Mass extinctions caused by large bolide impacts

Evidence indicates that the collision of Earth and a large piece of Solar System debris such as a meteoroid, asteroid or comet caused the great extinctions of 65 million years ago, leading to the transition from the age of the dinosaurs to the age of the mammals.

Luis W. Alvarez

A wealth of evidence has forced my colleagues and me to conclude that 65 million years ago a mountain-sized object hit Earth and caused the extinction of most of the then existing species, bringing a close to the Cretaceous period of geological history and opening the Tertiary period. Much of the evidence for this lies in the unusual layer of clay that separates those periods in the geological record, shown in figure 1. For example, this stratum contains anomalously high concentrations of iridium, an element whose abundance in the crust of the Earth is only one ten-thousandth that in meteorites and, presumably, in other "bolides," or large pieces of Solar System debris.

Our study of the geological record, bolide impacts and extinctions began nine years ago, and my colleagues in all phases of the work have been my son Walter Alvarez, who is a professor of geology at Berkeley, and Frank Asaro and Helen Michel, who are nuclear chemists at Lawrence Berkeley Laboratory and experts in neutron activation analysis.[1] This article describes the evidence that a bolide impact produced the great mass extinctions at the end of the Cretaceous period.

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Clay layer

As one might guess, it was Walter who introduced us to the 1-cm-thick clay layer that separates the latest Italian limestone deposits of the Cretaceous period, the last period of the Mesozoic era, or age of reptiles, from the earliest limestones of the Tertiary period, the first period of the Cenozoic or recent era, the age of mammals. Walter and I decided, incorrectly, that we might learn how long the clay layer had taken to form if we knew its iridium content and that of the rocks above and below it. Our assumption was that iridium from meteoritic dust accumulates at a more or less steady rate in sedimentary rock and thus would make a useful geologic timer. Hence we asked Asaro and Michel to make the measurement, and they brought us the data shown in figure 2. (In the earliest stages of Earth's formation, molten iron presumably scrubbed out the crust's iridium, platinum and other siderophiles—the word means "iron lovers"—and carried them down to the core.)

Figure 2 shows stratigraphic height in the sedimentary rock increasing vertically and iridium concentration increasing to the right. The data are from rock in the Bottaccione Gorge behind the medieval town of Gubbio in northern Italy, where Walter had been doing field work on paleomagnetism for several years. We were all surprised to see the iridium concentration spurt up by a factor of more than 30 at the bottom of the clay layer and then fall back more slowly to the background value, which is the same in the limestones above and below the clay layer. When we measure it these days, it goes up by a factor of 300 because we no longer dissolve away the calcium carbonate layer before doing the assay.

In the summer of 1979, while Walter was collecting more rock samples in Italy, I set myself the task of identifying the origin of the iridium, under the "ground rules" that the source of the iridium must also provide a plausible basis for what I called the "killing mechanism," to tie the iridium enhancement to the precisely coincident mass extinction of most of the zooplankton living in marine waters at the latitude of these deposits.

That exact coincidence can be seen by any interested person who drives up the Gubbio gorge equipped with a geologist's hammer and a hand lens. If he strikes a fresh surface of limestone with his hammer and looks closely at that surface with his hand lens, he will see in every field of view many small fossil shells called forams. That is true

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Geological record at Petriccio, Italy. This sedimentary rock contains a clay layer that marks the boundary between the Cretaceous and Tertiary periods of geological history. Alessandro Montanari, a geology postdoc at the University of California, Berkeley, rests his hand at the top of the Cretaceous layer. The slanting sediments were laid down horizontally on the sea floor but tilted as they were raised up to form the Apennines. Figure 1

at Gubbio for rocks extending more than 30 m below the Cretaceous–Tertiary, or K–T, clay layer. The prominent forams with a diameter of about 1 mm stop abruptly at the lower edge of the clay layer, indicating that they underwent an extinction at the very instant of geological time that the clay layer was deposited on the bottom of the sea. That is also true of the ammonites and several other major marine taxa of the Cretaceous period.

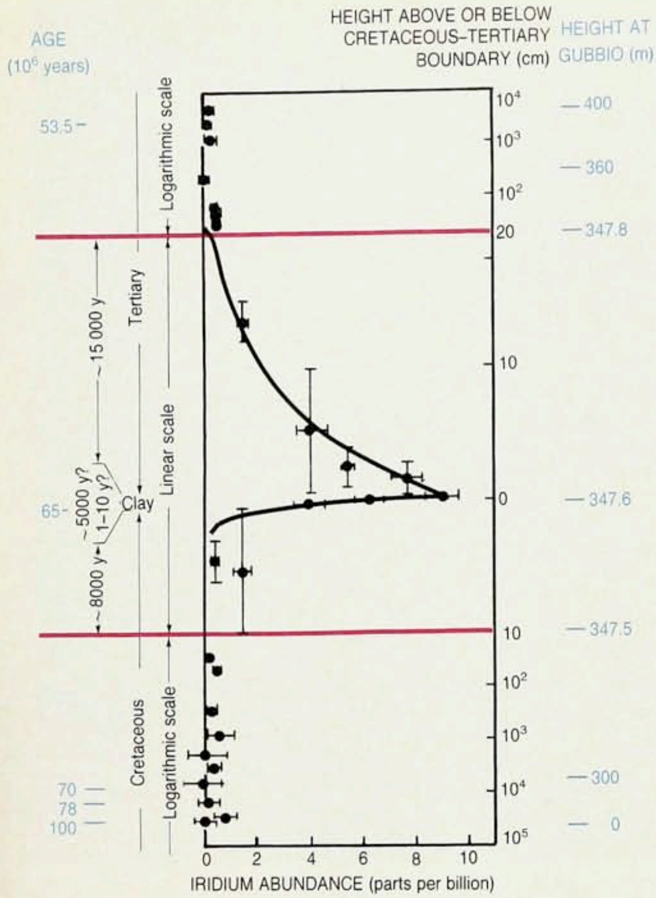
Walter aroused my interest in the clay layer when he told me that it was laid down at very nearly the time of the demise of the dinosaurs. He said that no one knew what made the clay layer or what, if anything, it might have had to do with the extinction of the dinosaurs, but as I will tell in this article, I think the answers to both of those questions are now well in hand. It was clear, nevertheless, that the clay layer was causally related to the extinction of the local forams. The probability that the disappearance of the large forams within a millimeter of the bottom of the clay layer is an accidental coincidence is easy to calculate: These most conspicuous forams are roughly constant in abundance from the clay layer downward for 30 m; the odds against such chance coincidence of the two events is just the number of millimeters in 30 meters, or 30 000 to one. To put that in perspective, I am an emeritus professor and I have not yet lived 30 000 days.

Bolide

Asaro has said that I tried out a new theory on him once or twice a week for six weeks, and shot each one down myself before anyone else had a chance to do so. Finally, I tried the idea that a bolide 10 kilometers in diameter struck the Earth and enveloped it in an opaque blanket of dust. While the dust fell for some months onto the ground and into the ocean, it cut out the sunlight, thereby stopping photosynthesis, so most of the missing animal life on Earth died of starvation. We now see the fallen dust as the worldwide K–T boundary layer. I'll describe a number of other consequences of the collision, all of which probably contributed to what has been called "the great dying."

Detailed computer modeling of the atmosphere has shown that it would have been extremely cold during the period of darkness,[2] that it would have been as though all the animals had been transported to present-day Antarctica. Cesare Emiliani, Eric B. Kraus and Eugene Shoemaker soon published a paper showing that after an impact in the ocean, the temperature would first go way down but then would increase as a result of a greenhouse effect, and that the heating could be a major contributor to the killing.[3]

Perhaps one of the most important killing mechanisms would derive from the shock-heating of the atmosphere by the expanding fireball: The impact would have released an energy equivalent to the detonation of 10^8 megatons of TNT. It would give rise to the production of huge amounts of nitrogen oxides in the atmosphere, leading to highly acidic rain and surface ocean waters with pHs low enough to dissolve the calcium carbonate shells of marine invertebrates. This important contribution came from a group at MIT.[4] I stress it here because William Clemens, our paleontologist colleague at Berkeley, recently discovered dinosaur fossils



Iridium concentration as a function of stratigraphic position in the geological record at Gubbio, Italy. Figure 2

observes between the diameters of the bolides and the mean times between their impacts with Earth. I know of no other set of experimental data that can be explained by a single power law over such a wide range of two variables. The data indicate that Earth should be hit by a bolide of diameter at least 10 km about once every 100 million years. Hence, one should not be surprised to learn that Earth was hit by a 10-km bolide 65 million years ago.

A few words on how theories become accepted are appropriate here. Most laymen feel that theories can be proved or disproved, but with very few exceptions, theories can't be proved, only disproved. For example, Newton's extremely accurate theory of gravity was disproved by Einstein's general theory of relativity, but Einstein's theory wasn't proved in that process—some new theory may prove that Einstein was wrong. So how do some theories gain nearly universal acceptance, when proofs are so rare? The answer is that every useful theory explains all known observations and makes predictions, and if the predictions turn out to be true, particularly if some of them are very surprising, then that theory becomes an accepted theory, even though someone may later find that one of its predictions doesn't correspond to reality and thereby invalidates it. An example of what I've called a surprising prediction comes from Maxwell's kinetic theory of gases, which predicted that the viscosities of gases would increase with temperature. This was counter to everyone's intuition—viscosities of liquids decrease with increasing temperature—but it turned out to be true.

in Alaska and properly asked, "If dinosaurs could survive the darkness and cold of an Alaskan winter, why would they be bothered by the darkness and cold of your K–T scenario?"[5] My best guess is that the answer lies in the rains, with their very high acidity—far beyond anything we now know as acid rain—and in the fact that it was warmer in Alaska during late Cretaceous times. Ronald Prinn of the MIT group said recently, "Essentially pure nitric acid would be pouring over about 10% of the global surface in the first few months."[6] Some paleontologists have been saying for the past few years that although the impact probably took place, it was only the straw that broke the camel's back. Pure nitric acid should make a fairly heavy straw!

I have discussed the need for a plausible killing mechanism, so I want to show that it is reasonable to assume that Earth was hit 65 million years ago by a bolide 10 km in diameter. (Mount Everest is 8.8 km high.) It is easy to estimate the effective diameter of the bolide, but before doing so we need to know that the worldwide K–T clay layer is everywhere enriched in iridium. That was the first prediction of the theory, and iridium enhancements have now been seen at about 75 locations throughout the world in K–T clay layers. If we add up the amount of iridium on each square centimeter of Earth's surface, we find a total of about half a million tons of iridium. If we use the iridium abundance of 0.5 parts per million found in certain primitive meteorites as representative of Solar System debris, then a simple exercise in geometry tells us that a spherical bolide that brings in that much iridium would be close to 10 km in diameter.

The impact of a 10-km bolide in the last 50 or 100 million years is reasonably probable. Data on the average time between collisions with Earth for bolides varying over an enormous diameter range of ten orders of magnitude (which translates directly into 30 orders of magnitude in bolide mass) were available to me in several pieces[7] in 1979. The data, plotted in figure 3, come from many sources, including lunar and terrestrial craters, tiny craters found on the surfaces of recovered spacecraft and telescopic observations of asteroids that cross Earth's orbit. Comminution—the process by which collisions of objects produce smaller objects—accounts for the simple power-law relationship that one

Predictions and 'postdictions'

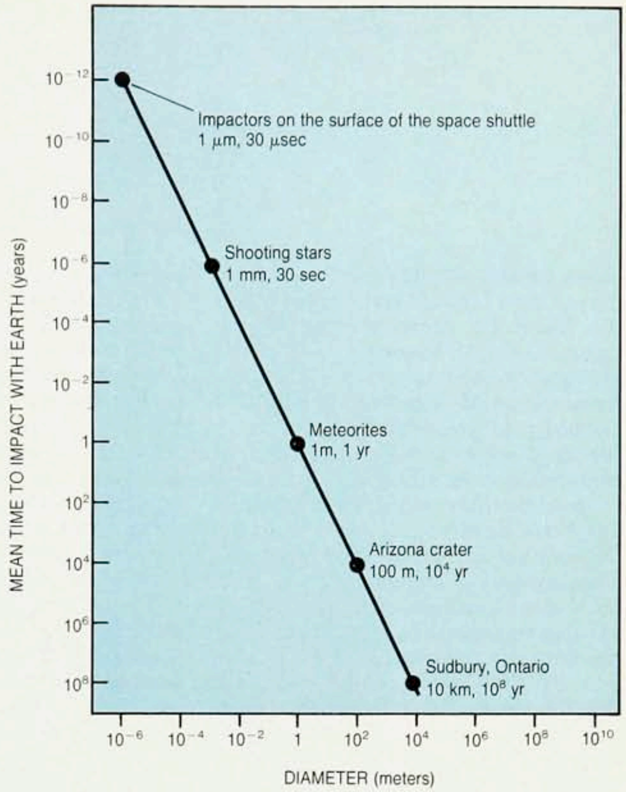
I will spend much of the rest of this article on 15 tests that have been made of our theory—all of which have turned out to support it. Most of the tests have been of predictions we made as the theory was evolving, but some have been of what are more properly called "postdictions." Confirmed postdictions are observations of phenomena that follow directly from the details of the theory but which, either because of lack of foresight or faintheartedness, we didn't list as predictions in our early papers. They are nonetheless predictions of the theory, so I won't stress their after-the-fact articulation; they test the theory just as well as formal predictions do. I have just discussed the first two predictions of our theory:

▶ that an iridium layer would be seen worldwide

▶ that the impact of a bolide 10 km in diameter is very probable on a 65-million-year time scale.

Our theory said that because major mass extinctions are rare—only five in the past 550 million years according to University of Chicago scientists David Raup and Jack Sepkoski[8]—iridium enhancements should also be rare. It has taken some time to confirm this, the third prediction, because until recently iridium assays at the part per trillion level were both time consuming and expensive. We are now able to measure chemically untreated samples using a detector, shown in figure 4, with a sensitivity of about 30 parts per trillion in a scanning mode.

The difficulty of the measurements I am describing here can be appreciated by noting that when you identify a particular person in the total population of the world, you are operating at a level of 1 in five billion, or 200 parts per trillion. In our iridium assays, we now work routinely with statistical uncertainties of 1 or 2 parts per trillion. Asaro and Michel are so worried about contaminating their samples with iridium that when Asaro recently visited Walter in Gubbio, he wouldn't touch the clay layer for fear he would carry iridium on his hands back to Berkeley and get false results on some new rock samples.



Impact frequency. Plotted is the mean time between collisions of Earth and Solar System debris of various sizes. (Based on data from Eugene Shoemaker, US Geological Survey.) Figure 3

Asaro and Michel's data show that on a time scale of a few hundred thousand years, large iridium enhancements are rare—there is only the originally observed K–T iridium spike in the several hundred thousand years of the magnetically reversed zone known as 29R—but what about longer intervals? In new observations by Frank Kyte and John Wasson[9] covering an interval of 34 million years the K–T iridium spike stands out clearly above the background and no other iridium enhancements do so. The data come from deep sea drilling cores from a part of the Pacific Ocean that has one of the slowest sedimentation rates I've ever heard of. Kyte and Wasson chose such cores so they could look at the longest interval of time in the smallest number of samples. The K–T iridium spike is the only obvious one showing, indicating that it was a most unusual event, one for which the word "unique" might well be used, and certainly confirming prediction 3, that such events are rare. We will soon see that the K–T iridium spike can be dated as simultaneous, in the geological sense of that word, with the extinction of the dinosaurs, to within the very small experimental uncertainties, so we can then invoke Occam's razor to say that they are causally related.

An obvious prediction of the theory is that the K–T iridium enhancement would always be seen, worldwide, in the same magnetic reversal zone, number 29R. All measurements place the K–T boundary in this zone, and I'll call this work the confirmation of prediction number 4, that all the K–T iridium enhancements worldwide were laid down simultaneously.

A fifth and very important prediction of our theory is that the iridium layer can be seen at sites that were not at the bottom of the sea 65 million years ago, as all our first sites were, but were either on dry land or in regions covered by fresh water. This prediction is important because some people dismissed the notion of a large bolide impact and substituted the idea that a sudden change in ocean chemistry had precipitated the observed iridium out of solution. In 1981 Carl Orth and his colleagues at Los Alamos National Laboratory and at the US Geological Survey found iridium in continental sedimentary rocks in cores from a drill hole in the Raton Basin of New Mexico.[10] The vertical axis in figure 5 shows the depth of the samples in the drill hole; in the left half of the figure we see the iridium concentration. It increases by a factor of 300 in a sharp spike, confirming prediction number 5.

Orth's drill hole also confirmed another important prediction of the theory: that plants as well as animals felt the effect of the bolide impact. We had been told by some of the best paleobotanists that the K–T extinction didn't extend from animals to plants. But it was central to our theory that the plants would also experience trauma, and even extinctions, and that can be listed as our sixth prediction. The confirmation comes in figure 5, which is one of the most exciting diagrams I've ever seen. Plotted on the right side of the figure is the ratio of fossil pollen to fern spores. The flowering plants clearly did feel the K–T impact, so the paleobotanists we had talked to were simply wrong. Orth and his colleagues published a magnified plot of both the iridium abundance and the pollen density, and the striking feature is that the extrema of the two peaks occur in the same *centimeter* of stratigraphic height, thereby eliminating random coincidence as the cause of this surprising observation. The sedimentation rate in the Raton Basin is close to 7 mm per 100 years, so 1 cm corresponds to about 140 years. The first time I showed figure 5, I predicted that before long it would be prominently displayed in all textbooks on geology and paleontology. It is too soon to check that prediction, so I'll return to my list of scientific predictions of the impact theory.

Chemical predictions

The next four predictions involve several chemical properties of the K–T boundary clay.

The easiest one to check was that the gross elemental composition of the K–T boundary clay should be different from that of the clay that constitutes 5% of the limestone above and below the layer. As far as I can tell, most of the geologists who were aware of the existence of the K–T boundary clay had naturally assumed that it came from the same source that supplied the clay component of the limestones—material eroded from the continents and washed out to sea by rivers, there to mix with the calcium carbonate from dead marine animals. When Walter first showed me a sample of the K–T boundary clay from Gubbio, he indicated that the simplest explanation for the clay was that for some unknown reason, calcium carbonate stopped accumulating on the ocean floor for several thousand years, and during that time the clay continued to be washed down from the continents. That scenario would lead to the trivial prediction that the elemental composition of all three clays—K, T and K–T boundary—would be the same. Our theory agreed that the gross chemical compositions of the K and T clays should be identical, but predicted they would be different from that of the boundary clay, because it came from a different place. I'll call that prediction number 7, even though it was the first one we were able to confirm. The observations could have been made in much earlier times, because most of the measurements can be made using the traditional techniques of analytical chemistry and don't require modern neutron activation analysis.

The next prediction was that the "chemical fingerprint" of the boundary layer clay should have been the same, worldwide, when it was deposited. This means that the plot of elemental abundance in the boundary layer versus atomic number would be the same, at all locations, if no changes had taken place in the last 65 million years. It took longer to confirm this prediction, partly because the present-day trace element composition depends to some extent upon the oxidizing or reducing state of the ocean at the time the deposit was made. By working with regions of comparable ocean chemistry, Asaro and Michel have found data that are in remarkable agreement with prediction and for which no other explanation has been advanced to my knowledge.

Figure 6 compares the chemical fingerprints of K–T boundary clays taken from sites on opposite sides of the globe—in Denmark and from a drill hole in the Central Pacific. Each point represents an element, and its position tells that element's fractional abundances at the two sites. Thus if the fingerprints were exactly the same, all the points would lie on the 45° line. Experts on the composition of ancient pottery, such as Asaro and Michel, look at figure 6 and say, "These two clays came from the same quarry." I believe the common quarry was the crater excavated by the bolide 65 million years ago, and I will continue to so believe until someone comes up with a more satisfactory explanation for these otherwise quite mysterious observations. As always, the fingerprint is quite different from that of the clay above and below the boundary. The boundary clay is, in geological terms, "exotic." It is, in fact, indistinguishable from one part chondritic meteorite plus ten parts average Earth's crust, and nothing like it had been described previously in the geological literature.

In 1982 Karl Turekian of Yale University proposed an ingenious test that he believed would show the K–T boundary clay to be of terrestrial, rather than extraterrestrial, origin.[11] Turekian pointed out that because rhenium-187 is radioactive and decays to osmium-187 with a very long halflife, the isotopic ratios of osmium-187 to osmium-186 found at various sites would depend on their history. In particular, he noted that this isotopic ratio is now about unity for meteorites, but between 13 and 30 for crustal rocks. The measurements he later made with Jean-Marc Luck, also of Yale, showed that the osmium in the K–T clay layer is certainly not of crustal origin but could be of bolide origin. That is what the theory predicted, so I will chalk it up as confirming prediction number 9.

The fourth chemical test of the theory was really a postdiction, which we and R. Ganapathy[12] of the Baker Chemical Company recognized independently at the same time. We, and more thoroughly he, found that the fingerprint of siderophiles in the K–T boundary clay was indistinguishable from that in the most common meteorites—the chondrites—and quite different from that in any known terrestrial rocks. In the above discussion I have concentrated on iridium abundances, simply because iridium has an exceedingly large cross section for the capture of slow neutrons and is therefore the easiest of the noble metals to measure by neutron activation. But the work I am now describing suggests that had our analytical techniques been more sensitive, we could have focused on any of the noble metals—platinum, osmium or even the lighter ruthenium, rhodium and palladium—and all our conclusions would have been the same, including that for the diameter of the bolide. That is the result of our belated test of the tenth "prediction."

Heating, shock and fires

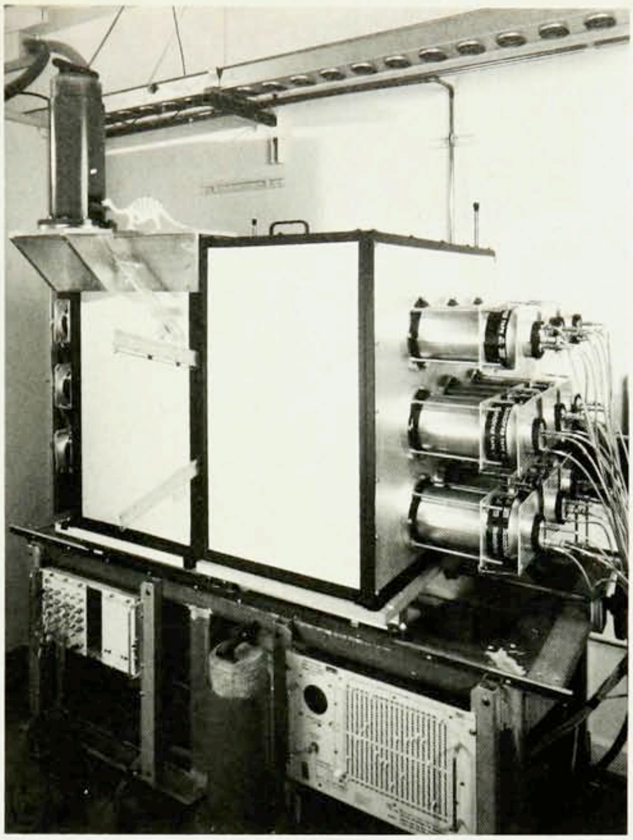
The K–T layer should contain evidence for the high temperature generated by the impact. This postdiction is number 11. The high-temperature signature, found by the Dutch paleontologist Jan Smit[13] and studied extensively by Alessandro Montanari, one of Walter's students, takes the form of sand-sized spherules of sanidine, a mineral usually formed at high temperature. Figure 7 shows some of the spherules. These spherules are seen in K–T boundary clay at sites all over the world. My geologist friends are sharply split on the significance of the sanidine spherules as temperature indicators, so I will simply say that for me they rule out volcanic theories of the origin of the K–T boundary layer.

There is certainly no chance that wind could carry sand-sized particles for large distances in the atmosphere, to which volcanic ejecta are confined. But calculations using hydrodynamics computer codes indicate that the rising fireball after the bolide impact would accelerate the dust from the bolide plus the extra crustal dust upward through the atmosphere and into ballistic orbits, spreading it worldwide in about an hour.[14]

The 12th prediction, actually a postdiction, is that shocked quartz might be found in the K–T boundary layer depending on the type of rock hit by the bolide. Bruce Bohor of the US Geological Survey found such shocked quartz in the K–T boundary layer in Montana, and later in many other locations.[15]

Until its discovery in the boundary clay, this altered form of quartz had previously been seen only near known impact craters, such as the one in Arizona, and near the sites of underground nuclear explosions. These are locations of not only high pressure, but high shock pressure. This sort of shocked quartz has never been seen in association with volcanic activity.[15] I have never seen a sample of shocked quartz, but I did see a sort of shock wave pass through the Earth sciences community when Bohor announced his discovery.

The next postdiction, number 13, is not a very strong one but might have some relevance to the impact theory. It comes from the discovery by the University of Chicago group of Edward Anders, Wendy Wolbach and Roy Lewis that the K–T boundary clay includes an amount of soot that could only result from the burning of an appreciable fraction of all the biomass present on Earth 65 million years ago.[16] Of course this conclusion is dependent on our experimental demonstration that the K–T boundary clay was deposited in about a year, and not over the several thousand years one would calculate from its stratigraphic thickness divided by the normal K or T sedimentation rate. Current thinking is that the fires were set not by infrared radiation from the fireball over the impact crater—that wouldn't involve a large enough area—but that the dust cloud dropped the temperature, killed much of the tropical rain forests and left them in a desiccated and flammable state highly susceptible to ignition by lightning.[16]



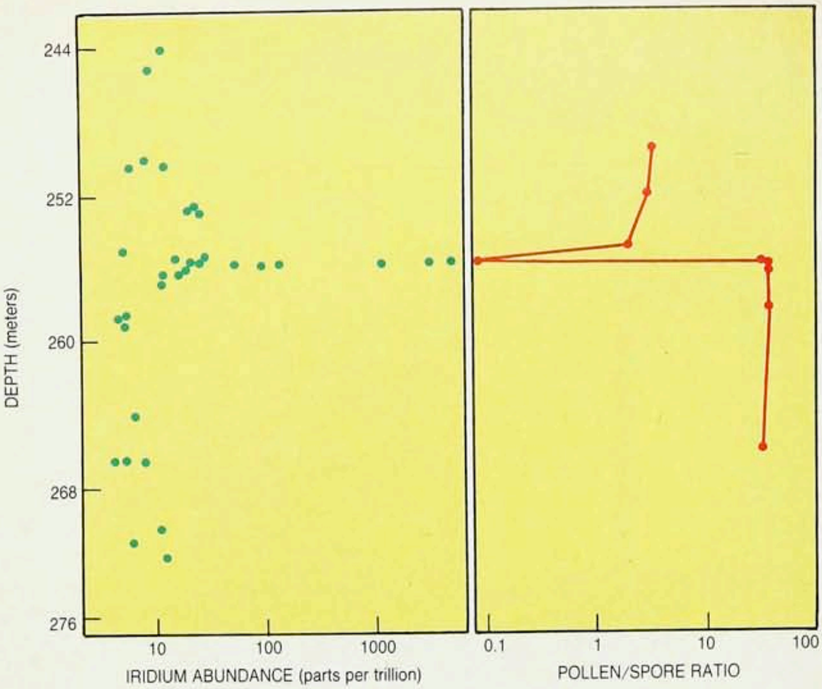
Detector capable of measuring iridium concentrations as low as 30 parts per trillion in a rapid search mode. By using longer counting times the sensitivity can be pushed down to a few parts per trillion. Figure 4

Survival of species

Some paleontologists see very little in the way of a pattern to explain why some species survived the crisis while other, related ones were wiped out. I have no problem with that, based on my extensive experience with the effects of increasing doses of nuclear radiation on animals. Plots of survival as a function of dose are similar for other "insults" to the population, such as doses of chemical poisons, heat and lack of oxygen. The curves all stay near 100% at low doses, but then fall off sharply at increasing doses and finally level off as they approach zero survivors. All such curves that I know of have this general shape. If the insult is large enough to predict a survival fraction of only 10^{-6}, then a species with a million individuals in the original population would almost certainly be wiped out. But another species, with perhaps 100 million individuals, would have a good chance to escape extinction.

We can divide environmental insults of the kind caused by a bolide impact into three classes: small, medium and large. If the insult had been small, no species would have gone extinct; the mammals would still be subordinate to the dinosaurs, and I wouldn't be writing this article. If it had been large, all life on this planet would have ceased, so again I wouldn't be writing this article. That tells me that the insult must have been of medium strength, and that for the rather uninteresting reasons I've just mentioned, some species survived and others didn't. I think the smallness of the dinosaur population may have been an important contribution to its complete and sudden disappearance. Dale Russell of the National Museum in Ottawa, Canada, an expert on dinosaurs, tells me that the K–T extinction wiped out virtually all species of land animals weighing more than 25 kilograms. Because population magnitudes are inversely related to individual weights, it may be true that the survival of the lighter-weight species was more a result of their larger populations than of their smaller body weights. I doubt that we will ever know the details of why certain species survived and others went extinct. It may even be a mistake to try to identify the difference between the two kinds of species; to me, that could be like trying to find a difference between two lottery ticket holders to explain why one of them won a million dollars while the other got nothing.

Dinosaurs. If the bolide impact was responsible for the extinction of the dinosaurs, as it obviously was for the forams, then we should find the iridium-rich clay layer just above the highest dinosaur fossil. This is prediction number 14. We obviously can't expect the iridium layer to be a fraction of a millimeter above the highest dinosaur, as it is above the highest forams, so by what measure do we judge that it is just above the highest dinosaur, as our prediction says it should be? It is easy to show mathematically that if the dinosaurs had been flourishing before a sudden extinction, as they had been for the previous 140 million years, and if the iridium layer really marks the time at which they underwent that sudden extinction, then the most probable position of the highest dinosaur fossil is below the iridium layer by a distance equal to the mean vertical spac-



Coincidence of iridium enhancement and drop in the ratio of fossil pollen to fern spores. These data from the Raton Basin of New Mexico indicate that plants as well as animals felt the effect of a bolide impact. The drop in the ratio of angiosperm pollen to fern spores indicates a shift in the flora from Cretaceous species to Tertiary species. The extrema of the two peaks occur in the same centimeter of stratigraphic height. Figure 5

ing of such fossils. The probability that the highest fossil will be found twice as far below the layer is e^{-2}, or 0.14. And we can use the mean spacing as a reasonable mean error for the predicted position.

With this as a prediction, we asked Clemens, the paleontologist, to collect rock samples above the highest dinosaurs in his research area in Montana so that we could test them for iridium. He tells us that the highest 17 articulated fossils in his area had an average vertical spacing of almost exactly 1 m, and despite what many dinosaur experts have said, there is no indication in his data of a gradual decrease in fossil density with height. (Articulated fossils are ones in which two or more bones are in their expected relationship, and are nearly the only ones that careful paleontologists consider to have any significance; very large single bones are also acceptable. The bone fragments or teeth that are found above the iridium layer are of no interest, because they could have been moved by running water or by animals that lived much later.) Hence we expect the iridium layer to be 1 ± 1 m above the highest observed fossil. Asaro and Michel found the iridium layer 2 m above Clemens's highest fossil, so we feel that our prediction has been well confirmed. Clemens, however, faults the impact theory because the iridium layer wasn't at the level of the highest fossil, and continues to talk about the "2-meter gap" as having disproved the theory. We know the most probable gap would be 1 m, but Clemens's desired gap of 0 m and the observed gap of 2 m are both consistent with the predicted value of 1 ± 1 m.

We continue to hear that paleontologists have recently disproved the century-old theory that after 140 million years of adaptations to serious temperature and sea-level changes in their environment, the dinosaurs suddenly went extinct on land, in the sea and in the air. The latest such story is based on dinosaur fossils found 500 feet above the K–T horizon, corresponding to a time a million years into the Tertiary period. But *The New York Times* reports that the investigator, Robert E. Sloan, "said the identity of most of the post-Cretaceous dinosaurs could not be determined because the bones were too fragmentary."[17] That indicates to me that non-articulated fossils were used to arrive at an invalid conclusion.

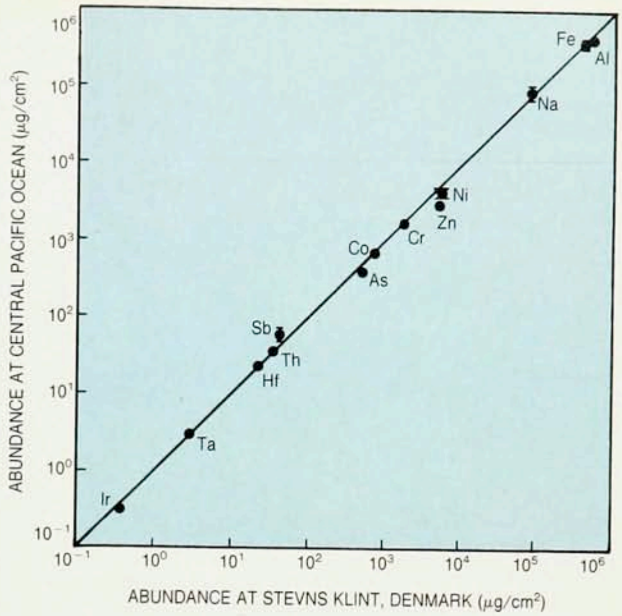
One of the most amusing features of the search for truth about the disappearance of the dinosaurs is that two different groups of paleontologists feel that they have shown we are wrong in asserting that the dinosaurs went extinct when the iridium layer was deposited. One group says the dinosaurs went extinct 20 000 years earlier, and the second group says they lasted for another million years!

Occam's razor tells us that when we find two extraordinary events that can be tied together as cause and effect by a reasonable theory, we shouldn't take seriously other theories, particularly when there is no valid evidence to support them.

At present, those who don't accept the impact theory of extinctions appear to have only two alternatives to suggest. One is a volcanic eruption, which I've mentioned as being in strong disagreement with three observations—the worldwide distribution of spherules, the greatly enhanced iridium concentration in the K–T boundary layer and the widely observed presence of shocked quartz in the layer. We can't dismiss the idea that the bolide impact triggered volcanic eruptions—it would have registered about 13 on the Richter scale—but such eruptions alone cannot account for the extinctions.

The second alternative appeals to many paleontologists. It is that the dinosaurs went extinct as the result of wide excursions of temperature or sudden changes in sea level. We can rule out sea level changes as being of any consequence by noting that in the 140 million years during which the dinosaurs existed, the sea level dropped suddenly by about 150 meters on two occasions, the same amount it dropped at the K–T horizon, and the dinosaurs didn't react adversely to those earlier changes. Even if drops in sea level were threats to the land-based dinosaurs, how could they cause the nearly (or exactly) simultaneous extinctions of the marine dinosaurs and flying pterosaurs? One should expect sudden drops in sea level to *follow* bolide impacts, however, as the sudden drop in temperature causes ice to accumulate on the continents.

I think it is now time for those who felt comfortable ignoring the impact theory seven years ago to recognize that it is the only existing theory that agrees with all the observations. I feel the shoe is now on the other foot, and that those who are pushing for the acceptance of non-bolide theories of the K–T extinctions should tell how they



'Fingerprint' comparison of K–T boundary layer clays from Denmark and from a drill hole in the central Pacific Ocean. The points are very near the 45° line, indicating that the two clays have a common source. Figure 6

can overcome the many objections that I have outlined here. If they can't do that—and I don't see much chance that they can—then they have only two choices: They can either accept some form of bolide impact theory or come up with a new non-bolide theory that agrees with all the observations. I think the chances of finding such a theory are rather remote, but I can't rule them out. Scientists embarking on such a search should remember that many bolide impacts in the 10-km diameter class are expected to have occurred in the last billion years, so if the K–T boundary layer was not caused by a bolide impact, then where is the evidence for such an impact with its now well-understood signature?

Extinction rate. Almost all of the genera that have ever existed on Earth have undergone extinction. Five mass extinctions stand out above a huge background of ordinary extinctions. Until recently, it was thought that mass extinctions and background extinctions differed only in "intensity," as measured, for example, by the number of families lost per million years. I believe our work led people to reexamine that postulate, and David Jablonski of the University of Chicago recently found it to be incorrect.[18] He points out that genera can become protected from ordinary extinctions in two ways. They can diversify, that is, evolve larger numbers of species, all of which have to be killed before the genus can be said to be extinct, and they can spread over wide geographical areas. However, Jablonski finds experimentally that these protective measures don't help a genus escape a mass extinction. I think it is correct to say that a background extinction takes place when a genus loses the Darwinian battle for the survival of the fittest—one species against another. But in the K–T mass extinction that Jablonski studied, there was no way that a genus could have evolved so as to be protected from an occurrence that happens suddenly once every 100 million years or so. I think we can add mass extinctions as a prediction of the bolide impact theory, to bring the total to 15.

Other extinctions

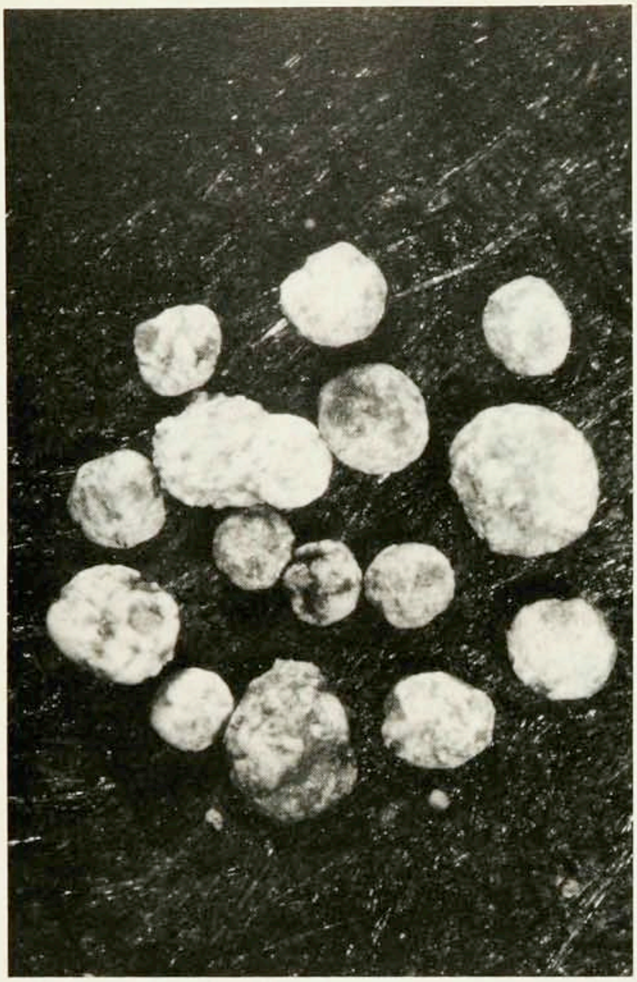
We can't help noticing that there have been five major extinctions in the last 500 million years, and that a bolide of the kind that caused the K–T extinction should hit Earth on the average of once every 100 million years. We wouldn't be responsible scientists if we didn't suggest that all five "majors" may have had similar origins, in which case we should find iridium layers associated with all five. We and other groups have looked for iridium enhancements at the four other major extinctions, with not as much success as we had hoped, but we certainly have not "struck out."

Among mass extinctions of the second rank, at least two have associated iridium enhancements. We and Ganapathy independently found one near the 35-million-year-old Eocene–Oligocene boundary. We have since shown that it consists of two or perhaps three closely spaced iridium "spikes," but the full story of the E–O boundary has not yet been told. Very recently, using our new detector, we found a sharp iridium spike laid down 11 million years ago; we haven't yet shown that it happened worldwide. We plan over the next few years to make a continuous search of the last 250 million years of the geological record.

Three years ago Raup and Sepkoski showed evidence that mass extinctions have occurred periodically, with a time interval of 26 million years.[19] The three known iridium enhancements—11, 38 and 65 million years ago—are all consistent with this timetable. Figure 8 is a replot of their data by my Berkeley colleague Richard Muller. The arrows are spaced 26 million years apart and have a phase that gives the best "eyeball fit" to the data. Muller and his coworkers have suggested that the regularity shown in figure 8 derives from a postulated solar companion star, called Nemesis, with a period of 26 million years.[20] According to their theory, this star, when near perihelion, perturbs the Oort Cloud and sends a shower of a billion comets into the inner Solar System, where several hit Earth by chance over a few million years. Indeed, the observed "fine structure" of the late Eocene impact record is best explained by a comet shower, but that shower could have come from a single passing star, with no requirement for periodicity. The Nemesis hypothesis is interesting and still developing, but I do not have space here to discuss it in more detail.

I don't want to leave the impression that we know everything about impacts and extinctions. A problem that is under strenuous debate at the moment is reconciling the paleontologists' belief in long-term extinction events that last more than a million years and our demonstration that at least one such event, at the K–T horizon, was basically instantaneous. A fascinating paper addressing this question has just been accepted for publication in *Nature*. Its authors include two astronomers, two geologists and four paleontologists—this is certainly a first!

The paper's thesis is that comet showers initiated many extinctions, so each extinction really consists of sever-



Spherules of sanidine. Sand-sized particles such as these are seen in K–T boundary clay at sites all over the world. Figure 7

al sharp components of the kind I've discussed here, but spread out over the few million years it takes for the comet shower to be cleaned out. Muller and Erle Kauffman of the University of Colorado have advanced this model for several years and have given it the name "stepwise mass extinctions."[21] It has much in its favor—not the least that it would end the debate over whether mass extinctions were geologically instantaneous, as I've described, or spread out over a few million years, as most paleontologists believe. If the authors of this new paper are right, then the two views are equally valid; it just depends on how you look at the record.

So far we have seen multiple major impacts at only one extinction event, the late Eocene, but there is other evidence for comet showers at several other extinctions. Gerta Keller at Princeton and Billy Glass at the University of Delaware saw evidence for multiple impacts before the iridium searches turned up such evidence. Keller had paleontological evidence and Glass observed multiple layers of microtektites. Walter and Muller, as well as Michael Rampino and Richard Stothers of NASA, have shown that large terrestrial craters have been produced with nearly the same period and phase as Raup and Sepkoski's 26-million-year extinction cycle.[22] That could only be true if some bolides had been bunched together, as in comet showers. Things are a bit murky at this point, with disagreements among the experts.

At this point, some readers may say to themselves, "I keep seeing articles by Charles Officer and Charles Drake of Dartmouth College purporting to prove that the K–T extinctions were caused by the nearly simultaneous eruptions of many volcanoes worldwide 65 million years ago. What is wrong with that theory?" My answer is that that theory[23] doesn't do either of the things a theory must do to gain acceptance. It doesn't explain the many known observations concerning the K–T extinctions—in fact, it is in strong disagreement with many of those observations, as I said earlier. Second, it makes no predictions that have been verified. Officer and Drake ignore the fact that volcanic ejecta are usually distinguished by the lowest iridium concentrations ever seen—most of the normally low iridium content of crustal rocks comes from the rain of meteoritic dust to which they were subjected as they were being laid down. Material that ends up in volcanic eruptions has previously been shielded from such meteoritic dust and is therefore the last place one should look to trace the very high iridium concentrations we find at the K–T boundary. And Officer and Drake make a serious scientific error when they call attention to the presence of gaseous iridium compounds in the effluent from the volcanic crater of Kilauea, in Hawaii, and say that this could explain the greatly enhanced iridium concentrations in the K–T layer. I call this a serious scientific error because it ignores the explicit warning by the discoverers of the gaseous iridium that their observations have no relevance to the K–T boundary layer iridium.[24] They say, "Kilauean-type aerosols cannot account for the other [than gold] observed siderophile element abundances in the boundary clay layer, which must be derived from the *impacting projectile*" (emphasis added). Furthermore, Officer and Drake offer no suggestions as to what mechanisms one might invoke to synchronize their postulated worldwide volcanic activity—something never before seen. We say that a release of energy that would register 13 on the Richter scale could trigger such volcanic activity.

Finally, they make light of the strong evidence for high shock pressures at the K–T boundary by asserting that shocked quartz has been found in association with volcanic eruptions. In a recent issue of *Science*, Richard Kerr, the magazine's geology editor, has this to say about the importance of the shocked quartz evidence for a K–T impact: "Try as they might, advocates of a volcanic end to the Cretaceous have failed to find the same kind of so-called shocked quartz grains in any volcanic rock. Because shocked quartz continues to maintain its exclusive link to impacts, the impact hypothesis would seem to be opening its lead over the sputtering volcano alternative."[15]

Now that I've told of some problems that remain in our understanding of the other extinctions, I'll return to the more thoroughly studied K–T extinction, and say that for all the reasons I've explored in this article, I see no way to escape the conclusion that the K–T extinctions, including that of the dinosaurs, were triggered by the impact of a 10-km-diameter bolide. At least from our human point of view, that impact was arguably one of the most important single events in the 4.5-billion-year history of our planet. Had it not taken place, the largest mammals alive today might still resemble the ratlike creatures that were scurrying around 65 million years ago trying to avoid being devoured by dinosaurs.

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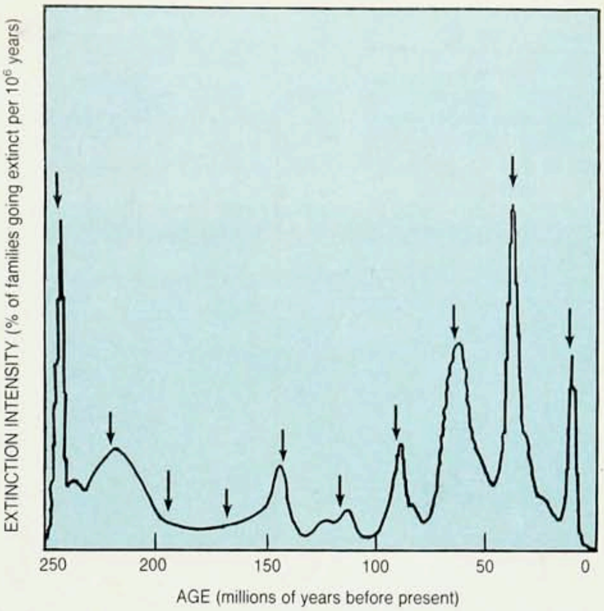

Extinctions during the past 250 million years. The arrows are spaced 26 million years apart. These data are the basis of the Raup and Sepkoski theory of periodic extinctions, in which a postulated solar companion star with a 26-million-year period, when near perihelion, perturbs the Oort Cloud and sends comets into the inner Solar System. Figure 8

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