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Chicxulub: The Impact and Tsunami

The Story of the Largest Known Asteroid to Hit the Earth

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Preface: About the Book

The story of Chicxulub describes what was likely the most traumatic astrophysical event visited upon the Earth, during the last 100 million years: that of the giant 10-km asteroid that plummeted into the ancient Gulf of Mexico.[1] Moreover, this singular event imposed a far greater disruption to the Earth's biosphere than the strongest earthquake or most violent volcanic eruption. This asteroid's mass (likely half of that of Mount Everest) blasted through the atmosphere within seconds. Its impact at the sea surface set off an explosion that penetrated through a kilometer or so of seawater and into the Earth's crust, reaching the upper mantle (some 20–25 km beneath the surface). Meanwhile, its original explosion had produced searing global heat ejecting Gigatons of debris and dust into the atmosphere.

In addition, a globe-circling tsunami was then launched into the Gulf and beyond, drowning some 25 % of the world's coasts and leaving a huge water-filled crater. Its crater water boiled into the atmosphere and altered regional oceanographic conditions. The resulting atmospheric contamination fueled a series of long-lasting climate disruptions. The totality of these short- and long-term changes resulted in the mass extinction of 60–80 % of plant and animal life (including the dinosaurs) and likely changed the path of human evolution.

The Prologue describes Chicxulub's apocalyptic early morning fall to Earth 65.5 million years ago. Chapter 1 examines the nature of orbiting asteroids and their kinetic energies, followed by a discussion of historical asteroid impacts and the probability of future Earth–asteroid collisions.

[1] The object hit a much larger and deeper Gulf of Mexico at the location of what is now the coastal fishing village of Puerto Chicxulub—hence its name.

Chapter 2 describes the discovery of Chicxulub, beginning with the 1980 "Alvarez" analysis of the Cretaceous Paleocene (K-Pg) boundary, whose chemistry suggested that it was derived from a massive asteroid's impact on Earth. Years following the Alvarez expedition, the existence of a huge crater deep under the Gulf of Mexico was confirmed later as the asteroid impact site. A summary is given of the latest analyses of the Chicxulub data, also suggesting effects on the Earth's biosphere.

Chapter 3 paints a possible scenario of the Chicxulub impact sequence. Its explosion is described as it blasted through the atmosphere, the Gulf water, and deep into the Earth's crust. These explosive effects are compared to those of an underwater nuclear blast and include a model suggesting sequential formation of the impact crater. Similarities are drawn between the Chicxulub event and those of other asteroid impacts and volcanic eruptions. Finally, the energy of Chicxulub is compared with those of explosive geophysical phenomena and geological and astronomical events.

In Chapter 4, we discuss the tsunami created by Chicxulub and include a general "primer" on these types of waves and properties of refraction and run-up. Additional comments are made about historic earthquake and tsunami-generated floods. Two models of enormous tsunamis generated from different sources are then described. The first traces waves produced from a hypothetical caldera collapse in the Canary Islands. The second illustrates a future impact in the North Atlantic Ocean by an asteroid of 1.1 km diameter (one-tenth that of Chicxulub)—predicted to pass close to the Earth in 2085. Both models describe huge tsunamis hitting the shorelines that border the Atlantic Ocean. Finally, we draw a comparison between a laboratory-produced "Edgerton Effect" impact and the tsunami splash into the Gulf. We then track wave inundations around ancient Gulf coasts, the lowland areas of Central and North America, and then its rampage over the world's oceans.

Chapter 5 discusses long-term effects of the boiling Chicxulub crater water that fed atmospheric cloud as well as subsequently raising sea temperatures and altering oceanographic conditions in the Gulf and western North Atlantic Ocean. Meanwhile, the debris cloud blocking the sunlight shut down photosynthesis and produced frigid global temperatures and gray blizzards over the continents. As the atmosphere cleared, the remaining greenhouse gases dealt a final blow to Earth's biota, which suffered sweltering temperatures, perhaps for centuries.

Finally, a tally is made of the loss of biota from the mass extinction where approximately 60–80 % of all plants and animals were destroyed, ranging from the tiniest ocean foraminifera to land-lumbering dinosaurs. Mysteriously, some small mammals survived.

The Epilogue concludes our tale by an example of how the notable Cambrian Burgess Shale became isolated by pure chance, and subsequently precipitated animal extinctions, altering the tree of life. A question could be posed—how could an improbable single Chicxulub event alter by a similar process the entire future path of human evolution.

A Note from the Author (David Shonting)

The framework for this story was derived from research on tsunamis. As lead author and physical oceanographer, I was drawn to contemplating both the tsunami and the effects of the hot impact crater upon the ocean environment. Whetted by my interest in the study of waves and in the underlying sciences involved, I set about to revisit the Chicxulub story. Our tale touches upon an eclectic interplay of subjects including astronomy, geology, oceanography, chemistry, biosciences, and even world history. We have attempted to present the material not in a text format, but rather as a narrative, based on science for the general reader. Because this book relates to so many disciplines, tedious referencing has been minimized in order to help the reader engage with the flow of the writing. Alternatively, footnotes are used to expand on an idea or to provide added information.

A Note from the Coauthor (Cathy Ezrailson)

This Chicxulub tale starts out in fantasy and supposition and then initiates a journey that takes us through reality with its marvelous unfolding mysteries. Having had a rewarding career teaching young adults, I undertake this collaboration with my coauthor in order to help present a unique piece of Earth's history to the general public and to a new generation of science enthusiasts.

Naples, FL
Vermillion, SD
January 2016

David Shonting, Sc.D.
Cathy Ezrailson, Ph.D.

This book is dedicated by DS to Bill Barrett, who nurtured my interest in science and took me at age 8 to an MIT Open House, and to Howard Wagner and Grace Farnum, my science and math teachers at Laconia (NH) high school.

Also, this book is dedicated by CE to Ronald Stocker, my secondary school physics teacher, who encouraged me to be tenacious; to Ray Lawson, who taught me to write more succinctly; and Elfi Werzer, who instilled in me the joy of learning.

Acknowledgments

Much gratitude is given to our reviewers and copyeditors—those who have improved the reading and accuracy of this book through their meticulous edits: Tom Duncan, Alan Gibson, Susan Gapp, Lory LaPointe, Alan Massey, Carl Stendhal, and Mark Sweeney. Thank you to Alan Hildebrand and Steven Ward for use of their data and figures. All line drawings in this book were done by author David Shonting, unless otherwise indicated.

Contents

Abbreviations, Notation, and Metric Units

Dates quoted in the text are written in the form 01/Jan/1999 (meaning January 1, 1999). Since this book deals with physical quantities spanning great ranges of magnitudes, scientific notation (based on powers of ten) is used in order to avoid writing out multiple zeros or using terms such as trillion, quadrillion, etc. As an example, 500,000 and 0.00005 are written as 5.0×10^5 and 5.0×10^{-5}, respectively, where the exponent indicates the number of zeros to the right (+) or to the left (–) of the first digit. Since comparisons are frequently made of dimensions of objects or scales of phenomena, we employ the symbols > or < as greater than or lesser than and ~ as approximate values. Finally, Metric units are used throughout with some parenthetical notation, e.g., 17 km (11 mi).

Table of metric units used in the text

Quantity/Unit	Symbol	Equivalent/Comment
Length (l)		
Meter	(m)	Adult's stride
100 meters		Football field + end zones
Kilometer	(km)	10 of the above or 1000 m
Area (A)		
(Meters) ^{2}	$(m)^2$	Desktop
Volume (V)		
$(Meters)^3$	$(m)^3$	1000 L 1000 kg (of H_2O) Metric ton (of H_2O)
$(Kilometer)^3$	$(km)^3$	~900 Rocks of Gibraltar
Mass (m) (Amount of matter in an object)		
Kilogram	(kg)	~2.2 lb
Metric Ton	1000 kg	
Gigaton	10^9 tonne	
Acceleration (a)		
Gravity (g)	$(m/s)^2$	~10 m/s^2, ~32 ft/s^2 (Earth)
Force (F) (Weight = mass × g)		
Newton	(N)	
Energy (E)		
Potential (Joule)	(PE)	Work to raise an apple ~1 meter
Kinetic (Joule)	(KE)	
Megaton (of TNT)	(Mt)	Million tons of TNT
Power (P)		
Watt (Joule/sec)	(W)	Raising an apple 1 meter per second

Prologue: The Arrival

Abstract: The Prologue describes Chicxulub's apocalyptic early morning fall to Earth 65.5 million years ago.

At the first sign of the object, a new star-like image appeared to move gradually across the night sky, its glow produced by reflected sunlight. Such was the beginning of the scenario that unfolded over subsequent days and led to that fateful event, when the giant asteroid crashed into the middle of the ancient Gulf of Mexico (Fig. P.1). Today, its impact site would be centered on what is the northern edge of the Yucatan Peninsula, a location near the little fishing village with the quaint Mayan name of Chicxulub (pronounced: chick-soo-loob).

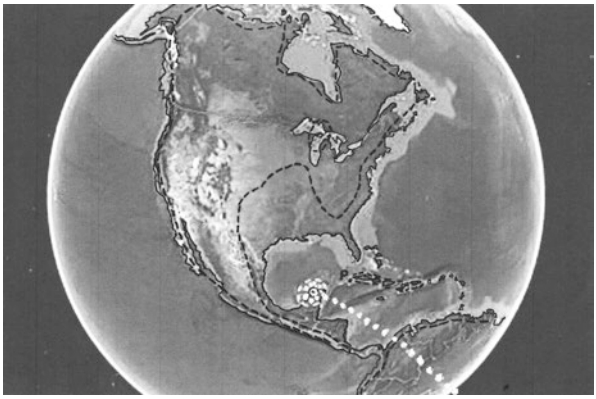

Fig. P.1 Schematic of trajectory and landing site of the Chicxulub asteroid in the ancient Gulf of Mexico. The broken line suggests the coastline 65.5 million years ago. See Chapter 3 for details. Our vantage point "P" (pictured) is on the west tip of Cuba

Imagine that we are perched, within a protective time machine, high upon a 1000 m mountaintop on the ancient island that today is called Cuba (see Fig. P.1*). There is a clear view to the western horizon where, on a calm patch of Gulf water some 400 km away, will soon become the Chicxulub object's "ground zero."*

From our vantage point, the asteroid appears to grow in size and intensity each night, soon surpassing the brightness of the "evening star"—the planet Venus. Within 6 h of its early morning Earth impact, this disc will have increased, appearing as a smaller version of our full Moon. As its position changes relative to our vantage point and that of the sun, it begins to move into the Earth's shadow, briefly appearing as a brilliant crescent. Soon, the object becomes fully eclipsed, vanishing into a black void as if turned off by a galactic switch.

Just before the object's collision with Earth, it enters the thin upper atmosphere white ball streaked with yellows and reds. It continues to punch downward, as if a sudden quarter-sized Sun gone amuck (Fig. P.2*). The night sky is lit up like a giant Roman candle.*[1] *Within seconds, the fiery object, with its blinding silver-white contrail, traverses its way through some 50 km (~30 mi) of atmosphere. This entire scenario is acted out as if in pantomime—in deathly silence.*

As the object, still silent, dips below the horizon, its contrail starts to fade. Seconds later, the night sky bursts forth with brilliance greater than the brightest

[1] Such galactic fireworks, unfortunately [or perhaps fortunately], might only have been witnessed by creatures such as dinosaurs, some of which likely roamed the ancient Gulf coasts or on hillsides of western Cuba.

Fig. P.2 The early morning arrival of Chicxulub as might be observed from a mountaintop from our vantage point (P in Fig. P.1) on the west coast of Cuba

noon. Chicxulub had struck! This scene was perhaps similar to what humans later observed when the first nuclear ignition flash was triggered at the historic "Trinity Site" in Alamogordo, New Mexico.[2]

After several more seconds, a reborn white sphere began to rise brightly in the west—illuminating the horizon like the dawn of a giant sun. This fireball lofted skyward as its contents expanded outward with a brightness that fully ignited the early morning sky. By the time it nears the top of the atmosphere, its vertical motion slows to a standstill, as its intensity starts to fade. Expanding horizontally, the massive sphere flattens out, metamorphosing, within minutes, into a giant mushroom cloud whose sides sharply reflect the early morning sunlight.

Within ~2 min of the impact flash, this mute fireworks display is shattered by an intense rumble as the ground starts to vibrate wildly (like from the passage of

[2] The 1945 desert test of the first atomic bomb.

a thousand freight trains). Announcing the arrival of the earthquake-like pressure waves generated by the exploding asteroid, it then passed through the seawater, blasting through the sea bottom and finally embedding into the Earth's crust. The ground vibrations taper off within a few seconds and are followed by a short period of silence. Suddenly, these shaking waves arrive as low frequency rumbles as the ground oscillates tens of meters in amplitude. These waves had energies that could only have been generated by earthquakes far stronger than the largest ever recorded (such as the 9.5 Magnitude 1960 Chilean tremblors). The shaking lasted for several minutes, as rocks tumbled from steep cliffs producing giant landslides. Soon, all was again quiet.

Then, within 20–25 min, two crushing airborne pressure waves suddenly arrive.[3] *The first is heralded by a mighty sonic "kaboom" from Chicxulub's atmospheric contrail. Even from our distant vantage point, this high decibel shock wave cuts through the atmosphere destroying all creatures' eardrums it encounters. A second or so later even more intense thundering and crackling airborne signals are felt from Chicxulub's Earth impact. These overpressures are sensed as hyper tornado-like 350 m/s (~750 mph) winds while adiabatic compression is causing air temperatures to soar hundreds of degrees. All around the vegetation, forests, and wildlife are simultaneously torn asunder and incinerated.*

Meanwhile, up in the sky, an expanding mottled gray-black cloud builds into a great cumulonimbus mushroom cloud, as if generated by a monster volcano. Dark layers that resulted from the cloud's fine sooty ash and rock particles condensing from the thousands of cubic kilometers of Gulf water vaporize into a giant billowing plume. Thunderous rumblings also follow lightning flashes as intense storms form within and around this towering column.

Within minutes, as ominous clouds spread overhead, hot ejecta, accompanied by a rush of intensely heated air, began to rain down. This fusillade hailed the returned to Earth of asteroid and crater material that had been blown into the air by the impact. Most of these plunging missiles are incandescent containing huge rocks and boulders, some far exceeding the masses of large buildings. These became fresh new meteors, hitting the land and exploding as firebombs. Debris falling into the sea is visible as towering splashes far out from the beaches.

The mushroom cloud stirred by upper winds now spread, like the drawing of a giant gray curtain, and blot out much of the morning sunrise. Soon, in the gathering dark, new visitors from the sky arrive—the first raindrops. Rapidly intensifying, they soon coalesce into torrential downpours at rates not in the usual millimeters but

[3] Earthquake P and S waves travel in the crust at about 6.5 km/s and 3.7 km/s, respectively, while the speed of the sound in air is a mere 0.34 km/s, hence the earlier arrival of the earthquake waves. Such waves are further discussed in Chaps. 2 and 3.

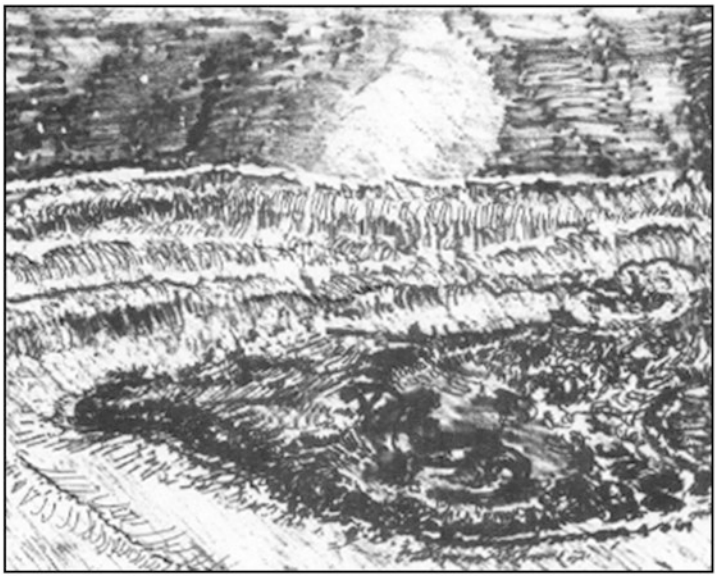

Fig. P.3 The arrival of the towering Chicxulub tsunami waves over the fire-razed Cuban coast. The downpour of the muddy rains almost erases the giant luminous impact cloud to the West

in meters per hour. The dirty gray-black precipitation has a pasty consistency with an odor suggesting strong sulfur or acidic content. Soon, the countryside, already littered with shredded and charred trees, vegetation, and wildlife, become covered with poisonous muck—rapidly accumulating on sloping terrain, transforming into huge run-off mudslides of acidic slurries that race down into the sea.

As this scene of devastation around us seems complete, our attention is drawn to a deafening roar arriving from the open seas to the west. Out of the gray mists and driving rains, there looms a parade of gigantic waves—the Chicxulub tsunami (Fig. P.3). They seemed to defy the laws of hydrodynamics as their frothing white crests grow upward, approaching our eye level with wave heights several hundred meters above the sea. As the first waves crash ashore, with crests separated by wavelengths of over a kilometer, they seem to be tipping over onto us. These waves met and swallowed up the gray outwash run-off that now was 50–100 m deep.
Within minutes, the Gulf waters pour inland, drowning the foothills to our west. The crests now decrease to some 200–300 m and came to a halt at the base of our

mountain vantage point. As the waves ebbed, they move in concert with the great outwash back into the sea, then again meet, and are swallowed up by the next even larger waves rushing shoreward. The entire inundation process repeats over and over until the oscillating waves exhaust their energy on the shores and finally die out. Meanwhile, the last of the giant tsunami waves still radiated out over the broad reaches of the ancient Gulf and subsequently into the Atlantic Ocean.
Thus ends the first act in the Chicxulub drama. From our perch, only the charred and gray landscapes remain—like fresh battlefields littered with destroyed life, sodden from pelting rains, and chilled from the darkened skies—all evidence of the massive asteroid's fatal collision with Mother Earth.

There is much more to this ancient Chicxulub saga and of its global consequences wreaked upon the Earth's environments. But, before we continue the story, it is instructive to back up a bit and examine the nature of asteroids in general—their physics, history, and the potential effects of their impacts upon land and ocean environments. Such background should assist the reader in comprehending the near-incomprehensible event—the great Chicxulub Impact.

Our story will be, as much as possible, based on available data, as well as conclusions from many scientists. However, it also inherently includes flights of imagination at times even approaching whimsey.

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