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The Tale of Chicxulub

Abstract After reviewing the character of asteroids, we now turn to the story of the discovery of the remains of the great Chicxulub object that fell to Earth, some 65.5 million years ago. Piecing together the data, scientists discovered worldwide evidence in the K-Pg Boundary portraying the mass extinction of 60–80 % of the life on Earth. Some 20 years later, further findings exposed the crater along with evidence of the effects of the impact from outcrops in ancient Gulf of Mexico and deep bore holes around the world. Also, described is the controversy in which claims that Chicxulub's extinctions were caused partly or only by the eruptions in the Indian Deccan plateaus.

The Alvarez Discovery: The Origin of the K-Pg Boundary

This part of our story begins in 1980 with a publication by scientists from the University of California, Berkeley, and the Lawrence Berkeley Laboratory (Alvarez et al. 1980). This group which, included the retired Nobel Laureate, physicist Louis Alvarez and his geochemist son, were examining ancient Earth rocks for evidence of past life extinction events. Their focus centered on exposed limestone formation in the K-Pg Boundary from an ancient deep-sea bed found in an eroded cliff near Gubbio, a medieval town in Northern Umbria, Italy.

The limestone was formed in part from tiny (~0.1–2 mm) fossilized calcium carbonate shells of benthic foraminifera (forams). These organisms have

evolved in the world's oceans over eons into thousands of species, many of which had developed unique shell forms during different geologic ages. Their shells and bony structures settled onto the ocean floor and over millions of years became compressed and fossilized, consolidating into much of the Earth's limestone deposits.¹ By vertically sampling carbonate sediments in the deep ocean as well as limestone from ancient uplifted sea floors, paleontologists have used forams to date rock layers and to reveal changes in marine environments (e.g., temperature and climate) occurring over millions of years.

In multiple locations, the Gubbio rock strata exhibited two rock layers each with distinctly different foram populations. The deeper (i.e., the older) layer formed from a dense concentration of foram shells, displaying a large diversity of species. The upper (younger) strata of rock contained a less dense fossil concentration with different varieties of forams. Between the layers lay a thin intermediate clay boundary that would become one of the most significant paleontological markers in geologic history.

The clay interface between these two foram layers ~1–2 cm thick, contained no carbonate fossils. Potassium-Argon radioactive dating placed this layer's age at 65.5 million years.² This fell precisely between the late Cretaceous and the beginning of the Paleocene Period known as the "K-Pg boundary."³ This boundary had been established in the 1970s as an indicator (in geologic time) of the most recent and extensive of the great biological extinctions occurring within the last 500 million years.

For a perspective of the time of the formation of the K-Pg boundary Fig. 2.1 displays the traditional Geologic Column (drawn from Leets and Judson 1958). Shown are five major mass extinction periods. The K-Pg boundary divides the late Cretaceous from the Paleocene period when the fossil records indicate the sudden disappearance of the dinosaurs.⁴

In order to explain the K-Pg extinction many hypotheses have been proposed. Scientists discussed this issue at several international meetings including in Ottawa (1976) and in Copenhagen (1979), but arrived at

¹ This type of limestone was used to build the pyramids of Egypt.

² Potassium-Argon dating is based on the measurement of the product of radioactive decay of an isotope of potassium (K) into argon (Ar). Potassium is commonly found in micas and clays. The decay product Ar-40 (a gas) escapes in liquid (molten) rock, but starts to accumulate when the rock solidifies (recrystallizes). The time since solidification is calculated by measuring the ratio of Ar-40 accumulated to the amount of K-40 remaining. The long half-life of K-40 allows calculation of the absolute ages of samples in the millions of years.

³ Paleontologists tend to keep changing their time scale names. What was referred to as the Cretaceous-Tertiary (K-T, noting Cretaceous in German is spelled with a K) boundary now is called the Cretaceous—Paleogene (or Paleocene) or K-Pg boundary.

⁴ We note that the period of *Homo sapiens* existence has occurred over only ~3 million years, far less than then the ~200 million years rein of the dinosaurs.)

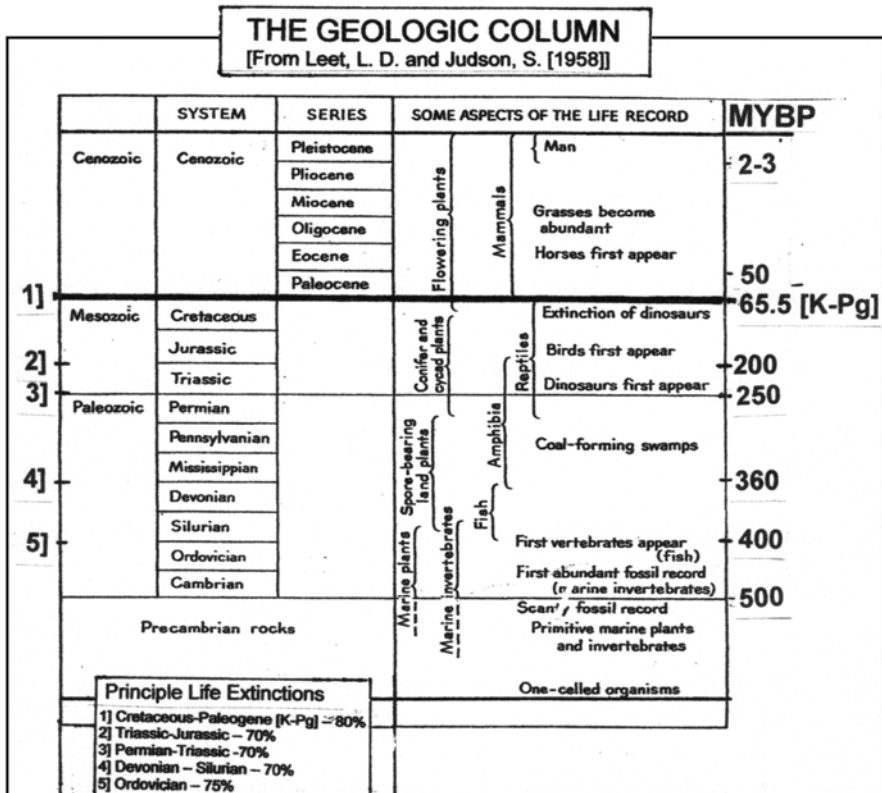


Fig. 2.1 The geologic column (redrawn from Leets and Judson 1958), showing the late Cretaceous—Paleocene (K-Pg) boundary (dark line) marking the life extinction. The *insert* shows the important life extinction events with percent of species destruction

little agreement as to its causes. Theories floated about included: (1) traumatic changes in oceanographic, atmospheric, or climate conditions which had been driven by continental-sized volcanic eruptions such as the Indian “Deccan” events discussed at the end of the chapter, (2) gross magnetic field reversals and polar shifts; and even more bizarre events, such as (3) those caused by a nearby super nova explosion, or (4) a possible flood from a giant underground Arctic lake.⁵ The problem with these hypotheses was that all lacked direct unambiguous physical evidence.

⁵ Supernovas are huge exploding stars. Those which have aged collapsing under their own weight, generate immense thermal energy from gravity, reaching ~45–50 billion degrees C. then exploding, flinging mass into space. Such material appears to have different isotopic ratios than that of our solar system.

The Alvarez geochemical analyses of the Gubbio K-Pg layer were most revealing: it contained unusually high concentrations of the platinum group elements, i.e., platinum, iridium, osmium, and rhodium. Concentrations of iridium, the easiest to quantify, were some ~30 times higher than was found in the strata above and below the boundary (see Fig. 2.2). Also there was a much higher concentration of iron pyrite (iron sulfide) in the boundary material, than appeared in the upper and lower layers. (This sulfur-based rock was to have strong significance as will be discussed further in our story).

The researchers, looking elsewhere, also identified the same 65.5 Million year old K-Pg boundary layer in Denmark (some 1400 km distant), which also had a high iridium spike coinciding with the Gubbio data (Fig. 2.2). Furthermore, the Denmark strata showed both similar abrupt changes in the vertical distribution of forams as well as the complete absence of fossils in the thin clay K-Pg boundary, again characteristics matching those of Gubbio. Searching further afield, they found high iridium in K-Pg layers reported in New Zealand—on the other side of the world—18,300 km away.

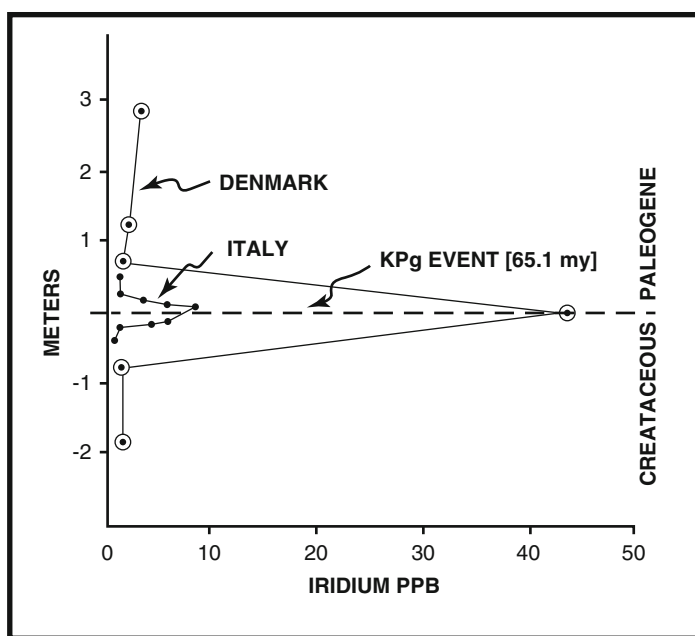


Fig. 2.2 Concentrations of Iridium (parts per billion) as a function of depth (obtained by Alvarez et al.) in K-Pg ancient ocean sediment rocks from Italy and Denmark. The Iridium concentration spikes around the 65.5 million year mark (determined by radioactive dating) and falls to ambient average Earth values below (earlier) and above (later)

What was the significance of the high iridium in the data? A compelling fact was that that iridium (and the other PGE's) was known to occur in much higher concentrations in most stony meteorites than are found in the Earth's crust. This suggested that the high iridium source was of extra-terrestrial origin. Analyses of the isotopic ratios in K-Pg layer samples indicated, however, that this material was still native to our solar system, i.e. unlikely formed from supernova ejecta.

By the process of elimination, similarities of the fossil changes across the globally distributed layers, and the identical age of the boundary samples, lead to the conclusion that the ubiquitous K-Pg layer was formed from the fallout from an impact explosion of a very large carbonaceous stony asteroid—native to our solar system. The extended geographic distribution and the thinness of the K-Pg layer also suggested that the iridium-rich material was spread worldwide over a short time interval, much of it settling out, perhaps within 10 years or so of impact.

On the Size of the Asteroid

An important parameter of an impacting asteroid is its size, which as we have shown in Chap. 1, governs the amount of explosive impact energy and hence is an indicator of its destructiveness to the Earth's living inhabitants. Alvarez et al. obtained a rough estimate of the asteroid's diameter, through four different thought experiments:

1. From several samples of the K-Pg layer an average Ir concentration per unit area of the Earth's surface was estimated. Multiplying this value by the Earth's area yields the amount of Ir delivered by the asteroid that had settled out in the K-Pg layer. Using the known average fraction of Ir in the typical stony-type asteroid, the total mass fraction of fallout forming the K-Pg layer was estimated. However, this left out the Ir within the ejecta that had remained in the atmosphere long after the K-Pg layer was formed. From studies of the Krakatoa eruption, it was estimated that ~20 % of the ejecta's finer particles remained in the atmosphere for a very long period.⁶ Adding this amount to the K-Pg layer's volume and using the mean density of 2200 kg/m³ yielded an asteroid diameter of ~6.6 km.

⁶Krakatoa was the great Sumatra island volcano eruption in 1883 that caused the largest documented Earth explosion, discussed further in Chap. 3.

2. Estimates of the frequency and the size of Earth orbit-crossing asteroids equal or larger than 10 km in diameter and the craters they produced (see Fig. 1.6), suggests that the mean time between collisions is about 100 million years—consistent with a 65.5 million year-old event. Moreover, the average time between major life extinctions happens to be ~ 100 million years, further suggesting that a 10 km object would be a reasonable candidate.
3. The K-Pg boundary thicknesses at widely separated sites would yield an approximate volume—if one assumes that the clay material in the K-Pg boundary was the total fallout from the atmosphere with no mixing from the layers above and below. Since asteroid impact models predict that the amount of ejecta thrown into the atmosphere was about 60 times the mass of the asteroid, working backwards, yields the asteroid's diameter as ~ 7.5 km.
4. The size of the object needed to supply enough fine particulates to be thrown into the atmosphere to shut out sunlight and stop photosynthesis, has been calculated. Referring again to the Krakatoa eruption, the particle concentration required for sunlight attenuation is relative to that of the asteroid impact and suggests its explosion energy was ~ 1000 times that of Krakatoa. This yields an asteroid-size calculation consistent with those from the other three methods.

The authors concluded, based on these four estimates that the Chicxulub's diameter was $\sim 10 \pm 4$ km. Using this size, together with a typical meteoric speed of ~ 25 km/s, it was calculated that the object's impact crater must have been more than 200 km in diameter. As we shall later see, this estimate of the crater size proved amazingly accurate.

Conclusions of the Alvarez Study

The Alvarez paper concluded that it was the asteroid's impact that had created the wide spread extinction in the biosphere at the K-Pg boundary. The impact explosion had propelled a mix of Gulf water, asteroid debris, sea bottom sediments, limestone and other fine rock fragments, into the atmosphere—totaling some 60 times the object's mass. The initial blast pressures, and heat equivalent to 10^8 Mt (~ 7 billion Hiroshima bombs), instantly destroyed life for hundreds if not thousands of kilometers out from ground zero. Within hours, the daylight turned into night, bringing on severe global cooling, and worse, shutting down photosynthesis on land and oceans. Aerosols and finer particles lingered in the atmosphere and prolonged the cold and darkness likely for years.

The presence of fossil structure and sediments around the K-Pg boundary, and from several other studies, suggested a destruction of 60–80 % of the

total Earth's animal and plant life. This included marine and flying reptiles, dinosaurs, larger mammals, most marine invertebrates, microscopic floating animals, and a variety of trees and plants.

The Alvarez paper generated intense interest (including much controversy) so scientists started to look around the planet for a very big late-Cretaceous asteroid impact site. However, as the Alvarez paper suggested, finding the crater would be problematic since, (1) land impact signatures could have long been buried by sedimentation or worn away by erosion, and (2), for a deep ocean impact (more probable) plate tectonics over the eons could have subducted the crater remnants into the mantle.⁷

Found: A Crater

Ironically, it turned out that an earlier observation had been made in the Gulf of Mexico that would eventually support the Alvarez hypothesis. In 1951, the Mexican oil company—Petróleos Mexicanos (PEMEX)—in its search for oil and gas had drilled exploratory wells into the Comanche Bank, the shelf north of the Yucatan Peninsula (Fig. 2.3). One borehole reaching 1300 m below the sea bottom unexpectedly came upon a layer, not of oil or gas, but of fragmented rocks (breccia) containing unusual fused rocks and shocked quartz minerals. Such materials (discussed further in Chap. 3) are often found at sites, which had experienced intense pressure pulses from traumatic explosive events, such as volcanic or atomic blasts. This site was documented as a volcanic dome—an anomalous feature that did not match with the local geology. Over the next 40 years, these data lay unexamined in company files.

In 1978, a PEMEX geophysicist Glen Penfield, while examining airborne magnetic survey data from the Comanche Bank, observed large semi-circular arc-like feature of magnetic anomalies of “extraordinary symmetry” (Penfield 1978). It appeared as part of a ring ~70 km in diameter in the sub—bottom, its east and west ends opening to the south (see Fig. 2.3—insert). Penfield, searching further, then found a map of Yucatan gravity anomaly data, made over the Bank some 10 years earlier, which yielded an even clearer semi-circular feature.⁸ This appeared as a deep formation since it was not obvious in the shallow sea-bottom bathymetry. Searching further, Penfield uncovered a later PEMEX gravity study, this time on the Yucatan peninsula, whose gravity

⁷This refers to “sea floor spreading” where volcanic magma at the mid-ocean ridges spread over the sea floor and at the continental edges is forced under the plates back into the mantle (the process known as subduction).

⁸This map suggested evidence of an asteroid impact to R. Baltosser, a contractor, but corporate policy prohibited his publishing at that time.

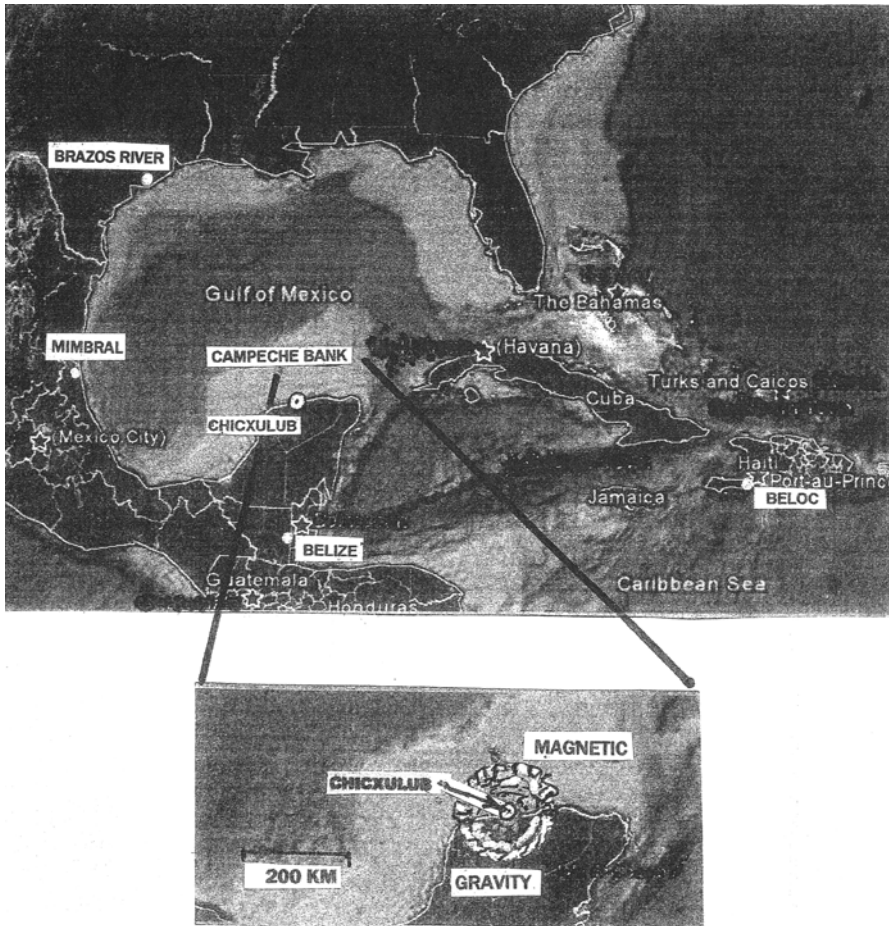


Fig. 2.3 The shallow Campeche Bank, a limestone extension of the Yucatan Peninsula, site of petroleum exploration drillings and the asteroid ground zero (*white circle*) centered at the fishing village of Chicxulub. Insert: The arc formations (upper-magnetic and lower-gravity) anomalies form the ~180 km circular crater

anomalies traced out another semi—circular arc—but whose ends opened to the north. Bingo! The two arcs fit remarkably well together; forming a circular pattern exceeding 180 km diameter and whose center was near the coastal village of Puerto Chicxulub (see Fig. 2.3). The inference here is the magnetic and gravity anomalies suggested that a giant crater had been discovered.⁹ It seemed that Alvarez's asteroid (to be) had found a home.¹⁰

⁹Local gravity in the impact site would have been altered, as was the magnetic field. The impact would have compressed or shifted the rock altering local gravity values. Crater patterns such as deep rings would show up as arc-like anomalies in the surface gravity data.

¹⁰It turned out that this crater, although existing under the sea, was not in a subduction zone such as borders the U.S. west and east coasts, hence it was shielded from sea floor spreading and preserved over the 65.5 million years.

Found: Tektites in Haiti

Fast forward to 1990, when Alan Hildebrand, a graduate student at the University of Arizona, was studying K-Pg strata deposits in an ancient limestone outcrop near the mountain village of Beloc, Haiti ~20 km southwest of Port au Prince, (see Fig. 2.3). This site had been considered to be an ancient volcano by Haitian Professor F. Moras. Hildebrand's analysis of the K-Pg boundary clay, however, revealed randomly distributed fused green glass spherules (Hildebrand 1980). These objects, called tektites (Fig. 2.4) are produced during high-energy events such as violent volcanic eruptions, nuclear blasts, or even from the rare asteroid impacts.

In the heat of the blast, minerals are fused (or even vaporized) as they are thrown out from the impact site. In the atmosphere, they condense and solidify, often forming semi-spherical or teardrop shapes ranging in size from 0.1 to 10 mm that then fell back to Earth. Analysis of the Beloc K-Pg layers also yielded high levels of Iridium. And, interestingly enough, adjacent to K-Pg strata, were large concentrations of ancient coastal marine sediments. Was it possible that these widely spread tektites were formed by ejecta from a massive meteor impact explosion? If so, then the marine sediment materials accompanying the tektites, could have been deposited by turbulent mixing of tsunami waves generated by an asteroid's oceanic impact. Hildebrand, unaware of Penfield's studies, was likely musing, "What happened to the crater"?



Fig. 2.4 Tektite glass spherules ejected in a molten condition from the Chicxulub impact found in Mimbral, Mexico (Photo by Hildebrand et al. 1991)

A Fortuitous Geology Conference

Later that year, when Hildebrand was presenting his findings at a geology conference in Texas, a Houston Chronicle reporter, Carlos Byars, told him about the 1978 (Penfield et al. 1981) discovery of the Chicxulub crater. Subsequently, the two scientists met and maybe toasted with Margaritas to a “Eureka Moment” as they together assembled pieces of the puzzle. The entire crater with evidence of its global debris field had been found. The Alvarez paper had set the scene and raised the questions. Then, with the Penfield and Hildebrand et al. discoveries, many of the dots had been connected.

Word of the impact crater discovery spread and soon opened the floodgates of further Chicxulub studies. Additional investigations attracted the talents of a diverse group of scientists including: geophysicists, geologists, geochemists, astronomers, biologists, paleontologists—and even cosmologists. Over the next 25 years or so, investigations of Chicxulub, using new scientific and engineering techniques, included the: (1) exploration in the crater using deep seismic refraction profiling studies, (2) borehole drillings from both in the crater area and globally in deep ocean sites. And, (3) further discovery and analyses of worldwide K-Pg boundary outcroppings.

For the remainder of this chapter, we briefly summarize the results of the Chicxulub studies undertaken since the Penfield and Hildebrand interaction in 1990, much of which is based on two comprehensive review papers. The first, published in 2010 by Peter Schulte et al. (with 40 co-authors and 57 references) was entitled “The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary.” This paper describes the asteroid’s impact and its effects on the Earth’s environments. It details analyses of deep core and outcrop samples of the K-Pg boundary and examines the effects on mass life extinctions.

The second paper published in 2013, is by S.P.S. Gulick et al. (with five co-authors and 89 references) entitled “Geophysical Characterization of the Chicxulub Impact Crater”. This paper concentrates on the geology and has solid review of the geophysics of the Chicxulub crater features at impact and details of the present structure. Also comparison is made of Chicxulub structures with two of the largest Earth impact craters; Sudbury, Canada and Vredefort, South Africa as well as two multi-crater Lunar structures.

Geophysical Gravity and Seismic Data

Following Hildebrand’s discovery, further gravity and seismic refraction measurements, both on land and over the sea-bottom, helped to determine shape (morphology) and size of the deep impact formation. An example is a



Fig. 2.5 Gradients of gravity anomalies from the deep Chicxulub crater reveal circular patterns of denser rocks created under the great impact heat/pressures centered on the present coastline (*black line*). Black dots on land are water-filled sinkholes (cenotes) probably formed from solution in the porous limestone formed over the crater from millions of years of sedimentation (A. Hildebrand, M Pilkington and M. Connors, 1995)

computer mapping of old gravity data anomalies (Fig. 2.5, shaded areas), was made by the Geological Survey of Canada. The mapping shows at least two dominant concentric craters with diameters of ~ 80 and ~ 180 km, centered on the present north coast of the Yucatan Peninsular (black line). Other features suggest a widely distributed debris field.

Along with the gravity patterns, a curious surface phenomenon was found on the landward (south) side of the outer crater. Black dots that were superimposed on the map posit hundreds of surface limestone sinkholes (cenotes). Their distribution, obtained from both land surveys and by satellite imaging,

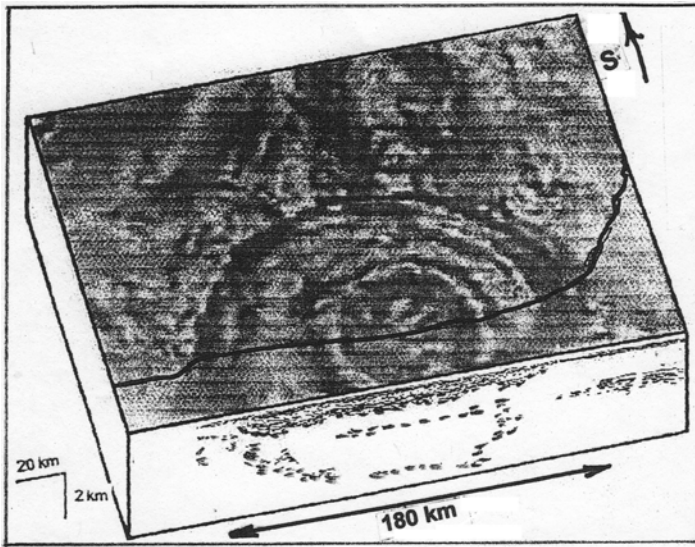


Fig. 2.6 The Chicxulub crater (looking south at about 60°) portrayed by computer analysis of the three dimensional gravity anomalies as underlying multiple crater rings centered on the present coast (*black line*). The cutaway (front face) displays the sub-bottom profile from a marine seismic section ~20 km off shore. Visible is the crater top with down-dropped blocks on its sides and the overlying layers of recent sediments, the same that formed the present Yucatan and Florida Peninsulas (M. Pilkington and R. Hildebrand 2000)

sharply frames the southern rim of the outer crater.¹¹ Their cause is unclear, but it appears that they were formed from an earlier dissolving of porous limestone accreting along the crater boundary that surrounded the impervious melt material during eons of post impact sedimentation.

Another high-resolution computer contouring analysis of the PEMEX data shows the shaded zones of gravity anomalies (Fig. 2.6). The circular structure of the multiple rings is portrayed magically as if the overlying Gulf water and the upper Yucatan limestone carbonate platform had been swept away.

The front cutaway view in Fig. 2.6 is of a vertical sub-bottom acoustic reflection profile made from a survey ship along an East-West transect.¹² The upper dark area is the ~1–2 km layer of limestone over the crater which formed the Compache Bank (see Fig. 2.3) which is similar to the Florida and

¹¹ Such formations, found throughout the low carbonate platforms of the Yucatan, Florida, and the Bahamas, are formed when ground water dissolves limestone channels, forming deep wells, caves and even sinkholes.

¹² To do this—as the seismic survey vessel proceeds, acoustical energy is projected downward and reflects off the different bottom layers, arriving back to the ship's hydrophones at different times. This creates a sub-bottom profile map of the various sediment and rock layers along the path (section) of the ship's course.

Bahama Bank platforms. Below, is the basin melt rock layer whose sides, are the wall profiles of tumbled rocks and breccia (fractured minerals) probably from the collapse of the initial transient crater (discussed in Chap. 3).

Most recent surveys confirm the crater as a multi-ring basin, whose outermost or most defining ring exceeds 200 km in diameter with debris fragments out as far as 50 km beyond. This established it as one of the largest impact craters ever-discovered on Earth, Moon, or Mars, Morgan J, et al. (1997); Morgan J and Warner M (1999).

Bore Hole and Crater Stratigraphy

The explorations of the Chicxulub crater and mapping the global distribution of the K-Pg boundary layer greatly benefited from the technologies of the oil industry. Giant floating oilrigs positioned in the Gulf drilled through the ocean floor sediments deep into the bedrock. These bore holes better revealed the 1–2 km of post-impact sedimentary Cenozoic layer of limestone (see Fig. 2.1) composed of fossil foram shells laid down during the ~65.5 million years after impact. Beneath this layer lay the crater basin—a ~50–200 m thick layer of impact melt breccia. These contained shocked minerals including quartz, feldspar, zircon (see Fig. 2.7), which under the Microscope displayed evidence of instant crystalline deformation imposed by the impact pressure waves.

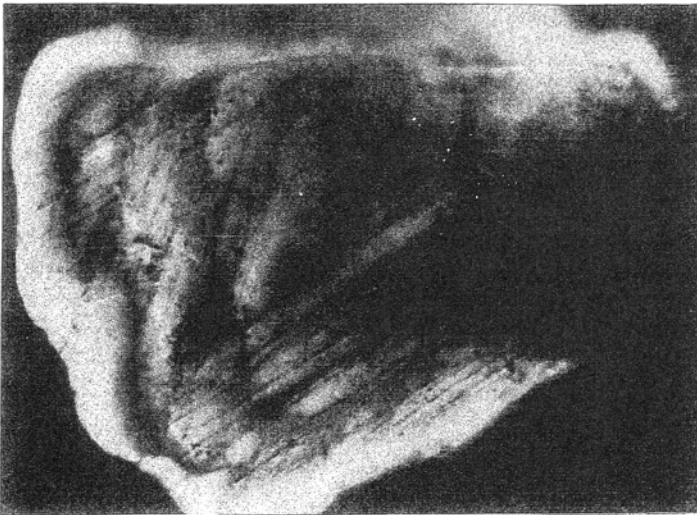


Fig. 2.7 A shocked quartz grain recovered from the breccia mixed melt sheet in a drill hole 50 km from the crater center. The shock impact causes the striations in the crystal planes (photo by Hildebrand et al. 1991)

Beneath the impact breccia is the heart of the crater—the pancake shaped “melt mass” of solidified rock up to 500 m thick and ~80 km in diameter, which, shortly after impact, formed from the molten rocks flooding the crater basin. The potassium-Argon dating, of 65.5 million years of the melt mass samples, was identical to that of the impact glasses found in the worldwide distribution of the K-Pg boundary clays.

Evidence of Ejecta in the K-Pg Boundary

Over the years further PEMEX data were obtained at various distances within and around the crater. Moreover, new core samples were gleaned from some 350 K-Pg boundary global locations—from both land and ocean drill sites (Fig. 2.8).

The K-Pg layer thickness, the character and the size of particle ejecta, and changes in geochemistry, were related to the distance from the crater. Within the crater zone there was more evidence of super-heated mass gravity flows. Within the ~200–500 km of the crater center, breccia layers up to 100 m thick were found mixed with spherules of tektite glass.

Further out, around the ancient Gulf borders, cores yielded layers varying from 1 to 80 m thick and contained a heterogeneous mixture of breccia clastic, fused quartz rock spherules and shocked quartz grains.

At distances of ~1000–5000 km from the crater in the Western Canadian interior and Southeast Caribbean, up to 5 m layers of clastic older rocks along with continued high concentrations of iridium were found. The Marine cores, over 5000 km from the crater boundary layers, were often characterized by

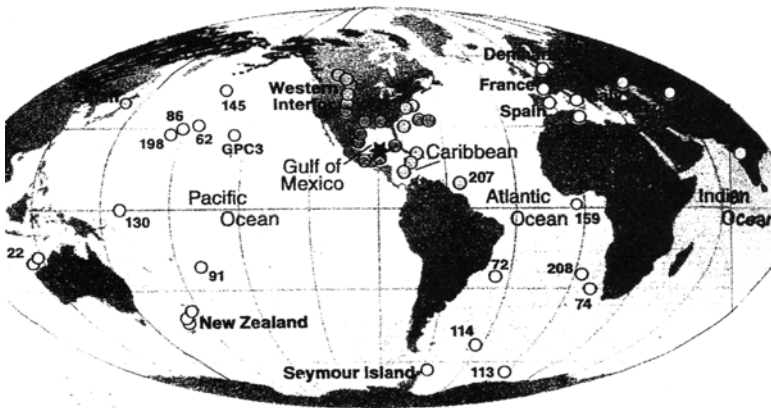


Fig. 2.8 Worldwide locations of K-Pg boundary sites which including outcrop riverbeds and drill holes in the crater zone and deep ocean bottom sediment cores (From Schulte et al. 2010)

a reddish 2–5-mm thick clay that was high in iridium and mixed with finer-grained impact tektites.

Following the original Alvarez K-Pg outcropping sites in Italy, Denmark, and New Zealand (and Hildebrand's findings in Haiti), further outcrops of impact ejecta were uncovered in Belize, North Mexico, Texas (Fig. 2.3), and even in Wyoming. Most of these outcrops were found on river banks where the natural erosion had cut through and exposed layers of geologic history.¹³ Examples of the boundary outcroppings are described below.

Arroyal Membral, Northeast Mexico

A dense distribution of tektite glass were found in the K-Pg layers at the Arroyal Membral riverbank in Tamaulipas State, Mexico (Fig. 2.3), some 900 km north-west of the Chicxulub crater. The Iridium rich K-Pg layer, a few cm thick, was underlain by a ~6 m thick layer of sandstone breccia and tektite spherules. Also found in the boundary were tiny diamonds, up to 30 μm in diameter, that may have been produced by the mega impact pressures shocking ambient graphite or possibly from condensation of the vaporized carbon plume.¹⁴

Brazos River, Texas

Moving north into Falls County, Texas, was found the eroded bank of the Brazos River some 1050 km north-northwest from the crater (Fig. 2.9). The K-Pg boundary displays strata of breccia, in which were found with anomalously high concentrations of iridium, gold, rhodium, arsenic, antimony, and selenium—all typically remnants of the exploding Chicxulub fragments. As was found in Haiti beneath the K-Pg layer, were ancient sea sediments that were possibly deposited by tsunami waves spreading over the shelves and onto the coastal planes in the ancient Gulf.

Dogie Creek, Wyoming

A most unique collection of Chicxulub tektites was uncovered in the K-Pg layer at Dogie Creek, Wyoming (Fig. 2.10) 2800 km north of the crater. A thin (~2 cm) K-Pg layer contained almost perfect ~1 mm spherules. These

¹³ A most notable example of outcropping is the Grand Canyon, which is but a pair of grossly oversized riverbanks.

¹⁴ We note that tiny diamonds were recovered at Barringer crater (Fig. 1.5). They had probably formed at impact by the mega pressures and heat imposed upon ambient carbonates.



Fig. 2.9 The K-Pg outcropping at Brazos River, Texas. The upper strata contain heated impact breccias (high in iridium) ejecta blasted from the crater, which settled out after impact forming the K-Pg boundary layer. The lower layer includes consolidated sedimentary mudstone (calcareous sandstone) mixed with underlying sediment material all of which was probably transported and deposited inland by giant tsunami waves sloshing around the Gulf (A. Hildebrand [1991](#))

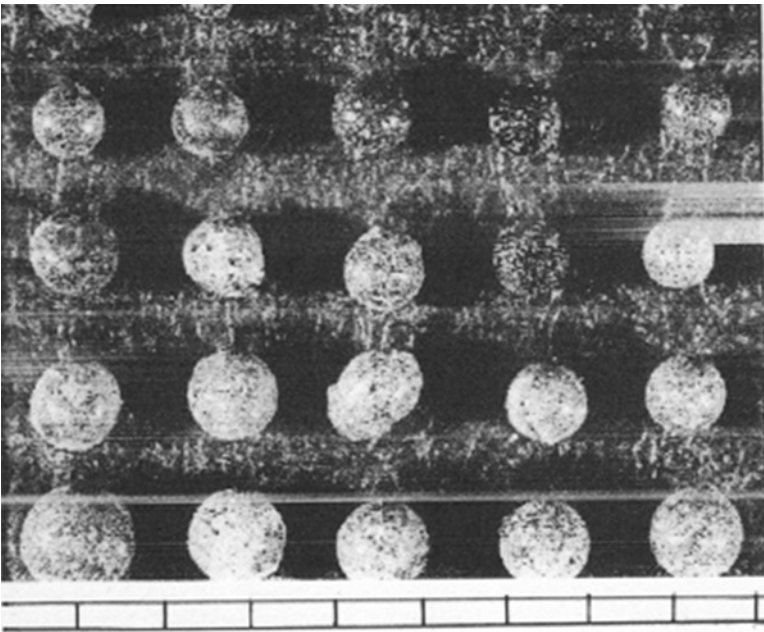


Fig. 2.10 Tiny tektites from the K-Pg boundary at Dogie Creek Wyoming. Apparently condensation of vaporized liquefied mineral glass formed the near perfect millimeter—sized spherules (A. Hildebrand [1991](#))

tektites, originally composed of fused glass, were pseudo-morphed (replaced by a secondary mineral) roughly akin to the mineral replacement of the wood in petrified forests). The spherical shapes suggest the objects were condensed from superheated vapors that, due to surface tension (like the creation of raindrops), formed spherical droplets and solidified.

A Typical Deep Ocean Core Through the K-Pg Boundary

Deep ocean sediment cores from the Atlantic and Pacific Oceans tell their own story of Chicxulub. The following is a schematic record example of a core from the North Atlantic Ocean (leg 207, some 3000 km SE of the crater) in Fig. 2.11 (Schulte et al. 2010). This core stratigraphy displays a record of events across the boundary located at the 65.5 million year horizon. The 2–3 cm thick K-Pg clay boundary contained tiny spherule-rich tektites 0.1–2 mm in diameter. Immediately below the layer were shocked-created minerals mixed with calcite and quartz grains.

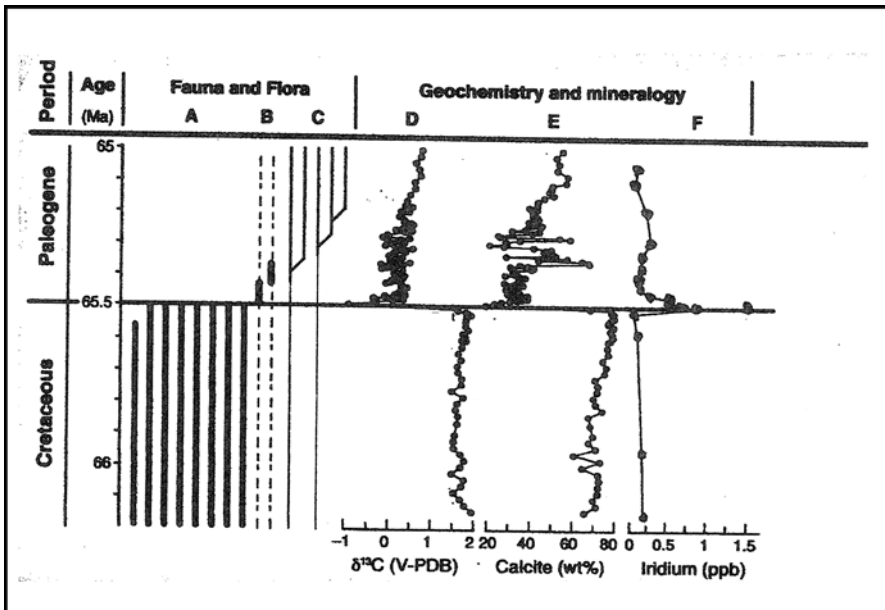


Fig. 2.11 Schematic record of suggested events occurring across the K-Pg boundary correlated from geochemical and mineralogical records from the deep sea North Atlantic Core 207 located in Fig. 2.8 (P. Schulte, et al. 2010)

Graph A suggests the mass extinction of plant species at the Cretaceous boundary while new species (B and C) were formed near the beginning of the following early Paleogene period. Graph D shows the vertical distribution of the quantity “delta” δ^{13} (a reference standard for organic productivity levels) indicating the sharp biotic decrease (i.e., a mass extinction) precisely across the K-Pg boundary.

Profile E likewise shows a sudden drop at the boundary of calcium—based nanoplaston sedimentation (i.e., forams suddenly disappeared). Finally, plot F indicates spiking of iridium associated with the fallout material from the exploding asteroid—clearly replicating the Alvarez data (Fig. 2.2).

Other Attributes of the Crater Target Zone

The Chicxulub multiple ringed craters can be contrasted with that of the relatively small Barringer simple ringed (~1.2 km) bowl—like crater (Fig. 1.5). This effect is also observed on the Moon and Mars where smaller diameter craters display a single rim whereas larger craters tend to have multiple rings. Since Chicxulub’s was over 700 million times the energy of the Barringer impact, it likely had more a complicated cratering process. The cause of multiple rings remains unclear. Possibly the initial surface S waves, caused the crust on impact to flex as if liquefied. Then like concentric waves on a pond, they moved out and solidified, forming the rings frozen in time and space.

Another feature of the multi-ringed crater is its asymmetry, suggesting a more oblique angle of attack. Whereas a lower impact angle should produce a more elliptical crater. Thus, energy (and ejecta) should spread out along the semi-major (long) axis. Pope et al. (1996) reports that ejecta accumulations around the outer ring, although quite irregular, suggest that Chicxulub arrived from the southeast at a moderately oblique angle. This would concentrate the impact blast to cause a disproportionate roasting of forests and vegetation toward the lower central United States. Evidence of residual charcoal ash was in fact found in K-Pg layer outcrops northwest of the crater area in Mexico and Texas. However, there was also plenty of carbon available from the impacted deep sediments and limestone.

Moreover, the argument for a lower object impact angle producing an elliptical crater seems in question, since the majority of observed Lunar and Martian multi rimmed craters appear quite circular, even though most of these impactors also probably arrived at random slant angles. Clearly, there is much to learn of the dynamics of cratering from large asteroid impacts.

Two other attributes of the Chicxulub crater were recently established whose evidence could enhance the damaging effects of the impact upon the biosphere.

The Impact Effects of a Deeper Gulf

Closer analyses of crater strata suggested that the ancient Gulf water depths in the target zone were more irregular and extended deeper than had first been assumed (Science Daily 2008). These “deeper depths” were estimated reaching ~1500 m on the north and east sides which increases estimates of the quantity of seawater blown into the atmosphere by ~6.5 times. This amplifies assumptions of the amount of mud and acid-laden fall-out rains returning to the Earth’s surface. More importantly, this deeper splash raises the estimates of the size of the initial tsunami wave heights, especially of those formed in the deeper water and headed northeast, toward the Gulf coast and open Atlantic. It is suggested that initial waves could crest at 2–3 thousand meters and advance far inland, drowning coasts of the ancient Gulf and Caribbean. Moreover, it would have greatly increased flooding along the North and South American Continents as well as in Europe and Africa (See more details in Chap. 4).

Effects of High Sulfates in Deep Target Rocks

As previously mentioned, the deep rocks of the impact site contained unusually high concentration of sulfur minerals (e.g., iron sulfide, sulfates, other sulfides, etc.). The impact explosion thus delivered into the atmosphere an estimated 100–500 Gt of superheated sulfur probably as SO_2 . Thus, when mixed, with some 35,000 km³ (~35 Gt) of hot Gulf seawater, it created great clouds of aerosols consisting of sulfuric and sulfurous acids. Much of this would condense out and return to Earth as deadly torrential rains, adding greatly to the global acidic-shocking of the biota over the land and in the upper oceans.

Reaffirming the Effects of the “Alvarez Asteroid”

Schulte et al. (2010) and Gulick et al. (2013) re-affirmed the Alvarez claim that the Chicxulub impact was likely the *sole* event—unprecedented in at least 500 million years of Earth history—causing the K-Pg boundary life extinction. It produced a “perfect storm” of multiple (and complex) events that transpired over time intervals spanning from minutes to several 100 years.

The recent studies corroborated the Alvarez findings, providing greater specificity of animal and plant groups that disappeared across the boundary. The list grew to include the non-avian dinosaurs, marine and flying reptiles, ammonites, rudists (spiral shelled mollusks), planktonic forams and calcareous nanofossils. As indicated by Fig. 2.11, new evidence displayed the abrupt

alterations of fungi and leaved plants as well as in marine productivity, which likely caused severe changes in the upper food chains. Curiously, the question still remained as to why certain creatures, e.g. crocodiles, snake, and most importantly, many small mammals, survived Chicxulub. More on this is discussed in Chaps. 3 and 5.

Chicxulub's Single Event-Caused Extinction: The Deniers

Some scientists still dispute the Chicxulub event as being the sole, or even the major, cause of the Late Cretaceous extinction. To wit, Schulte et al.'s (2010) Science paper promoting Chicxulub elicited strong negative responses (e.g., Keller et al. 2010). They centered on the Deccan volcanic eruptions which produced massive basaltic lava flows and poisonous gases that percolated through the crust, covering over ~25 % of the Indian subcontinent forming the great Deccan plateau.

The Deccan supporters' claim was that the massive eruptions, occurring from ~62 to 68 million years ago, allegedly bracketing the Chicxulub impact, causing severe greenhouse heating along with deadly acidification of land and oceans from toxic atmospheric precipitation. Both of which they claimed strongly, if not principally, contributed to the K-Pg extinctions (Archibald et al. 2010).

There was much confusion over when the Deccan eruptions occurred and how much their effects could contribute to the mass extinction. One question centered on timing—how well the dating of Iridium anomalies, spherule depositions, and tsunami-deposited sediments matched up with the Chicxulub event (Keller et al. 2010) and (Courillot and Fluteau 2010).

Counter arguments by Schulte et al. (2010) suggested that the Deccan greenhouse gases, only moderately affected climate change, since only ~2 °C warming was estimated at the end of the Cretaceous. Other disagreements concerning the amount of volcanic sulfur injected into the atmosphere that (aside from its greenhouse warming) were needed to produce enough acid rain to cause toxic poisoning of land and the Upper Ocean. Some estimates put the sulfur injection rates at ~0.05–0.5 Gt per year during the ~0.75–1 million-year-long period of extreme Deccan volcanism. But, the Deccan effects would seem no match to those from the Chicxulub impact. It introduced 100–500 Gt of sulfur into the atmosphere within minutes! The question is which is worse for the patient—a long dilute I.V. feeding of poison, or a sudden massive injection?

Over the past several years the “Chicxulubers” appeared to be winning out over the “Deccaners” as to which was the main cause of the K-Pg extinction.

However, new reports from Princeton University, (Stone 2014) suggested that the intense Deccan eruptions started some 250,000 years before Chicxulub and, in fact, lasted ~750,000 years—clearly overlapping the Chicxulub’s impact event. A group of paleontologists lead by Gerta Keller will try to determine if the Deccan eruptions were intense enough to have contributed to, or even upstage, Chicxulub’s effects on the great extinction.

But wait! To perhaps further complicate this issue—a report in *Science* by geochemists from the University of California, Berkeley (Renne et al. 2015) in dating of Deccan lavas, found that the eruptions possibly doubled in intensity within ~50,000 years of the asteroid impact. How this happened is still unclear, but it suggests that the massive Chicxulub seismic waves may have modified the Earth crust in the Deccan region allowing increase lava and toxic gas flows to strongly contribute to the mass extinction of the dinosaurs, et al. The controversy continues. Stay tuned.

Based on the data presented in this chapter, we next attempt to construct a scenario describing the sequence of short-term events associated with the Chicxulub’s impact.

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