# IMPACT CRATERING ON EARTH: A HISTORY OF CONTROVERSY

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**ABSTRACT:** The discovery and study of structures caused by collision of extraterrestrial objects with the Earth has had a history filled with controversy. In the late 19th century G.K. Gilbert suggested that the patches observed on the lunar surface must formed by geologic processes similar to those here on Earth, perhaps of volcanic nature. Later, he was able to test his hypothesis when studying a bowl-shaped depression in Arizona, now known as Meteor Crater. Gilbert rejected a meteoric origin and proposed an internal volcanic origin, "cryptovolcanism", for the crater. This hypothesis unfolded a dispute that lasted decades. Mining engineer Daniel M. Barringer and geologist Robert S. Dietz attributed Meteor Crater to a meteorite impact, an "astroblem". In 1960, Ed Chao and Eugene M. Shoemaker discovered a polymorph of quartz at Meteor Crater that linked the structure to extreme, high-pressures incapable of being produced by any other known geologic process. Disagreement arose again in the 1980s, when the Alvarezes proposed that a large impact event was responsible for the Cretaceous-Tertiary mass extinction 65 million years ago; however, the crater could not be found. Then, Alan Hildebrand and colleagues found what many termed "the smoking gun", a crater dating ~65 Ma buried underneath about one kilometer of sediments. It did not take long for others to disagree with Alvarez and Hildebrand. Still some disagree about the role Chicxulub played on the dinosaurs' disappearance and whether this impact was indeed produced by collision ~65 Ma.

About 170 impact structures, unevenly distributed, have been identified on Earth. However, the development of new technology provides refined ways to study impact craters on Earth and other planetary bodies. For instance, the Holocene Impact Working Group is using standard stratigraphic and petrographic methods as well as remote sensing, with new geophysical data to study possible impact events within the last 10,000 years. They have found evidence connecting V-shaped chevron deposits in Madagascar to an impact-induced mega-tsunami about 5,000 years old. The relation of impact craters to mass extinctions and mega-tsunamis remains to be demonstrated. Nonetheless, undoubtedly, impact structures hold further clues about the formation of the solar system, Earth's geologic history, as well as for their economic resources. This paper attempts to provide not only a modest synopsis of the controversy surrounding the beginning of impact crater studies on Earth, but also a glimpse at recent research and current disagreements.

## INTRODUCTION

On a clear night, patches of dark and light areas can be seen on the Moon's surface. Deciphering the origin of these areas has been a long and controversial process. As with any important historical event in science, the starting point for this controversy remains elusive. Perhaps, it is wise to start in the late 1800's when Grove Karl Gilbert systematically mapped these circular structures he attributed to "cryptovolcanic" origin. It did not take long for geologists to disagree with G.K. Gilbert, as he was known. The debate about the origin of these features continued for decades. It was not until rock samples from the Moon were analyzed that these craters were linked to shock metamorphism induced by collision of asteroids with the lunar surface. The resulting structures are now known as impact craters.

During the last three decades, impact cratering has been recognized as a significant process re-shaping planetary bodies. Books, such as "Impact Cratering: A Geologic Process" by Jay Melosh (1989), have extensively documented the mechanisms involved in developing these features. Currently, 174 structures on Earth have been attributed to the process of impact cratering (Earth Impact Database 2006). Fortunately no such hypervelocity impact has occurred during historic time on Earth. However, in 1994 the widely-viewed collision of comet Shoemaker-Levy 9 with Jupiter increased awareness of the threat that impacts represent to our civilization and even to the survival of life on Earth. Also, economic mineral deposits are often associated with large impact structures such as gold for the oldest impact on Earth, Africa's Vredefort (~2 Ga; Moser 1997) and the rich mixed-metallic deposits of the Sudbury structure on Canada (~1.8 Ga; Krogh et al. 1984). Beyond their economic value, undoubtedly impact structures hold further clues about the formation and evolution of the solar system and Earth's geologic history. This paper is an attempt to outline the historical events that led to our present knowledge of impact cratering as a geologic process, ending with a current controversy.

## G.K. GILBERT AND CRYPTOVOLCANISM

The prominent American geologist G. K. Gilbert (1843 – 1918) (**Fig. 1**) achieved fame for his field work on the Henry Mountains and Lake Bonneville, as the predecessor of the Great Salt Lake in Utah. Gilbert joined the newly created United States Geologic Survey (USGS) in 1879 and served as the senior geologist until his death (El-Baz 1980). Also, he was a planetary science pioneer. His enthusiasm for scientific knowledge led him to trigger a controversy that would last for over a century. Gilbert interest started when he noticed the circular dark patches on the Moon. He observed the Moon for 18 nights in 1892 using a telescope from the U.S. Naval Observatory, with a power of 400 (Gilbert 1893). In his public address on "The Moon's Face" to the Philosophical Society of Washington, he argued that these features on the Moon must have formed in the same way as similar features on the Earth. He discusses

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*Figure 1. Pioneer geologist G.K. Gilbert (1843-1918) (Photograph: Geological Society, London archive).*

several possible origins including volcanism, tidal effect, even snow accumulation, but prefered a combination of "meteoric" and volcanic origin. According to Gilbert, "cryptovolcanic" structures on Earth were caused by gas explosions due to heat rising from magma that never reached the surface. Thus, he argued this process could also happen on the lunar surface. In addition, Gilbert presents results of his experiments, including the dropping bullets onto wet clay deposits (Gilbert 1893).

Hearing of the discovery of pieces of iron near a large depression, Gilbert took the opportunity to test his hypothesis by studying Coon Butte, currently known as Meteor Crater, in Arizona (Gilbert 1896) **(Fig. 2)**. According to his hypothesis, if this crater had been formed by an explosion from underneath, then, the volume of material at the rim should be larger than the volume of the excavated cavity because of the addition of the blasted material. On the other hand, he reasoned that if it had been created as a result of a large iron mass collision with the surface, the projectile should be buried beneath the crater. Before he ventured into Arizona, Gilbert asked Willard D. Johnson for a detailed geologic map of the area. Surprisingly, mapping revealed a rim composition of sedimentary rocks tilting away from the central cavity **(Fig. 3).** This led Johnson to propose that a mushroom-shaped igneous intrusion uplifted and tilted these rocks, whereas erosion excavated the cavity. However, Johnson did not find any evidence of igneous rocks within or outside of the crater (Gilbert 1896). This lack of evidence supporting a cryptovolcanic origin prompted Gilbert to return to his meteoric hypothesis. He arranged for a magnetic survey, similar to those used for mining exploration, of the structure and surroundings to find the large iron mass responsible for the crater. Unfortunately, they found no magnetic signal within or close to the crater. Therefore, he concluded that metallic fragments around the crater were simply a coincidence and a steam explosion from below, a "geobleme", was the only possible geologic origin.

In his 1895 annual address as the president of the Geological Society of Washington, Gilbert revisited the controversy about the origin of Meteor Crater as an example for the "method of multiple hypotheses", originally formulated by Thomas C. Chamberlin in 1890 (Gilbert 1896). He discussed how new hypothesis are developed through analogy of previous hypotheses. For instance, any attempt to explain the origin of the bowl-shaped hollow with an

*Figure 2. Meteor Crater, also known as Barringer Crater, is among the youngest impact structures identified on Earth with an age of 49,000 ± 3,000 years (Photograph credit: David Roddy, United States Geological Survey).*

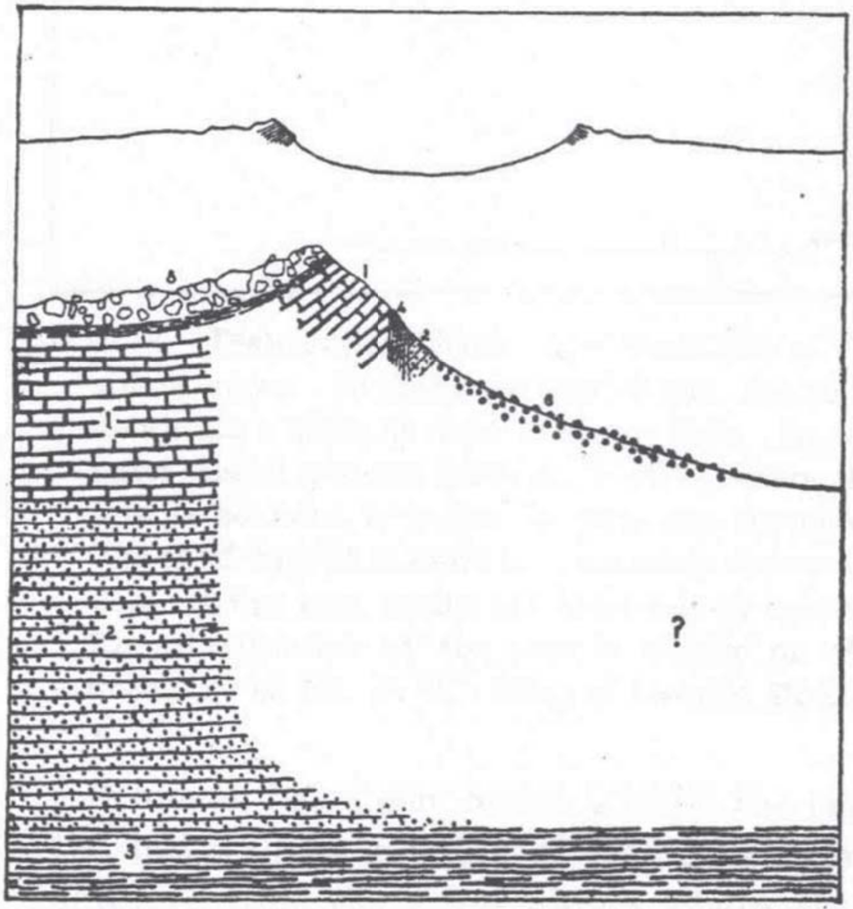

*Figure 3. Sketch of Meteor Crater's rim from the late 1800s. Top: topographic profile; Bottom: stratigraphic section at the rim (From Gilbert 1896, p. 7).*

approximately circular rim in Arizona should account for: the non-volcanic rocks in the crater, scattered iron masses, and the association between crater and iron. He described the progressive development of the hypotheses crafted to explain one or more of the features present at Meteor Crater, discussing in great details his own hypothesis. Hypotheses as outlined in Gilbert's speech include: (1) explosion similar to blasting in mining; (2) shower of fallen iron meteors or a star's collision; (3) igneous intrusion; (4) steam explosion; (6) limestone sink; and, (7) a combination of the meteoritic impact and volcanic explosion (Gilbert 1896).

G.K. Gilbert identified and characterized many of the features that we currently associate with impact craters, such as their hummocky ejecta texture and particle size distribution. However, based on the size of the excavation, he calculated that the projectile should have been ~250 m in diameter (Gilbert 1896). No large metallic body was found. As El-Baz (1980) noted, overestimation of the size of the expected iron mass clouded Gilbert's judgment. Therefore, he rejected the impact and favored the cryptrovolcanic origin for Meteor Crater.

## FROM COON BUTTE TO METEOR CRATER

Daniel M. Barringer (1860-1929), a Philadelphia mining engineer **(Fig. 4)**, purchased Meteor Crater in 1902 for $500,000 as a mining venture (Smith 1996). It did not take long for Barringer to disagree with Gilbert. When he noticed that small fragments of meteoritic iron were randomly mixed with ejected material from the crater's rim, he concluded these pieces must belong to a very large bolide that created the crater at impact. He expected there would be a metallic deposit with an estimated total value of $250,000,000 which will yield 500 times his initial investment. We can only wonder if he knew about Gilbert's 1890s magnetic survey that failed to discover a large iron mass.

Barringer then contracted Robert S. Dietz (1914 – 1995) **(Fig. 5)** as chief consultant for the Barringer Crater Company. This was a great opportunity for Dietz who had been interested in the cryptrovolcanic controversy during his doctorate studies, but was advised to pursue studies on marine geology (Bourgeois and Koppes 1998). Dietz agreed with Barringer and argued that the mechanism of

*Figure 4. Philadelphia mining engineer Daniel M. Barringer (1860-1929) acquired Meteor Crater in 1902. The Barringer family still owns the crater and maintains this popular, tourist attraction (Photograph credit: Barringer Crater Company).*

*Figure 5. In 1988 Robert S. Dietz (1914 – 1995) was awarded the Penrose Medal by the Geological Society of America (Photograph from Péwé 1989).*

formation of this crater involved a collisional explosion directly above the rocks rather than from below, an “astroblem”. In early 1929, field work did not locate the iron mass. Thus, Dietz realized it must have been vaporized during impact. By September 11 of that same year mining operations were suspended at Meteor Crater, and later on November 23 the last scientific report on the impact origin was released. According to friends and family, Barringer’s disappointment was so immense that a massive heart attack ended his life seven days later on November 30, 1929.

After his findings on Meteor Crater, Dietz decided to explore the Kentland structure in Indiana as another possible impact structure. Causing much surprise, he discovered a very important geologic criterion of impact craters used today for their recognition, “pressure-cones” or “shatter-cones”. He found these “cup-and-cone” structures located on limestone beds about 2 miles east of Kentland (Dietz 1947). These shatter cones were oriented perpendicular to the beds with their apexes pointing towards the top, and the “cup” section was displaced downward. Based on his observation, Dietz argued that this orientation indicate a unidirectional stress directly from above. Therefore, assuming the limestone beds were horizontal, a meteoric impact is the only geologic process capable of producing this type of deformation directly from above (Dietz 1947). On his effort to prove the impact origin of Meteor Crater, Dietz partnered with Eugene M. Shoemaker to look for shatter-cones. Unfortunately, they failed to find any evidence of these structures within or close to the Arizona crater (Bourgeois and Koppes 1998).

Nonetheless, Dietz’ hypothesis about the origin of Meteor Crater was revived in the late 1950s when a group of scientists led by Eugene M. Shoemaker (1928-1997) **(Fig. 6)** discovered a high-pressure polymorph of quartz there (McCall 2006). Gene, as his friends called him, was the first to identify the overturned stratigraphy at the rim of Meteor Crater; the overturned layers resemble the ones he observed while studying nuclear craters, recognizing this as a consequence of an impact (Chapman 2001). In their 1960 article for *Science*, E.C.T. Chao, E. M. Shoemaker, and B.M. Madsen documented the first natural occurrence of the mineral coesite, a polymorph of quartz with cleavage. They found this mineral in the compressed Coconino

*Figure 6. Eugene M. Shoemaker (1928-1997) was the founder of the USGS Branch of Astrogeology in 1961 and influenced science in many ways (Chapman 2001; Photograph by USGS).*

sandstone under the crater floor and in lenses of fragmented material, breccia. Before their discovery, coesite had only been produced in laboratory experiments at extremely high pressures not possible at the surface of Earth. Hence, Chao and colleagues concluded the only explanation for the high pressure mineral occurrence so close to the surface indicated it has been formed by pressures of > 20 kilobars due to an asteroid impact (Chao et al. 1960). For many scientists this was the missing piece to the puzzle. However, this was not the end of the controversy about Meteor Crater's impact nature. Only in 1969 with exploration of the Moon were craters finally linked to metamorphism induced by impacts. Since, impact craters have been extensively utilized as indicators of tectonic and/or volcanic activity on other planetary bodies (e.g. Matias and Jurdy 2005).

## IMPACT CRATERING AS A GEOLOGIC PROCESS

On Earth, as of August 2007, a total of 174 impact craters have been identified using remote sensing, field work, and geophysical data. Meteor Crater is among the youngest impact structures identified on Earth with an age of 49,000 ± 3,000 years. A detailed list of their names, location, size, age, and target rock could be found at the Earth Impact Database website (Earth Impact Database 2006). As more structures are studied and new surveys are acquired, this inventory evolves; the list increases or decreases according to the new findings.

Laboratory experiments have shown that the process of cratering, although complex, occurs in three progressive stages: contact and compression, excavation, and modification (Melosh 1989). The first stage begins with the contact of the projectile and the target surface **(Fig. 7a)**. Compression and acceleration of material starts when a fraction of the projectile energy is sent out through the point of first contact between the two materials. This stage, although a short one lasting only seconds, is characterized by high pressures, velocities and temperatures that determined the efficiency of the process. As a result both materials are subjected to partial or complete displacement, melting, and/or vaporization. Calculations for the iron projectile on Meteor Crater by Gilbert and Barringer certainly underestimated the amount of energy involved in this process; they ignored the possibility of melting and/or

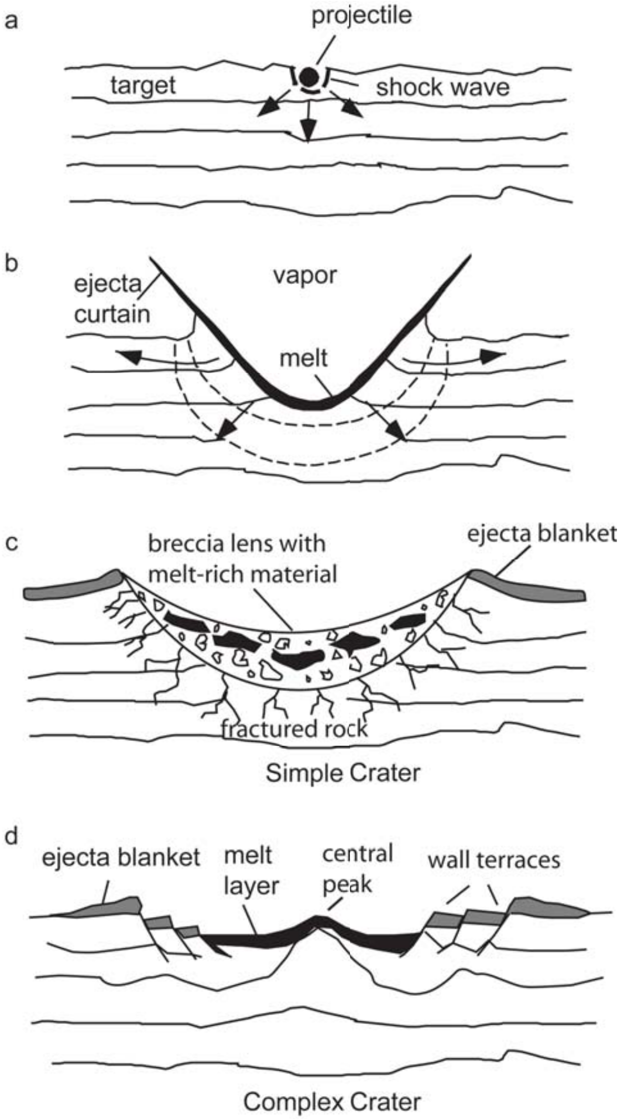

*Figure 7. Crater formation occurs in 3 stages. a) Contact and compression - waves propagate on both medias after first contact. b) Excavation - waves led to the formation of a transient crater. c and d) Modification - physical processes modify the transient crater, resulting in two main morphological type of craters: simple and complex (Modified from Melosh 1989).*

vaporization of material both from the projectile and the target.

During the excavation stage the hemispherical wave created by the impact continues to expand through the target until it weakens into a stress wave (Fig. 7b). Given that the wave expands in a hemispherical shape, its shallow portions interact with the surface reflecting downward and setting the rocks in motion (Melosh 1989). As a consequence, a bowl-shaped depression forms and ejected material begins to blanket the adjacent terrain. This fragmented material becomes finer in size as you move further away from the crater's rim, forming the hummocky texture Gilbert mapped so well in Meteor Crater. The crater grows in depth until the rock resistance exceeds the remaining energy. However, lower resistance close to surface allows continued growth of the diameter. Eventually, no material remains to be ejected from the cavity, and excavation ceases, leading the crater to its final stage (Melosh 1989).

Ultimately in the modification stage, physical processes (i.e. gravity collapse) sculpt the final crater (Fig. 7c-d). Collapsing can be a spectacular event producing pools of debris, central mountains known as central peaks, terracing of the walls and many other structures. There is no marked end for this stage; impact-related modification ends when there is no more material to move. However, long term modification (i.e. erosion) continues (Melosh 1989, French 1998).

Impact craters on Earth and other planetary bodies can be divided into simple and complex according to their morphology. Simple craters are typically bowl-shaped with a circular raised rim crest and an interior slope that is steepest closer to the rim (Fig. 7c). The rim-to-floor depth measures approximately one-fifth of their diameter and the rim height about four percent of their diameter (Melosh 1989). These characteristics were also observed by early surveyors of Meteor Crater such as G.K. Gilbert, D.M. Barringer, and R.S. Dietz. However, only Dietz could overcome not finding the big, iron mass responsible for its formation. On the other hand, for larger craters their depth is smaller relative to the diameter, so, gravity creates well-developed terraces on its steep walls, central peaks, and landslides. These craters are known as complex craters (Fig. 7d). Terrestrial and extraterrestrial studies have demonstrated that crater morphology also depends on target properties, impact angle, emplacement mechanisms, and/or atmospheric conditions at formation (Schultz and Gault 1984, Melosh 1989, Schultz 1992, Herrick et al. 1997, Stewart et al. 2001).

Earth has experienced the same bombardment as the other planetary bodies since the formation of the solar system by collisional accretion. F or instances, the surfaces of Mercury, Venus and Mars are significantly cratered. An impact of a Mars-sized object with an already differentiated proto-Earth offers the best working hypothesis for the origin of the Moon. Impacts have also play a role in the outgassing of volatiles in Earth's early crust.

Impacts have been linked to mass extinctions on Earth. Geologic evidence indicates an impact crater in the Yucatan Peninsula, Chicxulub, contributed to the end of the dinosaurs' 65 million years ago. In 1980, Nobel laureate, Luis Alvarez, presented this very controversial idea as part of the American Association for the Advancement of Science (AAAS) symposium held in San Francisco. To the surprise of the renowned geologist, organizer of the symposium and Chair of the Geology and Geography Section of the AAAS at that time, Gerald M. Friedman, Alvarez' appearance was non-planned and his talk information was not listed in the program (Friedman 2006). According to the address, Luis and a team of three scientists, including his son Walter Alvarez, accidentally discovered a high concentration of the rare earth element iridium while doing field work in Italy. This unusual concentration led them proposed that the impact of a large asteroid was responsible, creating a global effect that possibly led to a mass extinction. However, their conclusion was based solely on chemical composition and statistics; they were not able to find the crater or reveal exact abundances. As on many other new findings, controversy rapidly arose about Alvarez discovery. For Friedman and the unbelieving audience, the relationship between iridium anomalies and mass-extinctions was very suggestive but circumstantial (Freidman 2006). Nevertheless, Luis Alvarez was a well-established geologist and his idea was better received than Alfred Wegner's continental drift. Alvarez work was later published in Science (Alvarez et al. 1980), expanding the views of many scientists about the role of impacts on Earth.

Attempts were made to find a 65 Ma impact crater perhaps responsible for the Cretaceous-Tertiary (K/T) massive extinction (e.g. Parsons 1982, Grieve 1987). In 1990, Alan R. Hildebrand and William V. Boyton from the University of Arizona at Tucson proposed that the impact of an extraterrestrial object leading to the K/T extinction occurred between North and South America. They based their suggestion on three main pieces of evidences: concentration of shocked material (i.e. coesite); "impact-wave deposits" found in Cuba, Haiti, and southern North America; and, the location of a possible ejecta layer (Hildebrand and Boyton 1990). Hildebrand and Boyton went a step further and identify a potential impact site on what is currently known as the Colombian Basin. Seismic reflection data together with magnetic and gravity-field anomalies confirmed the presence of a multi-ring, circular structure with an outer ring ~180-km in diameter on the Yucatán Peninsula (Hildebrand et al. 1991). Buried underneath about one kilometer of sediments (Melosh 1997), this structure, named Chicxulub after the town close to the first well studied (Sharpton 1995), started a new controversy about impact cratering on Earth.

Independent $^{40}$Ar/ $^{39}$Ar dating analyses of centimeter-sized, glass globules called tektites from Haiti (Izette et al. 1991) and melted rock within Chicxulub (Swisher et al. 1992) gave ages of 64.6 ± 0.1 and 64.98 ± 0.05 million years, respectively. Thus, the structure has been widely considered to be the impact crater related to the 65 Ma, K/T boundary deposits (e.g. Sharpton et al. 1992, Alvarez et al. 1995). The actual size and morphology of the structure, nonetheless, is still dubious among scientists. Unfortunately, measurements obtained by geophysical methods such as gravity are vulnerable to diverse interpretations. Gravity results by Hildebrand et al. (1991) were challenged when a new, more complete gravity anomaly map including the northern section of the Yucatán by Virgil L. Sharpton and colleagues (1993). In addition to find clear evidence of the central peak and the three rings previously identified by Hildebrand et al. (1991), Virgil L. Sharpton et al. (1993) identified a possible fragmented fourth ring about ~ 300 km in diameter. Later, Pope et al. (1996) used Chicxulub's surface expression to estimate its diameter to be ~250 km.

Deep-seismic reflection sounding seems to have revolved the controversy about Chicxulub's size and also revealed some new insight into its morphology. This analysis suggests the crater's diameter is closer to what was originally proposed by Hildebrand et al (1991), 170-195 km (Morgan et al. 1997). In addition, the data revealed a prominent fault scarp with a vertical offset of ~0.5 km at about 170-195 km from the crater's center, were the outer ring is located (Morgan et al. 1997, Melosh 1997). This fault scarp is buried by crater's fragmented material, thus, it must have formed before and within minutes of the impact (Melosh 1997). Furthermore, the crust-mantle boundary underneath Chicxulub **(Fig. 8)** is higher at the center and lowers away from the uplift (Melosh 2001).

Remains of a possible piece of the projectile responsible from Chicxulub, and the death of the dinosaurs, was found in a core from the Northern Pacific Ocean. Chemical analyses for the "fossil meteorite" show characteristics typical to meteorites from a carbonaceous chondrite composition with a cleat iridium signature (Kyte 1998). Carbonaceous chondrites, although very rare, contain important clues to the formation of the solar system (Norton 1998). If indeed, this is a piece of the projectile that caused the K/T boundary mass extinction, then, impact models could be better constraint in order to simulate this catastrophic event.

After two decades of debate, the Chicxulub crater is widely considered to have been formed ~65 Ma when an asteroid, perhaps, 12-25 km in diameter (Melosh 2001) collided. Because it is under water and covered by sediments, this crater ranks as the best-preserved large impact site on Earth. This structure shows morphological complexity similar to large impact craters on other terrestrial planets: central peak, and three rings. Moreover, evidence of mantle rebound has been found underneath the central peak area. However, Chicxulub's critical role in the death of the dinosaurs has not been universally accepted (e.g. Keller et al. 2007).

## THE FUTURE OF IMPACT STUDIES: A NEW CONTROVERSY

Meteor Crater became a symbol for planetary scientists in the 1960s and it was used as a training facility for Apollo's astronauts. The Barringer family still owns the crater and maintains this popular, tourist attraction in northern Arizona. Both Robert S. Dietz and Eugene M. Shoemaker lived long enough to see the impact theory well accepted among their peers and reinforced by new technology. In fact, they were both recipients of numerous awards including the G.K. Gilbert Award (Shoemaker in 1983) and Penrose Medal (Dietz in 1988). Unfortunately Dietz, considered one of the most influential geologists and famous for his work on sea-floor spreading, died of a heart attack in 1995. A couple of years later, in 1997, Gene ironically was killed on another type of collision, a car accident while studying impact craters on the Northern Territory of Australia. His wife and research partner, Carolyn J. Shoemaker, survived the accident. However, the controversy about impact craters, their origin and consequences have not yet come to an end.

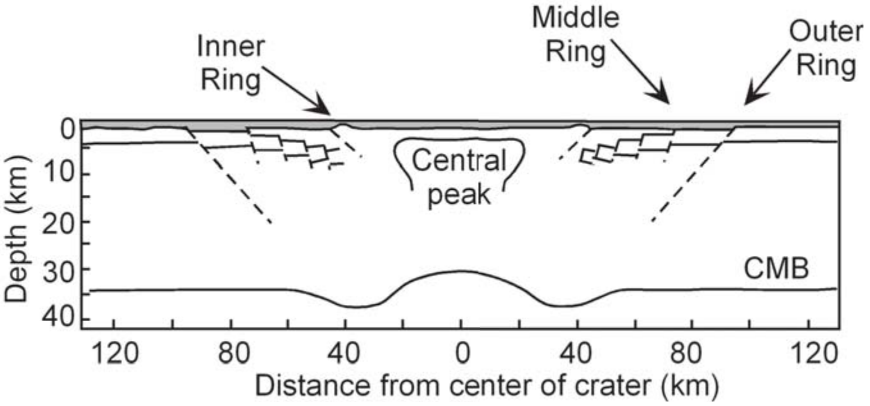

*Figure 8. Morphology of the Chicxulub crater according to studies expanding for two decades (Modified from Melosh 2001). CMB: core-mantle boundary.*

*Figure 9. V-shaped deposits like this one from Madagascar have been linked to impact-induced mega-tsunamis by the Holocene Impact Working Group (Photograph credit: Dallas Abbott).*

A group of scientists, calling themselves the "Holocene Impact Working Group", are using new technology to identify asteroid impacts that have happened within the last 10,000 years. Their integration of sea surface altimetry data, marine geophysical data, and satellite imagery have led them to identified at least 9 impact crater candidates on the ocean floor. What separates the Holocene Impact Working Group (HIWG) from other impact-scientists is their utilization of V-shaped, sublinear to parabolic depositional landforms known as "chevrons" (Hearty et al. 1998), as indicators of mega-tsunamis generated by ocean impacts in recent years. For many years chevron deposits, such as the ones shown in **Figure 9**, have been attributed to aeolian (Maxwell and Haynes 1989).

In 2006, W. Bruce Masse and members of the HIWG studied a cluster of chevrons in Madagascar pointing in the same direction, towards the middle of the Indian Ocean. Upon closer inspection of the ocean's surface, using laser altimetry data, they found a crater ~29 km in diameter. Moreover, the presence of marine microfossils and melted metals (i.e. Fe) on the chevrons deposits link the collision event responsible for the crater to the chevron deposits. Thus, Masse et al. (2006) concluded that the chevron deposits correspond to sediments carried to land by a mega-tsunami. This is not the first time such a potential link has been proposed using the geologic record. For instance, according to several studies (e.g. Bryant et al. 1997, Bryant and Nott 2001, Kelletat and Scheffers 2003) chevron deposits along the coastlines of Australia could be explained by one or more extreme tsunami. On an interview with the New York Times, Dallas Abbott from the Lamont-Doherty Earth Observatory announced that chevrons on other areas such as the Caribbean have also been connected to possible impact structures (Blakeslee 2006). However, the number of inferred impacts greatly exceeds the commonly accepted estimates based in statistics by astronomers.

In summary, in just over a hundred year the process of impact forming craters was proposed for the Moon, investigated at Meteor Crater, and rejected at least twice. Only many decades later proven. Technological advances have given us the first look at the crust-mantle boundary below the Chicxulub impact crater. Nonetheless, new controversies about the recent record of impact craters remain to be proven.

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