http://media.hhmi.org/biointeractive/activities/mesozoic/The_Day_the_Mesozoic_Died.pdf?download=true http://media.hhmi.org/biointeractive/films/The_Day_The_Mesozoic_Died.html

The Day the Mesozoic Died

"Understanding how we decipher a great historical event written in the book of rocks may be as interesting as the event itself."

-Walter Alvarez

Built upon the slopes of Mount Ingino in Umbria, the ancient town of Gubbio boasts many wellpreserved structures that document its glorious history. Founded by the Etruscans between the second and first centuries B.C., its Roman theater, Consuls Palace, and various churches and fountains are spectacular monuments to the Roman, Medieval, and Renaissance periods. It is one of those special destinations that draws tourists to this famous part of Italy.

It was not the ancient architecture but the much longer natural history preserved in the rock formations outside the city walls that brought Walter Alvarez, a young American geologist, to Gubbio. Just outside the town lay a geologist's dream-one of the most extensive, continuous limestone rock sequences anywhere on the planet (Figure 1). The "Scaglia rossa" is the local name for the attractive pink outcrops found along the mountainsides and gorges of the area ("Scaglia" means scale or flake and refers to how the rock is easily chipped into the square blocks used for buildings, such as the Roman theatre. "Rossa" refers to the pink color). The massive formation is composed of many layers that span about 400 meters in total. Once an ancient seabed, the rocks represent some 50 million years of Earth's history.

Geologists have long used fossils to help identify parts of the rock record from around the world and Walter employed this strategy in studying the formations around Gubbio. Throughout the limestone he found fossilized shells of tiny creatures, called foraminifera or "forams" for short, a group of singlecelled protists that can only be seen with a magnifying lens. But in one centimeter of clay that separated two limestone layers, he found no fossils at all. Furthermore, in the older layer below the clay, the forams were more diverse and much larger than in the younger layer above the clay (Figure 2). Everywhere he looked around Gubbio, he found that thin layer of clay and the same difference between the forams below and above it.

Walter was puzzled. What had happened to cause such a change in the forams? How fast did it happen? How long a period of time did that thin layer without forams represent?

These questions about seemingly mundane microscopic creatures and one centimeter of clay in a 1,300-foot-thick rock bed in Italy might appear to be



Figure 1. Luis and Walter Alvarez at limestone outcrop near Gubbio, Italy

Walter Alvarez's (right) right hand is touching the top of the Cretaceous limestone, at the K-T boundary. Photograph courtesy of Lawrence Berkeley National Laboratory.



Figure 2. Foraminifera of the Tertiary (top) and Cretaceous (bottom).

Walter Alvarez was puzzled by the rapid, dramatic change in foram size between the end of the Cretaceous and the beginning of the Tertiary periods, which is seen worldwide. These specimens are from a different location (not Gubbio). Images courtesy of Brian Huber, Smithsonian Museum of Natural History. trivial. But their pursuit led Walter to a truly Earthshattering discovery about one of the most important days in the history of life.

The K-T Boundary

From the distribution of fossils and other geological data, it was known that the Gubbio formation spanned parts of both the Cretaceous and Tertiary periods. The names of these and other geological time periods come from early geologists' ideas about the major intervals in Earth history, and from some of the features that mark particular times (Figure 3). In one scheme, the history of life is divided into three eras-the Paleozoic ("ancient life," the first animals), the Mesozoic ("middle life," the age of dinosaurs), and the Cenozoic ("recent life," the age of mammals). The Cretaceous period, named after characteristic chalky deposits, forms the last third of the Mesozoic era. The Tertiary period (which has been renamed and subdivided into the Paleogene and Neogene) begins at the end of the Cretaceous 65 million years ago and ends at the beginning of the Quaternary period 2.6 million years ago.

Walter and his colleague Bill Lowrie spent several vears studying the Gubbio formation, sampling up from the Tertiary and down through the Cretaceous. They were first interested in trying to correlate reversals in the Earth's magnetic field with the fossil record as a way of deciphering the time-scale of Earth's history. They learned to figure out where they were in the rock formation by the forams characteristic of certain deposits, and by learning to recognize the boundary between the Cretaceous and Tertiary rocks. That boundary was always right where the dramatic reduction in foram diversity size occurred. The rocks below were Cretaceous and the rocks above were Tertiary, and the thin layer of clay was in the gap between (Figure 4). The boundary is referred to as the K-T boundary.

One thousand kilometers from Gubbio, at Caravaca on the southeast coast of Spain, a Dutch geologist, Jan Smit, had noticed a similar pattern of changes in forams in rocks around the K- T boundary. Smit knew that the K-T boundary marked the the most famous extinction of all—the dinosaurs. When a colleague pointed out that fact to Walter, he became even more interested in those little forams and the K/T boundary.

Walter was relatively new to academic geology. After he received his Ph.D he had worked for the exploration arm of a multinational oil company in Libya, until Colonel Qaddafi expelled all of the Americans out of the country. His work on magnetic reversals had gone well but he realized that the abrupt change in the Gubbio forams and the K-T extinction



Figure 3. Geologic time scale



Figure 4. The K-T boundary at Gubbio. The white Cretaceous limestone is separated from the reddish Tertiary limestone by a thin clay layer (marked with coin). Photo courtesy of Frank Schönian, Museum of Natural History, Berlin.

presented a much bigger mystery that he became determined to solve.

One of the first questions Walter wanted to answer, naturally, was how long it took for that thin clay layer to form? To answer this he would need some help. It is very common for children to get help from their parents with their science projects. However, it is extremely unusual, as it was in Walter's case, that the "child" is in their late 30's. But few children of any age had a dad like Walter's.

From A-Bombs to Cosmic Rays

Luis Alvarez knew very little about geology or paleontology but he knew a *lot* about physics. He was a central figure in the birth and growth of nuclear physics. He received his Ph.D. in physics in 1936 from the University of Chicago and worked at Berkeley under Ernest Lawrence, the recipient of the 1939 Nobel Prize in Physics for the invention of the cyclotron.

His early work in physics was interrupted by the onset of World War II. During the first years of the war, Luis worked on the development of radar and systems that would help airplanes land safely in poor visibility. He received the Collier Trophy, the highest honor in aviation, for developing the Ground Controlled Approach (GCA) system for bad weather landings.

In the middle of the war, he was recruited into the Manhattan Project, the top secret national effort to develop atomic weapons. Alvarez and his student Lawrence Johnston designed detonators for the bombs. Robert Oppenheimer, the director of the Manhattan Project, then put him in charge of measuring the energy released by the bombs. Luis was one of the very few to witness the first two atomic blasts. He flew as a scientific eyewitness to the first test of the atomic bomb in the New Mexico desert and then shortly thereafter to the bomb dropped on Hiroshima, Japan.

After the war, Luis returned to physics research. He developed the use of large liquid hydrogen bubble chambers for tracking the behavior of particles. Luis received the Nobel Prize in Physics in 1968 for his work in particle physics.

That would seem to be a nice capstone to an illustrious career. But several years later his son Walter moved to Berkeley, where Luis had worked for many years, to join the university's geology department. This gave father and son the chance to talk often about science. One day, Walter gave his dad a small polished cross-section of Gubbio K-T boundary rock and explained the mystery within it. Luis, then in his late 60s, was hooked and started thinking about how to help Walter crack it. They started brainstorming about how to measure the rates of change around the K-T boundary. They needed some kind of atomic timekeeper.

Luis, obviously an expert on radioactivity and decay, first suggested that they measure the abundance of beryllium-10 (¹⁰Be) in the K-T clay. This isotope is constantly created in the atmosphere by the action of cosmic rays on oxygen. The more time the clay represented, the more ¹⁰Be would be present. Luis put Walter in touch with a physicist who knew how to do the measurements. But just as Walter was set to work, he learned that the published half-life of ¹⁰Be was wrong, The actual half-life was shorter, and too little ¹⁰Be would be left after 65 million years to measure it.

Fortunately, Luis had another idea.

Space Dust

Luis remembered that meteorites are 10,000 times richer in elements from the platinum group than is the Earth's crust. He figured that the rain of dust from outer space should be falling, on average, at a constant rate. Therefore, by measuring the amount of space dust (platinum elements) in rock samples, one could calculate how long they had taken to form.

These elements are not abundant, but they are measurable. Walter figured that if the clay bed had been deposited over a few thousand years, it would contain a detectable amount of platinum group material, but if it had been deposited more quickly, it would be free of these elements.

Luis decided that iridium, not platinum itself, was the best element to measure because it was more easily detected. He also knew the physicists to do the measurements, the two nuclear chemists Frank Asaro and Helen Michel at the Berkeley Radiation Laboratory.

Walter gave Asaro a set of samples from across the Gubbio K-T boundary. For months he heard nothing back. The analytical techniques Asaro was using were slow, his equipment was not working, and he had other projects to work on.

Nine months later Walter got a call from his dad. Asaro wanted to show them his results. They had expected iridium levels on the order 0.1 parts per billion (ppb) of sample. Asaro found 3 ppb of iridium in the portion of the clay bed, about 30 times more than expected and than the level found in other layers of the rock bed (Figure 5).

Why would that thin layer have so much iridium?

Before they got too carried away with speculation, it was important to know if the high level of iridium was an anomaly of rocks around Gubbio, or a more widespread phenomenon. Walter went looking for another exposed K-T boundary site that they could sample. He found a place called Stevns Klint, south of Copenhagen, Denmark. Walter visited the clay bed there and could see right away that "something unpleasant had happened to the Danish sea bottom" when the clay was deposited. The cliff face was almost entirely made of white chalk, full of all kinds of fossils. But the thin K-T clay bed was black, stunk of sulfur, and had only fish bones in it. Walter deduced that during the time this "fish clay" was deposited, the sea was an oxygen-starved graveyard. He collected samples and delivered them to Frank Asaro.

In the Danish fish clay, iridium levels were 160 times background levels.

Walter suggested to Jan Smit that he also look for iridium in his clay samples. The Spanish clay also contained a spike of iridium. So did a sample taken from a K-T boundary in New Zealand, confirming that the phenomenon was global.

Something very unusual, and very bad, had happened at the K-T boundary. The forams, the clay, the iridium, the dinosaurs were all signs—but of what?

It Came From Outer Space

The Alvarez's concluded right away that the iridium must have been of extraterrestrial origin. They thought of a supernova, the explosion of a star that could shower earth with its elemental guts. The idea had been kicked around before in paleontological and astrophysics circles.

Luis knew that heavy elements are produced in stellar explosions, so if that idea was right, there would be other elements besides iridium in unusual amounts in the boundary clay. The key isotope to measure was plutonium-244 with a half-life of 75 million years. It would be still present in the clay layer, but decayed in ordinary earth rocks. Rigorous testing proved there was no elevated level of plutonium. Everyone was at first disappointed, but the sleuthing continued.

Luis kept thinking of some kind of scenario that could account for a worldwide die-off. He thought that maybe the solar system passed through a gas cloud, that the sun had become a nova, or that the iridium could have come from Jupiter. None of these ideas held up. An astronomy colleague at Berkeley, Chris McKee, suggested that an asteroid could have hit the earth. Luis at first thought that would only create a tidal wave, and he could not see how a giant tidal wave could kill the dinosaurs in Montana or Mongolia.

Then he started to think about the volcanic explosion of the island of Krakatoa, in 1883. He recalled that miles of rock had been blasted into the atmosphere and that fine dust particles had circled the globe, and stayed aloft for two years or more. Luis



Figure 5. The iridium anomaly. The levels of iridium across the Gubbio formation are plotted. Note the spike in the K/T boundary clay. Data redrawn from Alvarez et al. 1980 by Leanne Olds.

also knew from nuclear bomb tests that radioactive material mixed rapidly between hemispheres. Maybe a large amount of dust from a large impact could turn day into night for a few years, cooling the planet and shutting down photosynthesis?

If so, how big an asteroid would it have been?

From the iridium measurements in the clay, the concentration of iridium in so-called chondritic meteorites and the surface area of the Earth, Luis calculated the mass of the asteroid to be about 300 billion metric tons. He then used various methods to infer that the asteroid had a diameter of 10 ± 4 kilometers (km).

That diameter might not seem enormous with respect to the 13,000-km diameter of the Earth. But now consider the energy of the impact. Such an asteroid would enter the atmosphere traveling at about 25 km per second—over 50,000 miles per hour. It would punch a hole in the atmosphere 10 km across and hit the planet with the energy of 10⁸ megatons of TNT. (The largest atomic bomb ever exploded released the equivalent of about one megaton—the asteroid was 100 hundred million times more powerful.) With that energy, the impact crater would be about 200 km across and 40 km deep, and immense amounts of material would be ejected from the impact.

The team had their foram- and dinosaur-killing scenario.

Hell on Earth

The asteroid crossed the atmosphere in about one second, heating the air in front of it to several times the temperature of the sun. On impact, the asteroid vaporized, an enormous fireball erupted out into space, and rock particles were launched as far as halfway to the moon. Huge shock waves passed through the bedrock, then curved back up to the surface and shot melted blobs and bedrock out to the edge of the atmosphere and beyond. A second fireball erupted from the pressure on the shocked limestone bedrock. For a radius of a few hundred kilometers or more from ground zero, life was annihilated. Further away, matter ejected into space fell back to earth at high speeds-like trillions of meteors-heated up on re-entry, heating the air and igniting fires. Tsunamis, landslides, and earthquakes further ripped apart landscapes nearer to the impact.

Elsewhere in the world, death came a bit more slowly.

The debris and soot in the atmosphere blocked out the sun, and the darkness may have lasted for months. This shut down photosynthesis and halted food chains at their base. Analysis of plant fossils and pollen grains indicate that half or more plant species disappeared in some locations. Animals at successively higher levels of the food chain succumbed. The K-T boundary marks more than the end of the dinosaurs, it is also the end of belemnites, ammonites, and marine reptiles. Paleontologists estimate that more than half of all the planet's species went extinct. On land, nothing larger than 25 kilograms in body size survived.

It was the end of the Mesozoic world.

Where Is the Hole?

Luis, Walter, Frank Asaro, and Helen Michel put together the whole story—the Gubbio forams, the iridium anomaly, the asteroid theory, the killing scenario—in a single paper published in the journal *Science* in June 1980. [1] It is a remarkable, bold synthesis across different scientific fields, perhaps unmatched in scope by any other single paper in the modern scientific literature. Jan Smit and Jan Hertogen published their study based on Spanish rocks in the journal *Nature*, and reached a similar conclusion. [2] They were concerned, however, that the scientific community was not well prepared to accept the impact hypothesis. They had good reason to be worried. For the previous 150 years, since the beginning of modern geology, the emphasis had been on the power of gradual change. The science of geology had supplanted biblical stories of catastrophes. The idea of a catastrophic event on Earth was not just disturbing, it was considered unscientific. Until the asteroid impact papers, explanations for the disappearance of the dinosaurs usually invoked gradual changes in climate or in the food chain to which the animals could not adapt.

Some geologists scoffed at the catastrophe scenario and some paleontologists were not at all persuaded by the asteroid theory. It was pointed out that the highest dinosaur bone in the fossil record at the time was 3 meters below the K-T boundary. Some suggested that perhaps the dinosaurs were already gone when the asteroid hit. [3] Other paleontologists rebutted that dinosaur bones are so scarce, one should not expect to find them right up against the boundary. [4] Rather, they argued the rich fossil record of forams and other creatures is the more revealing record, and forams and ammonites do persist right up to the K-T boundary.

Of course, there was a somewhat larger problem that begged explanation: Where on Earth was that huge crater? To the skeptics and proponents this was an obvious weakness of the hypothesis, and so the hunt was on to find the impact zone, if it existed.

At the time, there were only three known craters on Earth 100 km or more in size. None were the right age. If the asteroid had hit the ocean, which, after all, covers more than two-thirds of the planet's surface, then searchers might be out of luck. The deep ocean was not well mapped, and a substantial part of the pre-Tertiary ocean floor has been swallowed up into the deep Earth in the continual movement of tectonic plates.

In the decade following the proposal of the asteroid theory, many clues and trails were pursued, often to dead ends. As the failures mounted, Walter began to believe that the impact had in fact been in an ocean.

Then a promising clue emerged from a riverbed in Texas. The Brazos River empties into the Gulf of Mexico. The sandy bed of the river is right at the K-T boundary. When examined closely by geologists familiar with the pattern of deposits left by tsunamis, the sandy bed was found to have features that could only be accounted for by a giant tsunami, perhaps more than 100 meters high. Moroever, mixed in with the tsunami debris were tektites—small bits of glassy rock that were ejected from the impact crater in molten form and cooled as they rained back down to Earth. (Figure 6) [5, 6]

Many scientists were on the hunt for the impact site. Alan Hildebrand, a graduate student at the University of Arizona was one of the most tenacious. Alan concluded that the Brazos River tsunami bed was a crucial hint to the crater's location—that it was in the Gulf of Mexico or the Caribbean. He looked at available maps to see if there might be any candidate craters around. He found some rounded features on maps of the sea floor north of Colombia. He also learned of some circular-shaped "gravity anomalies," places where the concentration of mass varies, on the coast of Mexico's Yucatan Peninsula.

Alan searched for any other hints that he was on the right track. Alan noticed a report of tektites in late Cretaceous rocks from a site on Haiti. When he visited the lab that had made the report, he recognized the material as impact tektites. He then went to Haiti and discovered that the deposits there included very large tektites, along with shocked quartz grains—another signature of impacts. He and his advisor William Boynton surmised that the impact site was within 1,000 km of Haiti.

When Hildebrand and Boynton's presented their findings at a conference, they were contacted by Carlos Byars, a reporter for the *Houston Chronicle*. Byars told Hildebrand that geologists working for the state-owned Mexican oil company PEMEX might have discovered the crater many years earlier. Glen Penfield and Antonio Camargo had studied the circular gravity anomalies in the Yucatan. PEMEX would not allow them to release company data but they did suggest at a conference in 1981—just a year after the Alvarez's asteroid proposal—that the feature they mapped might be the crater. Penfield had even written to Walter Alvarez with that suggestion.

In 1991, Hildebrand, Boynton, Penfield, Camargo and colleagues formally proposed that the 180-kmdiameter crater (almost exactly the size predicted by the Alvarez team) one-half mile below the village of Chicxulub [Cheech-zhoo-loob] on the Yucatan Peninsula was the long-sought K-T impact crater (Figure 7). [7,8]

There were still crucial tests to be done to determine if Chicxulub was truly the "smoking gun." Another important issue was the age of the rock. This was no easy task to determine because the crater was buried. The best approach would be to test the core rock samples from the wells drilled by PEMEX in the



Figure 6. Tektites.

Tektites from Dogie Creek, Wyoming (top) and Beloc, Haiti (bottom). Note the bubbles within the glassy sphere, these formed in the vacuum of space as the particles were ejected out of the atmosphere. Top figure courtesy of Geological Society of Canada. Bottom figure from J. Smit 1999, used with permission.

region decades earlier. At first, it was feared that all of the core samples had been destroyed in a warehouse fire. They were eventually located and the rock that was melted by the impact could be dated by a number of laboratories. The results were spectacular. One lab obtained a figure of 64.98 + 0.05 million years, another a value of 65.2 + 0.4 million years. Right on the button—the melt rock was the same age as the K-T boundary.



Figure 7. Location of Chicxulub crater and key impact evidence sites.

The map shows locations of various impact evidence—the tsuanmi bed in the Brazos River, tektites in Haiti, the Ocean Drilling Site 1049 (see Figure 9), and the crater and surrounding ejected material on the Yucatan Peninsula. Map by Leanne Olds.

The Haitian tektites were also dated to this age, as was a deposit of material ejected from the impact. Detailed chemical analysis showed that the Chicxulub melt rock contained high levels of iridium [9] and that it and the Haitian tektites came from the same source. Furthermore, the Haitian tektites had extremely low water content and the gas pressure inside was nearly zero, indicating that the glass solidified while in ballistic flight outside the atmosphere.

Within a little more than a decade, what had at first seemed to be a radical and, to some, outlandish idea, had been supported by all sorts of indirect evidence, and then ultimately confirmed by direct evidence. Geologists subsequently identified ejected material that covers most of the Yucatan and is deposited at more than 100 K-T boundary sites around the world (see Figures 8 and 9). [10] We now understand that the history of life on Earth has not been the steady, gradual process envisioned by generations of geologists since Lyell and Darwin.

The identification of the huge crater, while a great advance for the asteroid theory, was bittersweet for

Walter. Luis Alvarez had passed away in 1988, just before its discovery.

Luis's ideas, however, continued to influence geology and the study of the K-T boundary. In 2001, a team of scientists used Luis' idea of measuring spacedust-particle accumulation to estimate the length of the K-T boundary period, the problem that Walter first asked his dad for help with. They used an isotope of helium [³He], instead of beryllium or iridium, as a timekeeper. The researchers estimated that the K-Tboundary clay was deposited in roughly 10,000 years. [11] These findings suggest that it took about 10,000 years for ocean food chains and ecosystems to recover to the point where the forams and other microscopic plankton were repopulated to the levels prior to the impact. But many large marine animals never recovered.

Out of the Ashes

On land, the first sign of life's recovery in the paleontological record above the K-T boundary is a spike in fern spores. [12] Whereas pollen must land on a live plant to reproduce, fern spores could directly give rise to a new plant even on a devastated landscape. Some flowering plants, albeit fewer species than existed before the impact, did survive, as did various species of small animals such as fish, frogs, turtles, and mammals. [13]

In the wake of the destruction of the Mesozoic world, a new age emerged in the Cenozoic—the age of mammals. This group of generally small species took advantage of the niches vacated in the demise of the Cretaceous. Mammals evolved rapidly into many various-sized species, including large herbivores and carnivores Within 10 million years, forms representing most modern orders appear in the Cenozoic fossil record. The dinosaur's demise was certainly the mammal's gain. Indeed, one can say that without the K-T asteroid clearing the way, our primate ancestors would not have flourished and our species would not be here today.

-Sean B. Carroll

Adapted with permission from: Into the Jungle: Great Adventures in the Search for Evolution Pearson/Benjamin Cummings (2008)



Figure 8. A K-T spherule layer.

An exquisitely well-preserved site near Tbilisi, Republic of Georgia, reveals a graded layer of spherules (smaller particles at the top, larger at the bottom) ejected from the impact that is also highly enriched in iridium (86 ppb). Image from J. Smit 1999, used with permission



Figure 9. The K-T impact documented in an ocean core sample.

This core sample, drilled at a site about 500km east of Florida (Ocean Drilling Project Site 1049), beautifully depicts the K-T event. Note the very large layer of ejected material on top of which the iridium-containing layer settled. Image courtesy of Integrated Ocean Drilling Program.

A Postscript

The discovery of the K-T asteroid impact prompted extensive examination of whether other extinctions were due to impacts. It appears that none of the other four major extinctions of the past 500 million years is attributable to an impact. Yet, there have been many sizable asteroid or comet impacts on Earth over the same period, although none as large as the K-T strike. Since most impacts do not cause extinctions, and most extinctions are not due to impacts, the question has been raised of why the K-T asteroid was so devastating?

Some scientists have suggested that where the asteroid struck was important. The target rock that was vaporized included a large amount of gypsum (CaSO4), which liberated a large amount of sulfur aerosols that could exacerbate the blockage of the sun, as well as produce acid rain that would alter bodies of water and soils. Furthermore, the impact and resulting explosion generated a large amount of chlorine sufficient to destroy today's ozone layer. [14]

In addition, other scientists have suggested that a period of massive volcanic eruptions might have weakened ecosystems before the K-T impact. The socalled Deccan Traps in present-day western India are proposed to have poured significant sulfur dioxide into the atmosphere in episodic eruptions beginning several hundred thousand years prior to the K-T impact. However, many scientists underscore the very sharp nature of the K-T extinction, without any preceding signs of distress in the oceans prior to the impact event as indicating that the K-T impact was the primary cause of extinction. [15]

Some paleontologists have also continued to maintain that dinosaurs were on the decline prior to the K-T impact, and thus their extinction is due to more than the K-T impact. This view has been disputed in various ways. First, dinosaur diversity does not appear to have been dwindling in particular locales during the late Cretaceous. [16] Second, the so-called "3-meter gap" below the K-T boundary in which no dinosaurs had been found has been dismissed on multiple grounds. It turns out that almost no vertebrate fossils have been reported in this zone, even of species of animals (fish, turtles, crocodiles, birds, mammals) that are known to have survived the extinction. In the Hell Creek Formation of western North America, this gap appears to be due to very poor fossilization conditions in soils just below the boundary. Thus, the gap is not valid evidence of the absence of dinosaurs. Moreover, dinosaur remains have recently been discovered very close to the K-T boundary, suggesting that with extensive searching, fossils can be found. [17]

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