The Chicxulub File

Discovering the K-Pg Mass Extinction: A Four Decade Perspective

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ABSTRACT

In 1979 geologists Luis and Walter Alvarez discovered a layer of iridium-rich rock in the Apennine Mountains dating from 66 to 65 million years BP, the time when dinosaurs went extinct. Their theory that an asteroid strike had caused this massive extinction remained speculative and controversial until the 1991 discovery of a telltale crater from a synchronous asteroid impact. The effects of this impact, centered at Chicxulub on the Yucatan Peninsula, were worldwide. Over the years, impact spherules were found at numerous sites, along with evidence of a massive tsunami throughout the Gulf of Mexico and adjacent coasts. From accumulating evidence, the theory was ratified in 2012, though many details remained unknown. However, a series of dramatic discoveries reported from 2019 to 2022 have led to a chronology of events both during and subsequent to the impact. Evidence for the rapid recovery and development of mammals has been found in the fossil record and, thus, the biological foundations of our own emergence. The final 2019 issue of Science (20 December) named this a "superyear" for studies of the Cretaceous-Paleogene (K-Pg) extinction as the runner-up science "breakthrough of the year." Through these separate discoveries, a coherent hour-by-hour narrative has emerged, marking the onset of the Cenozoic era and providing a foundation for the emergence of *Homo sapiens*.

Introduction

When scholars gather, they sometimes choose to memorialize their common interests, fields of specialization, or new perspectives on existing knowledge. In 1743, Benjamin Franklin and prominent leaders in and around Philadelphia founded the American Philosophical Society whose membership eventually included most of the founding fathers. Today it remains the grandfather of all such intellectual societies. In 1783, the philosopher-economist Adam Smith, the chemist Joseph Black, and geologist James Hutton formed the Oyster Club at Edinburgh, which became the intellectual center of the Scottish Enlightenment, with David Hume, John Playfair, and Sir James Hall among its early members. In 1892, the naturalist and intrepid explorer of the American wilderness, John Muir, founded the Sierra Club which, among many environmental groups, remains the most influential today. To these assemblies we could add hundreds more. In 2010, geologist Walter Alvarez led a small, multidisciplinary group of scholar-teachers to a place in the Apennine Mountains in Italy where, in 1979, he and his father had noticed a revealing iridium-rich layer at the Cretaceous-Paleogene (K-Pg) boundary, leading them to theorize that a massive asteroid had struck the Earth 66 to 65 million years ago, bringing such massive changes to the environment that the ruling dinosaurs were driven to extinction. This was an event that opened up a new chapter in the history of life.

The Alvarez theory, published in *Science* (Alvarez et al. 1980), followed by a search for evidence and the discovery of the Chicxulub crater a decade later (Hildebrand et al. 1991), blended cosmic, terrestrial, biological, and anthropological history into a single narrative.

Big Historians at K-T Boundary in Gubio, Italy: David Christian, Walter Alvarez, Craig Benjamin, Barry Rodrigue, Cynthia Brown, Fred Spier, Louis Spier, Lowell Guistafson

Figure 1. August 20, 2010: International scholars stand before the K-T (K-Pg) Boundary in Gubbio, Italy. Here, in 1989, geologists Luis and Walter Alvarez discovered a mysterious layer of iridium-rich debris signifying an asteroid impact 66 to 65 million years ago that corresponded with the disappearance of dinosaurs in the fossil record. Following this visit, they formed the International Big History Association (IBHA). Source: IBHA archives.

The theory and its verification became a paradigm for how the best science should work. The Alvarezes became the iconic scientist-explorers; Chicxulub became the symbolic center of a group of scholars who banded together to form the International Big History Association (IBHA). A decade later, the organization has scores of members, several associated big history organizations, its own scholarly journal, and has completed its fifth biennial conference.

I. Iridium

The disappearance of dinosaurs from the fossil record may seem unimportant, like the demise of trilobites or extinction of the dodo bird. Much less recognized except by biologists and anthropologists is the corollary emphasized by Alvarez (2017) that we live in a contingent universe. Had this event never occurred, all subsequent life on Earth would have been indescribably different, and humanity in its present form would never have evolved.

No matter how far we stretch imaginations, it is almost impossible to find an event that touches all four chapters of Big History: Cosmos, Earth, Life, and Humanity. As such, it provides a narrative bridge across C. P. Snow's "two cultures"—the sciences and humanities (Snow 1959; Wood 2013). This event impinges on so many dimensions of the grand narrative as well as being high drama in its own right that the dinosaur story has devolved into entertainment. Over three decades, Michael Crichton's *Jurassic Park* (1990) and five movie sequels have recreated the hazardous past of life on Earth, and dinosaurs have overtaken erector sets, Legos, Hot Wheels, and skateboards to become the most popular of children's collectibles, rivaled only by Barbie dolls and Beanie Babies. The Alvarez theory is now the assumed correct and unrivaled explanation for dinosaur extinction among the general public. We might easily conclude the case was closed thirty years later when forty-one scientists writing for *Science* declared the evidence sufficient to end all doubt and speculation (Schulte 2010), but we now know that Chicxulub is much more than an asteroid strike, a crater, and a catastrophic extinction. During the 1980s when the theory had not yet been verified, secondary evidence began accumulating, and this continues today.

The initial entry in the Chicxulub File was an assumption that the event was local or regional.

Figure 2. In 1979 Walter Alvarez and his father discovered an iridium-rich layer at the K-Pg Boundary in the Apennines dated at 65 million years BP. They initially assumed it was caused by a local asteroid impact. The subsequent discovery of the same layer around the world confirmed that this was a global rather than local event. He theorized that an asteroid impact was responsible for the extinction of the dinosaurs and upward of ninety percent of all life on Earth. The crater was discovered in 1991. Source: http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/massext.htm

Accordingly, Europe became the area of interest; however, no known asteroid strikes in the region could account for the plenitude of debris found in the Apennines. Exploration widened when geology colleagues discovered the same iridium-rich layer at distant locations around the world. Convinced that the theory was correct, Luis and Walter Alvarez published their findings in *Science* (1980) while assuming that the crater would eventually be found. Meanwhile, its debris circling the planet for months or years in the upper atmosphere and thus blocking out the sun was the assumed cause of dinosaur extinction. Their initial attempts to establish dates, along with early speculations and explorations, are recounted in Walter Alvarez's book, *T-Rex and the Crater of Doom* (1994).

II. Doubts

Despite its simplicity and clarity, the Alvarez theory gained little traction through the 1980s. Without a crater, the theory was easily dismissed. The well-preserved, 4,000-foot diameter Meteor Crater near Flagstaff, Arizona, marks the impact of a 150-foot diameter meteor approximately 50,000 years ago, but meteoric debris is limited to a radius of thirteen kilometers, or eight miles (Rinehart 1958). An asteroid explosion large enough to blanket the Earth with a relatively even dispersal of debris challenged the geological imagination. Almost immediately, a rival explanation surfaced. The Deccan Traps that cover 200,000 square miles of west central India and were originally, before erosion reduced the footprint, six times as extensive, were put forth as an alternate explanation (Courtillot 1980). Spewing volcanic debris and noxious gases both before and after the K-Pg Boundary, perhaps over thirty to one hundred thousand years, the Deccan Traps were considered climate-altering enough to bring on a mass extinction. This alternate explanation earned equal time through the 1980s (Beardsley 1988). For some, this seemed an equally tenable conclusion, especially given the extent of the Deccan Traps as the largest volcanic event on the planet. A single catastrophic event like an asteroid strike with power enough to do such extensive damage seemed beyond imagining, whereas a sustained alteration of Earth's atmosphere and climate over thousands of years seemed to provide a more reasonable explanation. The Achilles heel of the Alvarez theory remained the absence of an identifiable impact crater. This left the theory stranded for a decade.

That all changed in 1991 when satellite photography with ground-penetrating radar located a 110-mile-wide impact crater centered at Chicxulub, an ancient Mayan village near the northwest coast of the Yucatan Peninsula (Hildebrand 1991). Half the crater was situated on land; the other half lay under sea bottom sediment in the Gulf of Mexico, but the impact had occurred at a time when both the Yucatan Peninsula and the adjacent gulf were part of the same shallow prehistoric sea. Dating of materials from the crater rim became the arbiter; sea-bottom cores confirmed what Alvarez suspected: a massive asteroid had struck Earth 66 to 65 million years ago, after which dinosaur fossils disappear from the geologic record. The Chicxulub crater thus became the smoking gun for the last great mass extinction of prehistoric times.

This recognition opened up geology as a field of fascination. An old-style emphasis on catastrophic events as shapers of Earth history had seemingly been cleared from the table decades earlier; with few exceptions, the geologists were committed to gradualism—a view that said geological change occurred slowly and uniformly. This view had been woven into geological theory by James Hutton's *Theory of the Earth* (1788) and the eminent nineteenth-century geologist, Charles Lyell, who managed to set out a three-volume, thousand-page tome, *Principles of Geology* (1830-1832), with no mention of earthquakes and little on volcanoes other than his exploration of Mount Etna (1832, III). However, the discovery of the Chicxulub impact and its effect on life planetwide blew the lid off gradualism. Catastrophism moved to center stage.

Summarizing its importance, Richard Leakey (1995, 58) referred to this as "a new catastrophism" and summarized its importance. "This represents the second major revolution in the science of geology in this century. The first was the realization that the Earth's crust is fragmented as a series of plates whose gradual movement through the eons moves continents around the globe." However, extinction by asteroid opened up new questions. What other events of the past might have been triggered by catastrophes? Were earlier extinctions caused by catastrophic events? What lay behind ancient periods of global warming? Were eras of worldwide glaciation a result of gradual change or were they perhaps triggered by catastrophic events—nearby supernovas, stellar collisions, or sudden quakes within the Earth itself? Earlier mass extinctions were reexamined with the idea that cataclysmic cosmic events might provide explanations for what had hitherto remained a mystery. As Michael R. Rampino (2017) has shown, a whole new emphasis on cataclysms as primal shapers of a "new geology" began to gel, leading scientists to expanded explorations of extinction events.

III. Spherules

Meanwhile the hard work of sifting evidence went on. Experience gained from the study of more recent asteroid impacts such as Meteor Crater in Arizona had identified certain crystalline and mineral formations unique to such events—shocked quartz, tektites, and glassy spherules as small as or smaller than a grain of rice. Almost immediately, long-recognized deposits of such oddities along Caribbean shores gained relevant interpretation. What kind of local disruption would attend an asteroid impact?

Maurrasse and Sen (1991) drew attention to the Cretaceous-Paleogene (K-Pg) marker bed of the Belloc Formation on southern Haiti where a proliferation of tektites and shocked quartz had been discovered some years earlier. Attention began to focus on scattered impact materials and the so-far unimaginable effects of a colossal tsunami. With the location of the asteroid strike established at Chicxulub, the search for evidence by Alvarez, his colleague Jan Smit, and others now focused on the Gulf of Mexico and adjacent lands where ejected material from the impact would most logically be found. Evidence of a massive tsunami were found in

Figure 3. Glassy spherules measuring less than a millimeter in diameter, ejected skyward from the Chicxulub impact, are dated to 66 to 65 million years ago. Hundreds have been recovered from sites around the world. These spherules were recovered at the Tanis site, North Dakota. Photo source: See Sanders (2019).

the Brazos River Valley in Texas; some of these searches are narrated in Alvarez's later book, *A Most Improbable Journey* (2018). Since the age of the crater had been established from sea-floor cores drilled decades earlier during the 1957-1958 International Geophysical Year (IGY), attention turned to more extensive core analysis. From cores at Sites 536 and 540, Alvarez et al. (1992) found considerable disruption of Upper Cretaceous layers topped with iridium-laced impact materials, tektites, and tiny glassy spherules. Jan Smit et al. (1992) reported on a rock outcrop at Arroyo el Mimbral in northeastern Mexico nine meters (28 feet) thick interrupting a much thicker sequence originally deposited at a depth of four hundred meters (1250 feet). Dates linked these precisely to the K-Pg Boundary 66 to 65 million years ago. Moreover, they showed prominent ripples in sediment, evidence of turbulent wave action typical of seiches—oscillating waves that combine the motion of two wave systems sloshing in opposite directions. It appeared that some reaches of the Caribbean had been subjected to massive tsunamis and wave action rare in normal climate situations.

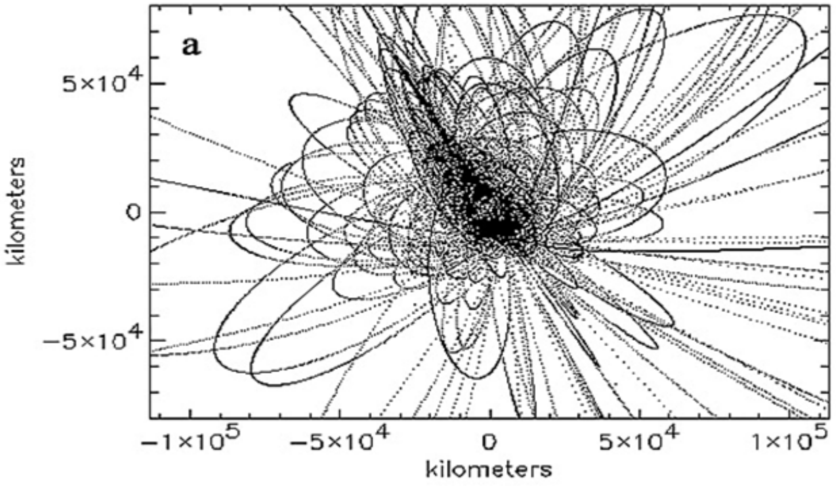
While Chicxulub gained credence as the cause of dinosaur extinction, attention thus turned to environmental disruption attending the event. One recognition after another dawned; the Chicxulub File swelled with theory and speculation sufficient to answer evidence. At the moment of impact, heat would have momentarily soared to the levels of a nuclear explosion releasing one hundred million times the energy of the largest thermonuclear bomb ever detonated. Debris launched into the sky would necessarily have spread fire over much of the planet; the resulting atmospheric perturbations would have caused extended planet-wide warming sufficient to bring on ecological collapse. The impact may well have jolted crustal faults enough to cause earthquakes and volcanic eruptions. It was clear that much of the telltale layer at the K-Pg Boundary was fallout from the fire and fury of a planet ablaze.

Sorting out the evidence was first a task of reconstruction. During the first seconds and minutes, the expanding crater would have bulldozed rock, sea-bottom sediment, and seething water to the extent of the eventual crater. Debris comprised of shattered asteroid materials, Earth crust dust, and regional rocks would have been ground together, the result being a chaotic scene of tumbled and tangled impact materials. Debris ejected above ground, parallel or close to parallel with the surround terrain, could be expected to leave a circle of evidence thinning with distance, like the debris left following denotation of a bomb. Yet millions of tiny tektites and glassy spherules had appeared far beyond such a circle, falling into distant valleys, watersheds, and alluvial plains, blanketing the planet, often encased in sediment turned to rock over the past 65 million years.

How all this distant debris had been scattered so far called for mathematical calculation. Even the smallest fragments of shocked quartz or tektites have mass; they are subject to physical laws; they have trajectories. As the study of debris dispersal expanded, the Chicxulub File grew far beyond the initial discoveries along the K-Pg Boundary.

It was soon clear that identifiable debris could arrive at a particular destination by many routes. As Bermudez et al. (2015) have shown, spherule deposits on Gorgonilla Island of the southwest coast of Columbia indicate that impact debris was launched into the upper atmosphere high enough to follow a trajectory above Central America and come to Earth hundreds of miles away in the eastern Pacific region. This, in miniature, is the archetype of trajectories. Taking into consideration the mass, ejection velocity, and angle of launch, Kring and Durda (2002) provide simulations for a range of material at varying velocities. The mass of ejected material was too variable for definitive conclusions.

In general, particulate debris of higher velocity will travel farther. Increasing the angle of launch beyond forty-five degrees may launch debris higher but not necessarily farther. Ejection velocity and angle of launch were the primary determinants. Maximum velocity and a near-vertical trajectory may propel material halfway to the Moon before gravity returns it to Earth while some would be launched into outsized



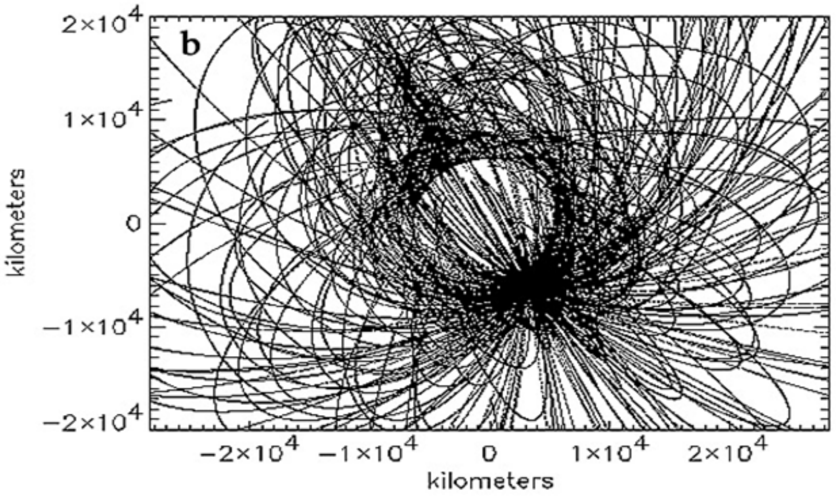


Figure 4a**.** The scale shows ejection trajectories out to 100,000 km (60,000 miles). Most high-speed ejecta came back to Earth with impact locations concentrated along an orbital line extended by the rotation of the Earth. Dotted trajectories indicate elongated orbits taking months or years to complete, with some propelled at escape velocity such that ejected material was destined to soar beyond the control of Earth's gravity.

Figure 4b**.** A smaller scale shows near-Earth ejection trajectories out to 20,000 km. Here variable but lower-than-escape velocities keep ejected material within the control of Earth's gravity, resulting in planet-wide distribution with a tendency toward concentration at the antipodes—the point directly opposite the original impact; in this case, such concentration lies at the bottom of the Indian Ocean to the southwest of India. Source: Kring and Durda (2002), Figure 5.

orbits, joining the ranks of near-Earth Objects (NEO) within the inner Solar System. Still other ejecta might well attain escape velocity such that they are now soaring like Voyagers I and II along trajectories that will lead them among the stars.

The sheer volume of asteroid debris at hundreds of identifiable sites indicates that unimaginable amounts of material were blasted skyward; an inventory of sites now runs to hundreds. Assemblies of tektites, microtektites, shocked quartz, and mineral spherules at hundreds of locations challenges imagination, though this is not surprising once the dimensions of the catastrophe come into focus. Calculations from the diameter of the crater (165 kilometers; 110 miles) and estimated impact velocity (30,000 to 45,000 mph) indicate kinetic energy from an asteroid eight to twelve miles in diameter. Working with a compromise diameter of ten miles, simple math indicates an asteroid of 520 cubic miles would lead to an enormous amount of material ejected into the atmosphere as superheated dust and gas. The resulting crater penetrating miles into the Earth's crust indicates several times this volume of Earth material was blown skyward—25 trillion tons according to one estimate—a mass close to the recent 30 trillion ton estimate of the mass of the technosphere—the entire human-made world of cities and civilization (Zalasiewicz 2014).

As impact debris was hurled outward, it cooled and blanketed the planet. Earthquakes and perhaps volcanic activity accompanied the impact, though evidence has long since been obscured. Undoubtedly, there is evidence so deftly hidden that it may remain forever beyond discovery. The history of the world is told in rocks, as Walter Alvarez is fond of noting. That is true, but some history is also written in tsunamis. Their impressions may last a long time, but these, too, may eventually disappear.

The progress of discovery over several decades has led to a more expansive analysis of the Chicxulub impact. One line of inquiry looked far beyond the Earth in search of a plausible origin. Was this impact a unique event? As E. M. Shoemaker (1998) has shown, asteroid craters preserved on stable cratons in North America, Africa, and Australia indicate a marked increase in Near Earth Objects (NEO) and an approximate doubling of one kilometer-plus asteroid collisions over the past 100 million years. While the full implications are still debated, William Bottke et al. (2007) have argued that breakup of a 180-kilometer asteroid 160 million years ago may have been the precipitating event. Such a "catastrophic disruption" is evidenced today by orbiting debris: the 40-kilometer diameter Baptistina asteroid surrounded by numerous smaller bodies that make up the Baptistina Asteroid Family (BAF). This cluster orbits on the innermost region of the main asteroid belt. Identified by unique but similar inclinations and eccentricities, "the BAF's location, age and fragment size distribution are remarkably well suited to generate a 100-myr-long surge in the multi-kilometer NEO population . . . [and] provides the most probable source for the projectile that produced the K/T impact on Earth." Philosophically, this analysis extends the whole discussion of contingency (Wood 2019) far beyond the Chicxulub impact to distant astronomical events—precisely the kind of multiple domain causation that distinguishes the inquiries of big history.

Originally regarded as a European occurrence, the discovery at Chicxulub has turned it into a global event: no other cataclysm has left such widespread evidence, from rippled sea bottoms and chaotic debris to shocked mineral and glass spherules on supersonic trajectories that took them to sea bottoms and mountain tops. Even so, this catastrophic event was not exhausted by the tracking of its spherules or its connection to the extinction of the dinosaurs. We could naturally expect that much was still hidden, like the crater itself, buried beneath half a mile of sea bottom sediment. We should, therefore, not be surprised that new discoveries are emerging—several, in fact, in 2019 and since.

IV. Crater

Asteroid craters on the Moon remain visible for millions or billions of years, but those on Earth disappear or blend into the landscape after a few million years from the steady forces of erosion. The Chicxulub crater is an exception. Buried under hundreds of feet of sediment, much of it has been preserved, thus providing a laboratory for the study of asteroid impacts**.**

In 2016, Sean Gulick, a research professor at the University of Texas Institute for Geophysics (UIG), led a study of the crater by drilling into the peak ring formed within the crater. Recovered cores revealed a sequence of sedimentation that told the story of the

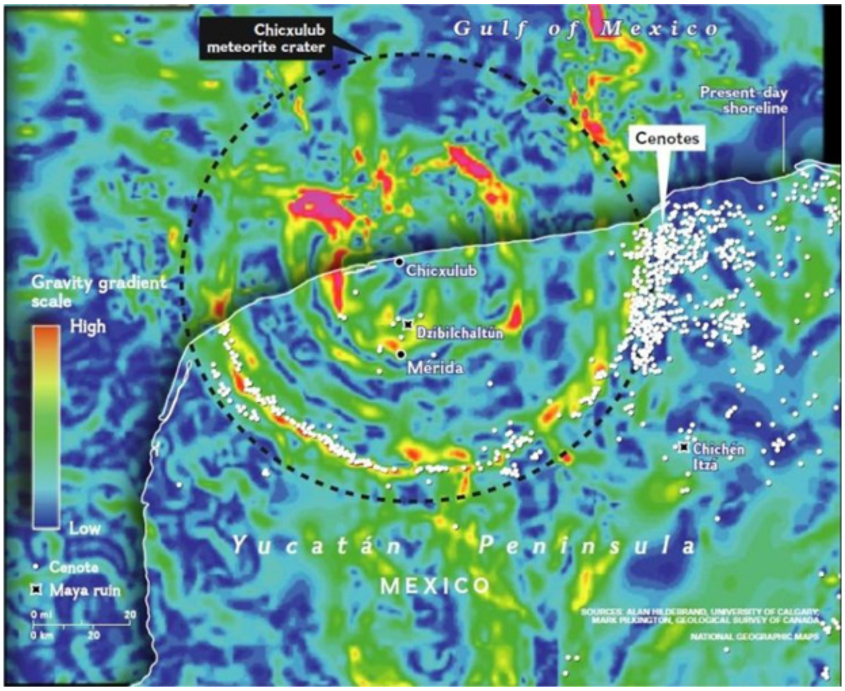


Figure 5. The original impact occurred at sea but changes in sea level have raised the point of impact at Chicxulub above water. However, before this uplift the entire crater was buried under half a mile of sediment. The southern ring of the crater on the Yucatan Peninsula is marked by numerous cenotes, probably because of the collapse of limestone piled up around the edge of the crater at impact. The peak ring halfway between Chicxulub and the outer crater is visible in patches of red indicating gravity anomalies, which initially revealed the location of the crater. The drill core extracted by Gulick et al. (2019) was recovered from the peak ring. Source: *Wikimedia Commons*. See also Hildebrand et al.

first few hours after the impact. The study, enticingly called "The First Day of the Cenozoic," was published in the *Proceedings of the National Academy of Sciences* (PNAS) in September 2019. We are thus able to visualize a detailed timeline of what happened in the minutes and hours on the day of the impact (Black 2019).

At the instant of the leading-edge touchdown, the trailing edge of the ten-mile diameter asteroid would hardly have entered the atmosphere. Traveling at ten or more miles per second with a volume of more than 500 cubic miles, it struck Earth with the power of ten billion Hiroshima bombs. A rereading of John Hersey's *Hiroshima* (1946) reminds us of how people hundreds of yards away were instantly incinerated by heat from the blast. Forests near asteroid impacts are vulnerable to a violent wave of radiation. "For Chicxulub, the plume was considered to emit sufficient thermal radiation to ignite flora up to 1,000 to 1,500 km from the impact site." At greater distances, it is argued, "High-velocity ejecta reentering the Earth's atmosphere emits thermal radiation that is sufficient to ignite dry plant matter and char living flora at sites within a few thousand kilometers from the crater and may directly ignite living flora at more distant locations" (Gulick et al. 2019).

Interpretation of impact energy indicates that the disintegration of the asteroid and its conversion to molten rock began instantaneously, with the Earth's crust in its path turned into a molten brew within microseconds. The ultimate cavity is 20 km (12 miles) deep with a deeper crush cavity to a depth of 20 to 30 miles—almost to the foundational levels of the Earth's crust. "Within tens of seconds of the impact, a ~40 to 50-km radius [60-mile diameter] transient cavity was formed and lined with impact melt" (Gulick et al. 2019). Material from this explosion consisting of 500 cubic miles of asteroidal material plus ten times that amount of crustal material that was excavated and blown skyward by "ballistic ejection," resulting in the iridium-rich layer discovered in the Apennines and spherules recovered at hundreds of sites around the world. The volume of molten material created could well have been ten to twenty times the original volume of the asteroid; that is, 2,500 to 5,000 cubic miles.

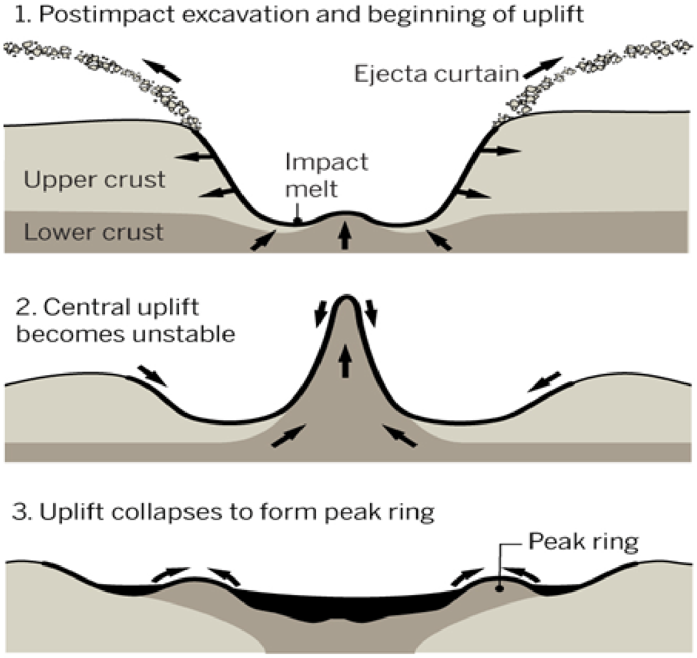


Figure 6 (1). A Minute After Impact. The asteroid has penetrated deep into the upper crust, producing a crater cavity up to 20 kilometers (12 miles) deep at the impact site, extending outward for an overall diameter of 160 kilometers (100 miles). Seawater towered into a tsunami hundreds of feet in height. Limestone sea bottom plowed outward formed the crater rim. The mass of the asteroid and much of the crater interior was ejected skyward at supersonic velocities by the force of an explosion estimated at 100 million times the largest thermonuclear explosion ever detonated.

Figure 6 (2). Liquified granitoid material from the lower crust surged upward as a central "splash" of molten rock, momentarily forming a tower of lava-like material up to 10 km (6 miles) above sea level, then collapsing and surging down and out in all directions.

Figure 6 (3). Deep crustal material, now brought to the surface, flowed out to form a peak ring with a diameter of perhaps 60 miles. Over the next hour, melt rock poured over the peak ring and into the crater to a depth of hundreds of meters. Within hours a tsunami resurge poured in sand, gravel, and charred forest debris from Gulf of Mexico coasts. Source: See Altounian.

Gulick's geological team was able to drill to a depth of 750 meters. The Chicxulub crater floor is now 600 to 1000 meters (1800 to 3000 feet) below sea level, but their drilling position over the peak ring was optimal for analyzing the sequence of events. The drill core brought

Figure 7. Drill Core from the Chicxulub Peak Ring. Seen here is a visible transition at a depth of ~700 meters. The pink and white composite granite on the right, originating in basement levels of the Earth's crust, was splashed up as liquified rock, then washed outward to form the foundational material of the peak ring. During rebound, molten rock washed back over the peak ring, burying it under 40 meters of breccia and suevite, seen to the left. More then poured into the crater. Subsequently, tsunami backwash added layers of sand, gravel, and charred floral remains that were swept into the crater from distant beaches and burning forests. Source: See Smith.

up composite granite from 700+ meters that originated as "fluidized basement rock" from much deeper in the Earth's crust. This was brought to the surface by rebound issuing in a vertical splash momentarily towering to the height of Mount Everest. Immediately, it began to collapse, carrying melt rock downward and outward to form the primarily granitoid peak ring.

The sequence from the ring core shows 130-meters of impact melt rock covered by fluidized basement rocks that form the peak ring, covered over with 40 meters of brecciated melt rock and suevite—a composite of rock, crystals, and glass typical of impact events. As is known from deposits in Mexico and Texas, the impact created a massive tsunami that may have towered hundreds of feet, virtually driving Gulf of Mexico water miles away from the crater. Within hours, melt rock rebound surged over the peak ring and poured into the crater, adding 90 meters of breccia. Within a day the resurge added hundreds of feet of debris from surrounding sea bottom and coasts, including sand, stone, and gravel—material brought hundreds of miles from distant beaches around the gulf. The team concluded that an abundance of charcoal in the top layers likely "originated from impact-related combustion of forested landscapes surrounding the Gulf of Mexico, as the impact site was entirely marine" (Gulick et al. 2019). Compared to the explosions of sudden volcanic eruptions, earthquakes, and landslides, the infilling of the Chicxulub crater is thought to be the most massive rapid transport and deposition of Earth material in geological history.

A corollary of this study is the absence of sulphates in the impact region. The evidence suggests that the impact hurled most sulfur compounds skyward. "In the atmosphere, sulfate combines with water vapor to form sulfate aerosols that impede solar insolation." The cause of floral and faunal die-off is clear: an almost total interruption of photosynthesis in plants with a domino effect through the entire faunal food chain. "Global surface temperatures would have declined by >20° C, and that disruption of the Earth's climate could have lasted ~30 years" (Gulick et al. 2019).

Another recent study has added to the extinction record. Michael Henehan et al. (2019) have analyzed the chalky sea bottom remains from foraminifera, single-celled planktonic animals whose shells settle into thick ocean-floor sediments. Boron isotope measurements in layers of ancient foraminifera indicate a rapid drop in pH levels in ocean-surface waters immediately following the Chicxulub impact. This increased ocean surface acidification, the result of which was extensive extinction of marine life. Additional measurement shows that former pH levels returned within a few tens of thousands of years, leading to the emergence of a new generation of marine creatures.

The significance of the Chicxulub event for the emergence of mammals and primates is now well known (Alvarez 1994); the importance of this event for the emergence of human life has been explored (Alvarez 2017); the obvious contingency as a dimension of human existence forms a multi-episode chapter of big history.

In a recent study, G. S. Collins et al. (2020) remark that theoretical studies of impact kinetic energy have usually been calculated "under the simplifying assumption of a vertical trajectory" though this is statistically less common. Modeling various angles of impact and velocities, this team combined calculations with onsite geological evidence to work out the most likely trajectory of the Chicxulub asteroid. As a target, Earth presents an area of 100 million square miles with the bullseye for a near-vertical strike limited to one or two million square miles. The off-center target area is thus many multiples of the bullseye area. Statistically, the majority of trajectories will occur at an angle; thus "a near-vertical impact is unlikely. Only one quarter of impacts occur at angles between 60° and 90° and only one in fifteen impacts is steeper than 75° (Collins et al. 2020). Variations in a three-dimensional profile of the Chicxulub crater suggest an angular strike. Offsets between the positions of central uplift, the peak-ring center, and maximum mantle uplift along a northeast-southwest line suggest that the asteroid struck from the northeast at an angle between 60° and 75°. Prior to these calculations, imaginative illustrations of the asteroid arrival varied: in *Fantasia* (1997) Walt Disney pictures the asteroid speeding across the sky at a shallow angle as small as 30°, whereas William K. Hartmann's painting in Alvarez's *T-Tex and the Crater of Doom* depicts a near vertical trajectory.

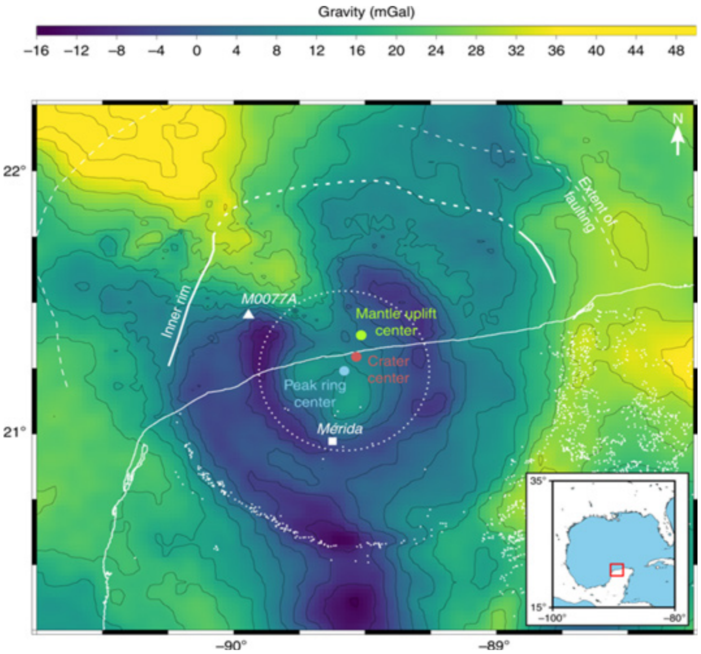


Figure 8. The white line marks the emergent Yucatan Peninsula coast from seafloor uplift subsequent to the Chicxulub impact. Separation between the maximum uplift center (green), crater center (red) and peak-ring center (blue), indicates an angled trajectory estimated at 60° to 75° from the northeast to southwest. Source: Collins et al. (2020. Figure 1. Adapted from Gulick, S., et al. 2013. "Geophysical Characterization of the Chicxulub Impact Crater." *Reviews of Geophysics* 51: 31–52).

V. Seaway

Most of exploration of the Chicxulub impact was undertaken without consideration of geographical constraints other than the marine location of the impact. However, the depth of the Gulf of Mexico 66 to 65 million years BP and thus the dimensions of the resulting tsunami have been difficult to determine with any certainty. Tsunami heights of 300 feet to a mile have been suggested, clear indication that here we are in the realm of speculation. Tsunami impact points around the Caribbean and the coast of the gulf can be surmised from a map of the region, but North America today is geographically quite different from what it was then. During the mid-Cretaceous Era 100 million years ago, North America was divided by what has been called the Western Interior Seaway that ran through the Great Plains from the Gulf of Mexico to the Canadian Arctic (see Figure 8). At its greatest extent it covered most of the Midwestern Prairie, a vast landmass between the Western Mountains and the Appalachians, to a depth of 2500 to 3000 feet.

In recent times this region has been memorialized in myth and movie as the land of big ranches and cattle drives. One hundred million years ago, North America had separated from Pangea and was drifting north a few millimeters a year, but it still lay several hundred miles south of its present location. Thus, the Western Interior Seaway was a tropical ecosystem of jungle and wetland with abundant flora and fauna—one of the richest of habitats anywhere on the planet for amphibian and reptilian life, including dinosaurs, whose fossilized remains are found in great numbers today along the former seaway shores in the Great Plains. By

Figure 9. The Western Interior Seaway at its greatest extent joined the Gulf of Mexico to the Arctic Ocean, originally presenting unobstructed passage north. By the time of the Chicxulub impact, the northern seaway region through Canada had begun to close and the American Great Plains had devolved into a series of linked lakes and wetlands. A tsunami originating at Chicxulub had an unobstructed 2,000-mile, sea-level route into the northern prairies, though how long it could sustain momentum was dependent on factors so far unknown. Effects through the waning seaway were likely more dependent on seismic disruptions and seiches on bounded lakes. Source: See Sampson et al. (2010).

the end of the Cretaceous, the seaway was somewhat diminished due to sea level change and orogenic uplift associated with the rising of the Rocky Mountains, but what remained nevertheless provided a straight-line unobstructed riverine valley system from the mid-Texas coast north to Montana and the Dakotas.

Given the 800-kilometer/500-mile distance traveled upstream by the *Pororoca* (tidal bore) on the Amazon River, it seems likely that an asteroid-impact-driven tsunami would roar northward through the center of North America. A tsunami of gargantuan proportions would easily override all obstructions, though its dimensions remain one of the great unknowns.

Apart from variable waterways, forces of erosion were formative in the northern prairie region. Over millions of years following the end of the Cretaceous, a widespread layer of buff-colored sandstone and drab-green shale 90 to 600 meters (300 to 2000 feet) in thickness built up as outwash from eroding mountains along the edge of the seaway. Known today as the Lance Formation, it is visible at the surface by the drab, gray-green of sterile badlands typical of the region. Atop this formation, along a region adjacent to Fort Peck Lake, Hell Creek State Park protects part of an unusually rich fossil-laden formation that extends well beyond Montana to Wyoming and the Dakotas. Here the first specimen of *Tyrannosaurus rex* was discovered in 1902. Fossils from all eight of the most common dinosaur families have since been located in the Hell Creek Formation; thousands are now housed in the Museum of the Rockies in Bozeman, Montana. The story has been amply told by Lowell Dingus in *Hell Creek, Montana: America's Key to the Prehistoric Past* (2004).

VI. Tanis

Across the state line from Montana in North Dakota, Robert DePalma, then a graduate student at University of Kansas, discovered an area of the Hell Creek Formation that looked particularly promising. In 2010, he commenced informal excavation until his discoveries turned from informal to serious and systematic. Returning summer after summer, keeping his discovery as secret as possible, he chose his own private name for the site: Tanis, the name of a relatively unknown city in Lower Egypt made famous in the film, *Raiders of the Lost Ark*. For DePalma's purposes, the name is appropriate: the real Tanis remains in ruins. An article on satellite archaeology of the original Tanis in *National Geographic* (February 2013) indicates that scores of ruined dwellings are hidden beneath the sand. Symbolically, the Tanis of the film was buried

Figure 10. Fossilized fish piled one on top of one another, crowded together with limbs, logs, and insects suggests that they were flung ashore and died soon afterward, stranded and trapped together on a sand bar after a seiche withdrew, then covered and sealed in with several feet of debris by a final tsunami. Photo source: See Sanders (2019).

by a catastrophic storm, while the real Tanis, once the capital of Ancient Egypt, has achieved mythic status as the holder of untold treasures comparable to the tomb of King Tut. DePalma's choice of name now seems prophetic.

Over the years, DePalma has gathered hundreds of fossils and made plaster casts of many more, spending winters in a Florida lab identifying and classifying a collection that includes remarkable numbers of fish of all sizes. Some tektites, he discovered, were drawn into the gills and were caught on gill rakers of fish taking their last gasp (Figure 10). The presence of tektites at this precise time when beached fish were dying indicates he was not studying an era: he was looking at the story of an hour. What DePalma had discovered was an unusually dramatic assemblage of flora and fauna jumbled together, with fresh-water fish crowded together with salt-water reptiles, three-dimensional fossils preserved in hardened clay with marine creatures intermixed with logs and branches, cones and seeds, mollusks mingled with tiny mammals, amphibians tangled with sturgeon—the whole a massive killing field of creatures caught in a cataclysm in their final hour.

DePalma's central discovery was glass-and-clay tektites caught in fish gill rakers that date to 66 to 65 million years ago. The find was more than any other assemblage of fossils where sedimentary layers signify the passage of time—where a few inches above or below could be the measure of thousands or millions of years. Here, fish had died while asteroid-impact spherules were raining down and churning through the water in their gills. Time was suddenly telescoped. A new vision of the Chicxulub impact swam into view. DePalma called in the original formulator of the theory, Walter Alvarez, and his long-term colleague, Jan Smit, an expert on mass extinctions who had studied tektites at dozens of sites. Over the previous quarter century, Alvarez and Smit had done much of the spade work of discovery associated with Chicxulub (See Figure 11).

As they studied the evidence, observations coalesced into a refined narrative. It was likely that seismic activity generated by the Chicxulub impact had caused earthquake reverberations spreading out over thousands of miles. This, they reasoned, would have reached the region of Hell Creek within a quarter hour. The result, which they had already explored in sites

Figure 11. Walter Alvarez and Robert DePalma on site at the K-Pg Boundary in South Dakota forty years after Alvarez's discovery of the K-Pg Boundary marker in the Apennines. Over several years, DePalma has excavated the site he calls Tanis in South Dakota, bringing to light a remarkable story: the final moments of the great extinction 66 to 65 million years after the fact. Photo source: See Sanders (2019).

around the Gulf of Mexico, was the creation of seiches—chaotic water sloshing. This could have occurred on numerous inland waterways along the Western Interior Seaway, sending waves into multiple rivulets and valleys with fish and other creatures caught in tempestuous waters, then beached and crowded together in a tangle of branches and vegetation. Then, minutes later, vaporized rock blasted into the stratosphere at Chicxulub 2,000 miles away would begin to arrive, falling from the sky among beached sea life trapped in a tangle of uprooted flora and fauna. Here, as elsewhere, fiery fragments from the asteroid explosion had already set fire to forests, blanketing the Earth with smoke and dust. Meanwhile, tektites falling at Tanis were drawn into the gills of dying fish. Evidence of this fall of debris was ubiquitous; it was a geologist's dreamscape. Some tektites that had landed on branches or trunks of trees in sticky sap were now encased and preserved in amber. Others landing on sand created a tiny impact crater two or three inches in diameter and a penetration cone where, at its base, the spherule came to rest, with a single fossil preserving the crater, cone, and spherule—a unique case of petrotemporality (Wood 2015).

Since 2019, the discovery at Tanis of fossilized fish with tektites lodged in their gills along with tiny impact craters and tektites preserved in amber have provided evidence for a mass extinction caused by the Chicxulub asteroid (Hadingham and Wu 2019). The impact has always been associated with the extinction of the dinosaurs. However, the dramatic discovery at the Tanis site of a fossilized dinosaur leg, with flesh and muscle preserved, has reconnected the asteroid impact with dinosaur extinction. While the evidence has not yet established an absolute chronicity, the majority opinion, based on its location and proximity to other debris, places the death of this dinosaur within a few hours of the Chicxulub impact (Martin 2022). The dramatic importance of the Tanis discoveries has attracted the British Broadcasting Company, which has been filming at Tanis for an 87-minute documentary to be aired on April 15, 2022, with later release through NOVA (Thompson 2022).

Identifying events of the last day of the Cretaceous down to the final hour is testimony to a remarkable reconstruction of a time long past. However, a question remains: can more be discovered about that final day? A team led by Melanie During has provided an answer through osteohistology of bones from fossilized fish at Tanis. Although North America had been drifting north since the breakup of Pangea, by 66 million years ago Tanis was located at a latitude subject to a seasonal cycle. Like tree rings that preserve annual growth, Tanis bone fossils preserve a seasonal record. Microscopic examination of fossilized bones from several species of fish reveals that seasonal rings uniformly terminate at a time of active growth, thus demonstrating that "the impact that caused the Cretaceous–Palaeogene mass extinction took place during boreal spring" (During et al. 2022).

Fossils convey structure, rarely process. Those at Tanis break all expectations in the narrative they tell. In the next act of this drama, a mix of tsunami and seiches through the Seaway covered everything with several feet of sand and clay, sealing in a whole ecosystem of evidence to be discovered 65 million years later. Finally, over the next few weeks, months, or perhaps years, smoke from burning forests, charred debris, and iridium-laden asteroid dust slowly settled, blanketing the land, sealing in the last chaotic times of the Cretaceous in a wrapping that spanned the globe.

Thus understood, the debris-laden assemblage takes on new meaning, Here recorded in stone was the final springtime instant of a cataclysm, a combination of impact, earthquake, seiche, and tsunami—a drama as complex as anything Sophocles or Shakespeare could have written with acts and scenes assembled from what at first looked like little more than land life, sea life, wasted wetlands, and fragmented forests strewn across an ancient beach. Here, for the first time, we could actually see the moment of the great dying.

VII. Biosystem Effects

Given the destructive power of this gargantuan impact, it is surprising that anything could survive, but survive they did. The avian dinosaurs survived to morph into modern birds. Despite acidification of the oceans, much of the deepest marine life survived, protected from atmospheric climate change. On land, small mammals survived by hiding, burrowing, and scavenging—behavior that had served them well through millions of years of dinosaur dominance. The primary benefit of the asteroid impact for mammals, however, was the removal of predators. Here, the effects were dramatic. Summarized in reportage in *Science* in 2019, the Chicxulub superyear, Corral Bluffs, near Colorado Springs, has yielded a rich assemblage of post-impact fossils that indicate both floral and faunal rebound (Pennisi et al. 2019; Lyson et al. 2019). Mammal skulls, hundreds of vertebrate remains, and thousands of fossilized leaves and pollen grains tell the story. Within 300,000 years of the mass extinction, mammalian species had doubled their taxonomic richness with a tripling of body mass, aided by parallel increases in megaflora, including protein-rich beans and other legumes.

The extinction of non-avian dinosaurs and rise to prominence of mammalian life are the best known biosystem effects of the Chicxulub event. However, extensive study of plant fossils before and after this event have clarified effects on vegetation, particularly in rainforests. Carvalho et al. (2021) have examined plant material from Columbia showing that pre-Chicxulub forests were characterized by gymnosperms (cone-bearing plants) and tree-size ferns, resulting in an open canopy and abundant light available at lower levels. However, over a period of ~ six million years following the Chicxulub event, fossilized leaves from more than eighty species of angiosperms (flowering plants) indicate a new dominance in forest communities. The result was the highly stratified, multi-layered canopy of today's neotropical rainforests. Fifteen hundred kilometers south of the asteroid impact, Columbia exhibits a greater shift to angiosperm dominance than Patagonia, 8,000 km away where less severe consequences preserved gymnosperm dominance. Changes in forest composition in New Zealand, 12,000 km away, show minimal change from pre-impact forest composition. The mass extinction produced a "different world," but "the consequences depended on proximity to the crater" (Jacobs and Currano 2021, 29).

Carvalho et al. suggest that the pre-Chicxulub open canopy may have been the result of ground level "disturbance . . . sustained trampling by and extensive feeding by large herbivores, mostly dinosaurs" that curtailed proliferation of low-level flowering plants (2021, 67). The extent of dinosaur impact on vegetation is suggested by a recent study of *Tyrannosaurus rex* population (Marshall et al. 2021). Through careful study of fossil sequences and abundance along with probable animal density, they estimate that *Tyrannosaurus rex* persisted for ~ 127,000 generations with a worldwide population of ~ 20,000 individuals at any one time. Assuming an equal distribution over six continents, we could conclude that some 3,500 individuals may have occupied each continent. The effect of forest-floor trampling and herbivore feeding is multiplied when we add multiple species of sauropods—brontosaurus, spinosaurus, titanosaurus, argentinosaurus, and dozens more—that roamed in equally large numbers. Tens of thousands of dinosaurs, many of them larger and heavier than today's largest mammals, render the theory of dinosaur trampling a viable explanation for suppression of angiosperms and the open canopy of pre-Chicxulub forests. The diversity of the lower canopy in today's forest communities is thus a relevant ecological effect of dinosaur extinction from the Chicxulub event.

Conclusion

The link between the Chicxulub impact and the formation of IBHA is a simple one: Walter Alvarez's decision to lead others to the site in the Apennines and share what he must have felt that day of discovery in 1989 turned individual experience into collective learning. In a very real way, IBHA is the unexpected heir of his discovery. More than a decade later, the organization is focused on understanding, describing, and presenting the integrated narrative of Cosmos, Earth, Life, Humanity, and Culture using the best scholarly methods available, emphasizing its relevance to the human situation.

Now, more than forty years after Alvarez's reasoned guess that an asteroid strike had driven the dinosaurs to extinction, Sean Gulick et al. (2019) have provided a geological timeline for "the first day of the Cenozoic" while Robert DePalma (2019) has published a simultaneous scenario of "the day the dinosaurs died." Both transcend anything we could have imagined. DePalma's discoveries leave open the question of the precise time when dinosaurs went extinct, though the charred remains of burning forests swept into the Chicxulub crater and the likely decline of global temperature leave little doubt about what happened in the aftermath. Added to this are studies documenting massive sulphate pollution of the atmosphere, acidification of the oceans, rapid floral and faunal recovery, and new flowering-plant diversity in the forest understory that laid the groundwork for subsequent mammalian dominance.

Meanwhile, a compromise has emerged: the eruptions that gave rise to the Deccan Traps undoubtedly added to the poisoning of the atmosphere, thus intensifying the great extinction (Schoene 2015). What DePalma's excavations have shown is a much more precise connection between Chicxulub and the demise of an entire ecosystem, a scenario that could easily be fitted into an hour-long news program: *Sixty Minutes*, *A Special Report*, a cold case reopened 65 million years after the fact. It is appropriate that DePalma, Alvarez, and Smit are coauthors of the article where this is unfolded in *Proceedings of the Natural Academy of Sciences* (April 23, 2019), forty years after the initial discovery. Few scientific discoveries keep yielding evidence for so long, but this one has and likely will.

As I completed a first draft of this article, an e-mail message from Walter Alvarez, "from Coldigioco, where IBHA had its start!" indicates that he and his wife Milly "[were] in Italy for intense fieldwork." Consequently, it is clear that the Chicxulub File will continue to grow because there is evidence to be found around the world and its discoverers are still hunting down its effects. Those who have seen the DePalma excavation site say there is enough in and around Tanis to keep geologists busy for half a century. Undoubtedly, too, there are discoveries yet to be made at Corral Bluffs. We can thus expect an even fuller story to unfold through the years, with each new piece of evidence adding to one of the most remarkable discoveries of our time.

DePalma's story has been told in *The New Yorker* (29 April 2019), where novelist Douglas Preston spells out his lifelong fascination with bones while witnessing and describing his excavation and recovery work in South Dakota and his winter lab in Florida—a lively piece of journalism. Unhappily, though, DePalma's discovery and the wealth of detail he has uncovered casts us as witnesses to the death of an entire ecosystem—a warning today as forest fires leave behind blackened stumps and the unplanned consequences of the human enterprise come to rest on species extinction and oil-soaked seabirds. Meanwhile, Tyler Lyson's similar fascination with bones and his discovery of ecosystem rebound at Corral Bluffs has been the subject of a *NOVA* documentary narrated by Keith David (30 October 2019). Although the demise of an entire ecosystem is an environmental tragedy, it is remarkable that we could ever witness the final hours of life gasping for a final breath following a catastrophe that happened 65 million years ago. Balancing this catastrophe, the subsequent ecosystem recovery reveals the tenacity of life on Earth that lies behind the subsequent emergence of *Homo sapiens*.

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