in geosciences education and outreach. Field trips to geological sites are part of educational curricula and in workshops, meetings and congresses. National parks, GeoParks and UNESCO heritage natural sites attract large numbers of scholars and students as well as visitors.

The Chicxulub Center for Scientific Research and Advanced Studies (CCSRAS) is a multi-disciplinary center integrating research laboratories, a core repository and a science museum (Fig. 1). The CCSRAS is located inside the Chicxulub crater in a unique position to engage school children, students and visitors to Earth´s processes and life evolution in a broad context. Comprehensive, informative educational, outreach and science communication programs are needed to face pressing challenges (Stewart and Lewis, 2017). Climate change, growth of the global population, demographic changes, increased demands of energy and mineral resources, environmental deterioration and biodiversity losses present major urgent challenges to society.

The Chicxulub impact is among the most important single events shaping life on Earth (Alvarez et al., 1980; Schulte et al., 2010). The impact marks the end of the Mesozoic era, with the mass extinction wiping out ~76% of species including dinosaurs, ammonites, marine and flying reptiles, and the start of the Cenozoic that saw important radiations of many groups including mammals and birds. Chicxulub crater, formed by an asteroid impact on the Yucatan carbonate platform in

https://doi.org/10.5194/gc-2020-13
Preprint. Discussion started: 14 April 2020


southern Gulf of Mexico (Fig. 3), was first identified in oil exploration surveys and drilling programs by Petroleos Mexicanos (Pemex) (Penfield and Camargo, 1981). It has a ~200 km rim diameter and a peak-ring and multi-ring morphology (Fig. 4); the structure has been investigated by an array of geophysical/geological surveys and drilling programs (Figs. 5, 6).

The K/Pg boundary is marked globally by the impact ejecta layer, characterized by the iridium and platinum group elements derived from the impacting body (Fig. 7; Schulte et al., 2010). The impact and its effects on Earth's climate and evolution of life have been intensively studied (Alvarez et al., 1980; Mukhopadhyay et al., 2001; Schulte et al., 2010; Lowery et al., 2018). Impact had massive immediate, medium and longer-term global effects on the climate and environment, providing important lessons for understanding the effects of human-made greenhouse emissions. Although the mechanisms for the extinction and subsequent species diversification remain under scrutiny, studies of this mass extinction uncover general principles governing species/clade resilience and evolvability in response to rapid climate and environmental changes. CCSRAS research rests on multi-disciplinary and international cooperation to tackle these issues.

## 2 Chicxulub Center

The CCSRAS is housed over an area of ~19 square kilometers located in the central sector of the Yucatan Science City ("Parque Científico Tecnológico de Yucatán" - PCYTY) in the state of Yucatan, southern Mexico (Fig. 2). CCSRAS is a joint project between the National University of Mexico, the National Council of Science and Technology and the Ministry of Science and Higher Education of Yucatan.

The project developed over the course of a decade, first emerging with the aim to establishing a site museum dedicated to the Chicxulub impact, its effects on the planet and showcase the research past and present to better understand the world around us. The first phase of the Chicxulub Science Museum was completed in 2011 within the Yucatan Science City, housed in the Central Library (Fig. 8). The second phase was the Chicxulub exhibition in the Meteorite Hall of the Grand Museum of the Maya World ("Gran Museo de Mundo Maya") inaugurated in December 12, 2012.

The Grand Museum Chicxulub exhibition was coordinated by Enrique Ortiz Lanz and has attracted large number of visitors, including students and researchers (Fig. 9). The exhibition provided an introduction to comets, asteroids and meteorites, early observations, myths and interpretations of meteorite falls and cometary showers, which later evolved as part of the studies of the planetary system. It included exhibits of the fossil record, particularly during the Mesozoic and evolution of the dinosaurs, marine microorganisms, ammonites and flying and marine reptiles, which went extinct with the Chicxulub impact. The crater studies are presented within the context of the oil exploration in southern Mexico and the geological characteristics of the Yucatan peninsula. The surface geological processes, including the groundwater flow and fracturing are influenced by the buried crater, which can be traced by the ring of cenotes and semicircular topographic depression over the crater rim. Chicxulub exhibition was awarded the 2013 Miguel Covarrubias Prize from the National Institute of Anthropology and History. Related programs at the museum have included conferences, seminars and symposia, with progress reports of studies and drilling projects.

Around the initial aim, plan for a larger facility in addition to the museum exhibits was born in 2015, which rapidly expanded to have laboratories, offices and the core repository of material from successive drilling programs. The PCYTY houses academic institutions and start-ups research-oriented firms, including the Yucatan State University, National University, National Council of Science and Technology research centers, CINVESTAV Center for Research and High Education, National Hydrocarbon Core Repository and apartment blocks for visiting scholars and students.

## 3 Chicxulub Science Museum

Studies on large meteorite impacts, dinosaurs, mass extinctions and life evolution attract the interest of wide audiences, opening interesting possibilities for science communication. The museum exhibits are organized around the studies of the Solar System, impact cratering, evolution of planetary surfaces, impact, crater formation, impact effects on climate and life-support systems, extinction of organisms, biotic turnover and life evolution. Exhibits aim to present, inform, engage and entertain visitors on the Earth and planetary sciences through studies on the Chicxulub impact, life evolution, K/Pg turnover and related inter- and multidisciplinary research.

Exhibits on the Universe hall introduce to the origin and evolution of the Universe, formation of stars and galaxies, the Milky Way galaxy, planetary system formation and the Solar System. The formation of planetary systems involves dynamic processes with collisions at different scales, with formation of first solids, planetesimals and large bodies. The evolution of planetary systems are marked by collisions of bodies, which are the main process in the formation of planets, satellites,

https://doi.org/10.5194/gc-2020-13
Preprint. Discussion started: 14 April 2020


dwarf planets, asteroids and comets. Large-scale collisions resulted in construction and fragmentation of proto-planetary bodies.

The impact cratering hall presents the characteristics and evolution of planetary surfaces, impact dynamics, crater formation, impacts on time and space, comets, near-Earth asteroids and impact hazards. Hypervelocity impacts deliver high amounts of energy in short time scales; resulting in deep excavation cavities, material transport and deformation. Planetary surfaces preserve a record of impacts, with the magnitude and frequency of impacts higher in the early stages. Impact cratering is a major process in the evolution of planetary surfaces and the deep interiors. The terrestrial crater record has been erased and modified, with limited number of craters preserved in contrast to other bodies like the Moon, Mars, Venus and Mercury.

Exhibits on Chicxulub crater give an introduction to the impact and impact effects. Chicxulub is the best preserved of the three large impact structures in the terrestrial record, being a natural laboratory for investigating impact dynamics, crater formation and planetary surface evolution in the Solar System. The crater is presently located half on land and half offshore, with geometric center at Chicxulub Puerto on the coastline; it has a peak-ring and multi-ring morphology, which characterizes complex craters on the Moon and other Solar System bodies.

Hall on the End-Cretaceous extinction and life evolution introduces to the meteorite impact end effects on life-support systems, linking the impact processes with the mass extinction. Exhibits introduce the fossil record, geological processes, the geological time scales and concepts of deep time and life evolution. The mass extinction marks a major boundary from the Mesozoic to the Cenozoic. In the geological record the boundary is marked by the Chicxulub ejecta layer. Interactive exhibits are used to introduce species communities and diversification after the impact and macro-evolutionary trends.

Exhibits present challenging themes such as extinction of species, emergence of species, macroevolution and global climate change (Sepkoski, 1998; Jablonski, 2006, 2008). Experiences in Science Museums and Museums of Natural History emphasise roles of teachers and museum staff in interacting with visitors, particularly with school groups and students. In this regard, exhibits on asteroid impact effects on life support systems permit to address present day extinctions and global warming.

https://doi.org/10.5194/gc-2020-13
Preprint. Discussion started: 14 April 2020


The exhibition in the Grand Museum of Maya World was planned at the time of the Mayan prophesy of the end of the world and included displays on historical accounts of catastrophic prophesies at various cultures. They included beliefs on what celestial phenomena such as comets and lunar and sun eclipses were associated with catastrophes, diseases, warfare and social unrest. How they were presented in the framework of the end of the Mesozoic era and mass extinction was subject of discussion.

Chicxulub Museum takes advantage of the research programs, laboratories and core repository, providing up to date information on studies and drilling projects. Plan is to also host temporary exhibits on studies of Yucatan peninsula, Gulf of Mexico-Caribbean Sea, mineral and energy resources, climate change and biodiversity.

## 4 CCSRAS Research

CCSRAS has a core repository and six laboratories for core analyses, sample preparation, petrography, micropaleontology, geochemistry and physical properties. Laboratories are equipped with analytical instruments, including core scanners, X-ray fluorescence system, gamma-ray core logging system, magnetic susceptibility meters, electrical resistivity meter, petrographic microscopes, laser particle analyser and an electronic scanning microscope (e.g., Fig. 10). The core repository has storage space for core samples and for conducting experiments, including low-speed impacts. It has facilities for slim-core logging and geophysical field equipment, including electrical resistivity, gravity and magnetic meters.

Projects focus on crater structure, dimensions, morphology, ejecta deposits, melt sheet, target deformation, impact-induced hydrothermal system, pre-impact structures and post-impact processes. The crater has been investigated with a wide array of geophysical methods, including gravity, magnetics, electromagnetics and seismic reflection (Hildebrand et al., 1998, Sharpton et al., 1993; Collins et al., 2008; Urrutia-Fucugauchi et al., 2011; Morgan et al., 2016).

The crater and ejecta deposits are not exposed at the surface, making drilling an indispensable tool to sample the impact lithologies and pre- and post-impact sedimentary rocks. Initial drilling was carried out by Pemex oil company, with intermittent core recovery providing samples of the carbonates, impact breccias and melt that were key for confirming the impact age, corresponding to the K/Pg boundary (Hildebrand et al., 1991; Sharpton et al., 1992). Subsequent drilling programs

https://doi.org/10.5194/gc-2020-13
Preprint. Discussion started: 14 April 2020


incorporated continuous core recovery and geophysical logging (Urrutia-Fucugauchi et al., 2004, 2008, 2011) (Figs. 8, 9), with tens of thousands of core samples distributed to groups in different countries, which has allowed to expand the research on the crater and K/Pg boundary.

Impact resulted in global effects on the climate and life support systems triggering a mass extinction in the marine and continental environments (Alvarez et al., 1980; Schulte et al., 2010; Lowery et al., 2018). Recent studies are shedding light on the likelihood of taxa becoming extinct as in the case of arboreal birds after forests disappeared (Field et al. 2018). Mass extinction coinciding with the impact was followed by radiations in numerous taxa including mammals (Dos Reis et al. 2012), worm lizards (Longrich et al. 2015) and birds (Field et al., 2018). Further investigations of factors driving species extinction and radiations are crucial to understand the effects of human-induced changes.

The CCSRAS conducts research relevant to communities at the Yucatan peninsula, which is characterized by karstic terrains, with low elevations and smooth relief (Fig. 2). The city of Merida, located ~30 km away from the coastline, is just a few meters above sea level. The platform is an extensive low-inclination shallow ramp, which records the sea-level fluctuations during the Late Pleistocene glaciation and the Holocene. The region is in the trajectory of hurricanes and tropical storms, with a thin soil cover and no surface waters, being vulnerable to coastal erosion, marine intrusion, aquifer contamination and to global warming with changes of precipitation, sea level, cloud coverage and evaporation.

The buried crater structure exerts a strong influence in surface geological processes including groundwater flow, subsidence, fracturing, coastal and karst processes. The density and distribution of karstic structures are related to dissolution and in turn to fracturing, topography, rainfall and groundwater flow. The sinkhole distribution correlates with the buried crater, notably with the cenote ring located over the crater rim. Surface fracturing is related to the stress/strain state, with the regional tectonics and differential subsidence of fractured breccias and carbonates, inside and surrounding the crater. Coastline morphology and processes are related to the buried structure, marked by the correlation at the intersections with the crater rings. The crater is marked on the surface by a gravity and magnetic semi-circular concentric pattern (Fig. 4), associated with the basement uplift, peak-ring and impactite deposits.

## 5 Discussion

The Chicxulub museum has been designed in a broad context, focusing on the Chicxulub impact and crater, and also including life evolution, impact dynamics and cratering on planetary scales. As a site museum, it joins other museums located in impact craters (e.g., Pösges, 2005). The mass extinction and K/Pg boundary provide interesting start point and context for addressing Earth´s evolution and how life evolves linked to geological processes, climate and environment. Exhibits allow introducing fundamental concepts on geological processes, life evolution, Earth System connections, feedback Earth component mechanisms and role of sudden global changes.

Mujtaba et al. (2018) reviewed the learning potential of natural history museums, focusing on school students, interactions museum-school, science engagement, opportunities and teachers' professional development. Natural history museums have a rich tradition, with exhibits, interactive displays and collections of rocks, minerals, fossils and animals and plants. Site museums play also important roles in conservation and preservation of fossils, minerals and geological sites (Lipps and Granier, 2009; Boonchai et al., 2009). Natural history exhibits and interactive displays on life evolution permit presenting and understanding difficult concepts in the life and geological sciences (Baum et al., 2005; Diamond and Scotchmoor, 2006; Spiegel et al., 2012; MacDonald and Wiley, 2012). They include the theory of evolution, natural selection, speciation, extinction, concepts of deep time, intense sudden high-amplitude events versus gradual incremental changes, global versus local processes, extinctions, speciation and macroevolution. Visitors to natural history museums are in general more familiar with evolutionary concepts. Studies on how visitors view, approach and accept/reject/ignore evolution show that museum visitors accept and are more familiar with evolution than general public (Mujtaba et al., 2018). However, large sectors of the public have difficulties comprehending those concepts, including students and teachers, which is also the situation with other topics such as climate change, sea level rise and cause of global warming.

Museums that take advantage of attractive locations, expand learning experience with field observations of geological outcrops, fossils and local flora and fauna. Chicxulub is located next to the PCYTY Botanical Garden and fossiliferous outcrops which are open as part of the museum visit. Additional activities include microscopic observations for petrographic and microfossil analyses. With the advent of the internet, digital tools, apps and new spaces particularly for the

https://doi.org/10.5194/gc-2020-13
Preprint. Discussion started: 14 April 2020


natural and physical sciences are developing (e.g. Braund and Reiss, 2004, 2006). Plans include field trips to K/Pg boundary sites (e.g., Fig. 7), with nearest sites in Campeche, Quintana Roo and Belize. Exhibits of boundary sites are complemented in videos and computer simulations, which illustrate how ejecta was emplaced at distant locations.

The crater and proximal ejecta deposits are not exposed at the surface, which is a challenge in comprehending the huge dimensions and characteristics. We found that visitors have difficulties understanding how and why dinosaurs went extinct, dynamics of asteroid impacts and crater formation, sequence of events, other species affected, what happened with the mammals, why and how some mammal species did not go extinct, how some species went extinct while others do not. The crater size and relation of buried structure and the ring of cenotes generate questions, with difficulties following the sequence of events. For instance, many visitors consider that impact formed the cenotes, though they acknowledge the crater lies deep beneath, covered by young rocks and that the cenotes are much younger surface features. The origin of the crater also generates confusion, though there are exhibits on the impacts, craters on the Moon and other bodies, asteroids, etc., some visitors have difficulty understanding volcanic craters and volcanoes as different geological processes.

Presenting and understanding geological time, evolution and fossil record are not easy tasks. Museums have developed a wide range of approaches (Braund and Reiss, 2004, 2006; Mujtada et al., 2018). Results show mixed responses and the complex interactions, which have been discussed and evaluated in different contexts. Exhibits on dinosaurs attract more interest than displays on other groups. Widespread interest in dinosaurs comes from their large sizes and diversity, including predators like the T Rex and raptors as well as the feathered dinosaurs. The dinosaurs were a highly successful group during the Mesozoic, occupying the ecosystems in the continental land masses including the polar regions (Sereno, 1999; Barret et al., 2009). Mammals are also attractive, particularly those on the Late Pleistocene megafauna from the Last Glacial age or the large land and marine mammals like whales and dolphins. Exhibits on human evolution and primates are more popular than similarly well-structured exhibits on other species. Chicxulub exhibits focus on relations and evolution of the various groups particularly the dinosaurs and mammals. Dinosaurs and mammals coexisted for a long time, with the different spatial distributions, habitats, body masses and life styles. What happened after dinosaurs, marine and flying reptiles, ammonites and many other groups went extinct helps to appreciate macro-evolutionary traits, species interdependency, how species evolve and interact, how ecosystems develop and function and how species relate and react to environmental and climatic conditions (Jablonski, 2005, 2008; Bambach, 2006; Barrett et al., 2009).

The End-Cretaceous mass extinction is the fifth and last large extinction event recognized in the geologic record (Alvarez et al., 1980; Emiliani et al., 1981; Bambach, 2006). Exhibits on the other major extinction events and the extinction rates for genera, families and species during the Phanerozoic in the marine and land realms allow to present macroevolution and changes through time (Sepkoski, 1998; Jablonski, 2005, 2008). Paleogeographic reconstructions document the evolving distribution of continents and oceans, with assemblage of the Pangea supercontinent and its breakup and drift apart. The changing ocean-continent distribution, ocean circulation, climate and landscapes form the backdrop for life evolution.

Impact affected the climate and environment at global scales, with a sharp sudden period of darkness and cooling caused by the fine dust ejecta in the stratosphere. This impact winter was followed by a global warming caused by the massive injection of carbon dioxide and other greenhouse gases (Alvarez, 1997; Schulte et al., 2010). The deposition of the fine ejecta resulted in severe changes in the sea surface water chemistry, affecting the marine organisms. The warm climates of the Cretaceous were followed by a cooling trend during the Cenozoic, with the formation of the ice polar caps and the Late Pleistocene glaciation (Zachos et al., 2008). Evolution of the different genera, families and species correlates with the long term climate evolution and changing paleogeographic and climate evolution during the Cenozoic.

Geo- and biological sciences scholars and students often have problems grasping details of evolutionary processes (Mujtada et al., 2018). This illustrates the challenges particularly for non-formal curricula and learning outside the classroom. Highlighting importance of formal and informal comprehensive education and outreach programs, science museums and supplementary activities directed to inform and engage the public on what science is and what represents. What is the scientific method and what makes it unique in understanding the natural world? In recent years with the development of molecular biology, with genetics, molecular clocks and metagenomics, evolutionary studies entered into a new field (Chen et al., 2014). Introducing new developments and findings present opportunities and challenges. Recent discoveries provide unprecedented detail into the events before, during and after the impact and mass extinction, which allow for a narrative of events, integrating evidence in a multidisciplinary approach.

CCSRAS has a research approach, displaying new results and challenges, with exhibits, displays and virtual experiences (Louw and Crowley, 2013). It provides an attractive forum, although its potential still needs to be further developed. In particular, we require to implement an evaluation of the programs, visitor experiences and ways to engage with teachers and students. Museums that house research and educational departments permit to keep up to date advances. Needed is a closer and better structured relationship with other actors in the science park and state education system. We require a strategic plan for science communication, with a wider scope and well defined priorities (Stewart and Nield, 2013: Stewart and Lewis, 2017).

Key aspects for science communication include global changes and effects on biodiversity and threats presented by the global warming and environmental affectations, which present severe effects on the biodiversity, with the loss of species at global scales. Displays showing examples on how studies connect to fundamental questions of life evolution can be used with reference to familiar groups of organisms. For instance, studies by Field et al. (2018) examined the extinction of birds, showing that the birds spared from extinction were land dwelling groups. This in contrast with what one will expect considering the abundance of arboreal stem birds before the impact during the Mesozoic and that flying capacity could offer survival advantages. The study, based on examination of the fossil record and molecular phylogenies, analyzes the extinction event and the post-impact radiation of crown birds. An explanation for the selective extinction of birds relates the widespread affectation of forests as a result of the impact. Studies show the intricate interconnections and complex responses during major biotic transitions and the post-mass extinction processes.

## 6 Conclusions

The CCSRAS is the first museum and research center built around the Chicxulub impact and the End-Cretaceous mass extinction, being part of a multi-disciplinary project integrating research laboratories and museum exhibits that conducts research, outreach and educational programs. The wide range of projects opens new inquiry lines as well as applied studies on environment and biotic conservation. The museum provides a space for learning, exploring and experimenting aimed to engage the interest of children, youngsters and adults. Science museums are important for science communication and important components of the natural sciences research enterprise; part of the discovery process and integrating and housing research laboratories enhances the capacities, making them more attractive to learn, wonder and experiment.

Science research and technological development are the driving forces for transformation of the societies. The museums of science are linked to development of modern societies and key components, fulfilling a recognized task for "effective dissemination and communication of the (geo)sciences to decision makers and society" (Arattano et al., 2018; Stewart and Lewis, 2017; Illingworth et al., 2018).

Knowledge among the general public of the Earth System characteristics and processes, principles of species evolution and extinctions and the power of human activities to transform our planet and impact on other species is critical to address the geo-environmental hazards (Stewart and Lewis, 2017; Illingworth et al., 2018). The CCSRAS combines features of natural history museums and research facilities, with exhibits that cover from hypervelocity impacts, high pressure/temperature processes and rheological properties to the delicate balance of geological processes and life. The Yucatan peninsula, known as the cradle of the Maya civilization that reached high levels of development, offers additional advantages for the project. The CCSRAS aims to become a multi-disciplinary hub for academics and students, expanding the capabilities for research, outreach and science communication programs of the PCYTY.

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https://doi.org/10.5194/gc-2020-13
Preprint. Discussion started: 14 April 2020


## List of Figures

Fig. 1. Chicxulub Center for Scientific Research and Advanced Studies in the Yucatan Science City of the Parque Cientifico Tecnologico de Yucatan. Views of the Chicxulub research complex, with the museum, laboratories and core repository (photos J Martinez, Z Mendoza).

Fig. 2. View of the Yucatan Science City (Parque Cientifico Tecnologico de Yucatan, PCYTY) in Sierra Papacal, Yucatan, Mexico. View to the south of the central sector, with the Central Library Building (Drone image, www.pcty.com.mx; Parque Cientifico Tecnologico de Yucatan, PCYTY).

Fig. 3. Chicxulub crater. Satellite interferometry radar image of the northern Yucatan peninsula (image courtesy NASA Jet Propulsion Laboratory), showing the surface topographic semi-circular depression above the buried Chicxulub crater rim. The location of the Chicxulub CCSRAS Center is shown by the star. Also marked for reference the location of Merida City and Chicxulub Puerto. (inset) Map of Gulf of Mexico and Yucatan peninsula, showing location of the Chicxulub crater.

Fig. 4. Chicxulub crater Bouguer gravity anomaly (Sharpton et al., 1993), showing the concentric semi-circular pattern, with the central gravity high and gravity rings marking the peak-ring and multi-ring morphology. (inset) Schematic structural model of Chicxulub crater, showing the basin, central uplift, terrace zone, melt sheet, breccias and target Cretaceous sediments (Collins et al., 2008).

Fig. 5. Chicxulub drilling programs. View of the drill rig for the Yaxcopoil-1 borehole, core samples for the impact breccias-Paleocene carbonates contact and core repository (Urrutia-Fucugauchi et al., 2004, 2011).

Fig. 6. View of drilling platform for the Chicxulub IODP-ICDP Expedition 364 drilling project over the peak-ring zone. Marine geophysical surveys, view of the UNAM R/V Justo Sierra.

Fig. 7. The Cretaceous/Paleogene (K/Pg) boundary is marked globally by the ejecta layer (Schulte et al., 2010). K/Pg boundary sites are interesting geological sites, marking a major event in life evolution. In the Gulf of Mexico-Caribbean Sea area the boundary is characterized by the presence of high energy sediments that lie in between the basal spherules and clay layers.

Fig. 8. Chicxulub Science Museum in the Yucatan Science City PCYTY. Views of the Central Library building that houses the museum in the second and third floors and views of the exhibits (Perez-Cruz and Urrutia-Fucugauchi, 2015).

Fig. 9. Partial view of displays of the exhibition on Chicxulub and the extinction of dinosaurs in the Gran Museo del Mundo Maya in Merida, Yucatan.

Fig. 10. Chicxulub laboratories, with view of the six laboratory facilities and some of the instrumental facilities.

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Fig. 1


Fig. 2

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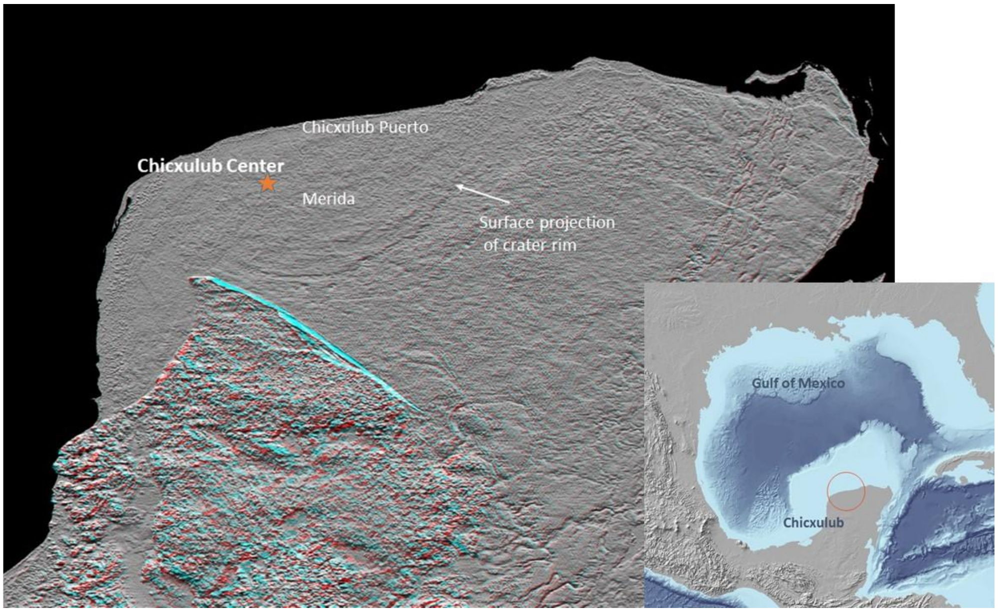


Fig. 3

520

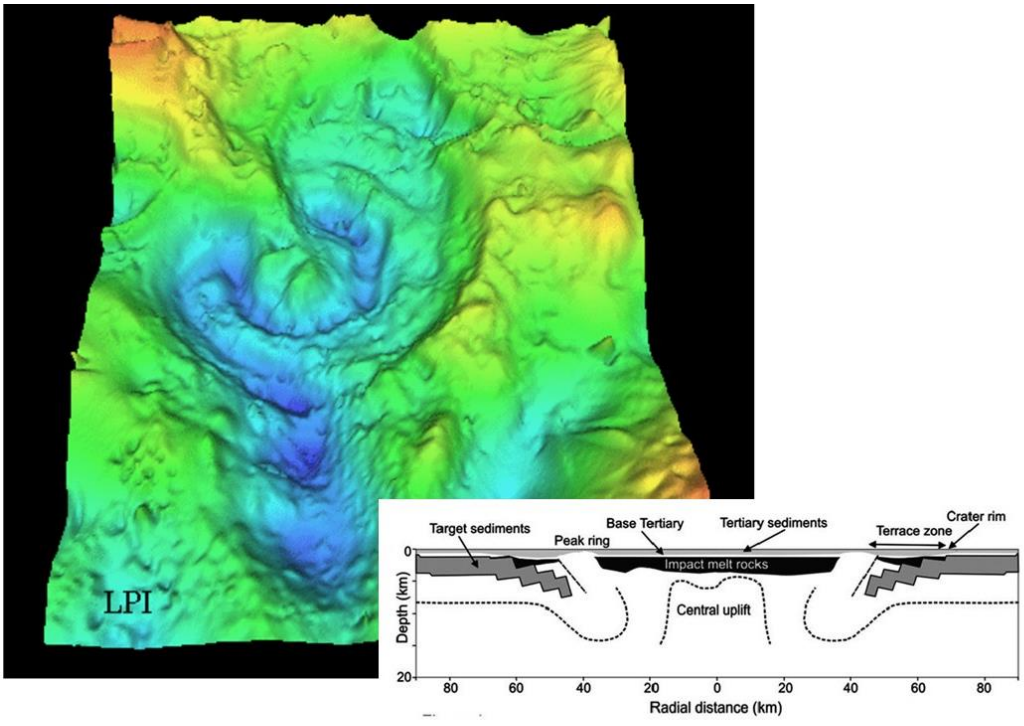


Fig. 4

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Fig. 5


Fig. 6

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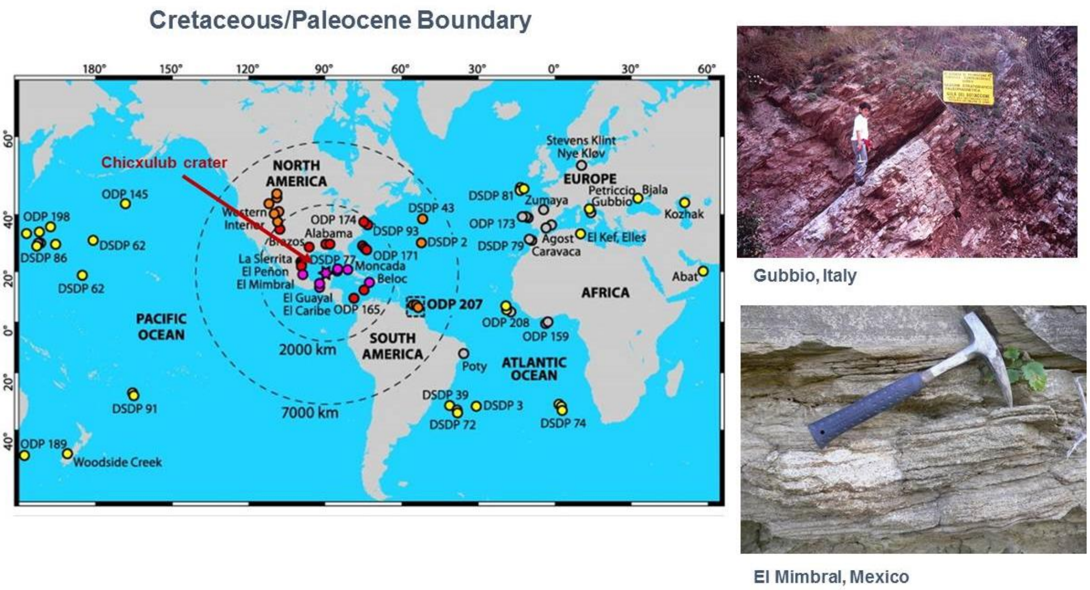


Fig. 7

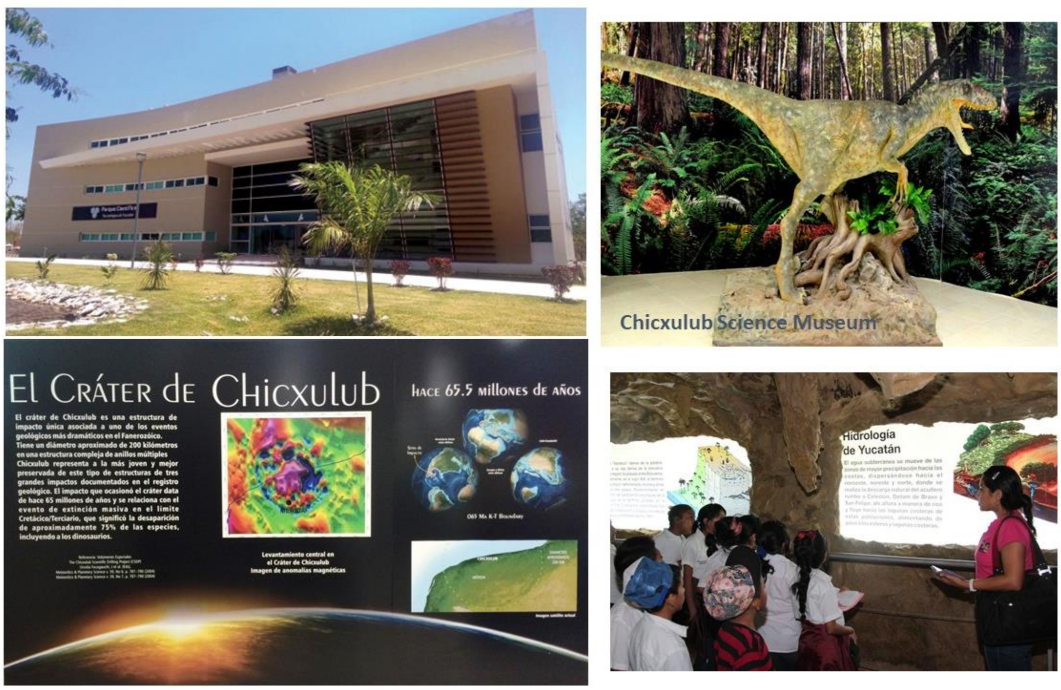


Fig. 8

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Fig. 9


Fig. 10