An Extraterrestrial Impact

Accumulating evidence suggests an asteroid or comet caused the Cretaceous extinction

by Walter Alvarez and Frank Asaro

About 65 million years ago something killed half of all the life on the earth. This sensational crime wiped out the dinosaurs, until then undisputed masters of the animal kingdom, and left the humble mammals to inherit their estate. Human beings, descended from those survivors, cannot avoid asking who or what committed the mass murder and what permitted our distant ancestors to survive.

For the past dozen years researchers from around the world, in disciplines ranging from paleontology to astrophysics, have mustered their observational skills, experimental ingenuity and theoretical imagination in an effort to answer these questions. Those of us involved in it have lived through long months of painstaking measurement, periods of bewilderment, flashes of insight and episodes of great excitement when parts of the puzzle finally fell into place.

We now believe that we have solved the mystery. Some 65 million years ago a giant asteroid or comet plunged out of the sky, striking the earth at a velocity of more than 10 kilometers per second. The enormous energy liberated by that impact touched off a nightmare of environmental disasters, including storms, tsunamis, cold and darkness, greenhouse warming, acid rains and global fires. When quiet returned at last, half the flora and fauna had become extinct. The history of the earth had taken a new and unexpected path.

Other suspects in the dinosaur murder mystery, such as sea level changes, climatic shifts and volcanic eruptions, have alibis that appear to rule them out. Some issues, however, are still unclear: Where was the impact site? Was it a single or multiple impact? Have such impacts occurred on a regular, periodic timetable? What is the role of such catastrophes in evolution?

WALTER ALVAREZ and FRANK ASARO are longtime collaborators on the impact hypothesis of mass extinction. Alvarez is a geologist at the University of California, Berkeley; his laboratory is the Apennine mountains of Italy, where he is a honorary citizen of the town of Piobbico. Asaro is a nuclear chemist at the Lawrence Berkeley Laboratory. Before his work with Alvarez, he made chemical analyses of archaeological materials; he determined that one of Berkeley's prized possessions, an inscribed brass plate attributed to Sir Francis Drake, was not authentic.

The puzzle presented by a mass extinction is both like and unlike that of a more recent murder. There is evidence—chemical anomalies, mineral grains and isotopic ratios instead of blood or fingerprints or torn matchbooks—scattered throughout the world. No witnesses remain, however, and no chance exists of obtaining a confession. The passage of millions of years has destroyed or degraded most of the evidence in the case, leaving only the subtlest clues.

Indeed, it is difficult even to be sure which of the individual fossils that survive are those of victims killed by the impact. But paleontologists know there must have been victims because fossil-bearing sedimentary rocks show a great discontinuity 65 million years ago. Creatures such as dinosaurs and ammonites, abundant for tens of millions of years, suddenly disappeared forever. Many other groups of animals and plants were decimated.

This discontinuity defines the boundary between the Cretaceous period, during which dinosaurs reigned supreme, and the Tertiary, which saw the rise of the mammals. (It is known as the KT boundary after *Kreide*, the German word for "Cretaceous.")

When we began to study the KT boundary, we wanted to find out just how long the extinction had taken to occur. Was it sudden—a few years or centuries—or was it a gradual event that took place over millions of years? Most geologists and paleontologists had always assumed that the extinction had been slow. (These fields have a long tradition of gradualism and are uncomfortable with invoking catastrophes.) Because dinosaur fossils are relatively rare, their age provides little detailed information on the duration of the extinction. It was possible to view the extinction of dinosaurs as gradual.

When paleontologists looked at the fossils of pollen or single-celled marine animals called foraminifera, however, they found the extinction to be very abrupt. In general, smaller organisms produce more abundant fossils and so yield a sharper temporal picture.

The extinction also appears more sudden as paleontologists study closely the fossil record for medium-size animals such as marine invertebrates. Among these are the ammonites (relatives of the modern chambered nautilus), which died out at the end of the Cretaceous period. The best record of their extinction is found in the coastal outcrops of the Bay of Biscay on the border between Spain and France.

In 1986 Peter L. Ward and his colleagues at the University of Washington made detailed studies of these outcrops at Zumaya in Spain. Ward found that the ammonites appeared to die out gradually—one species disappearing after another over an interval of about 170 meters, representing about five million years. But in 1988 Ward studied two nearby sections in France and found evidence that these ammonite species actually survived right up to the KT boundary. The apparent gradual extinction at Zumaya was merely the artifact of an incomplete fossil record. If organisms whose fossils are well preserved died out abruptly, then it is likely that others that perished about the same time, such as dinosaurs, whose remains are more sparsely preserved, did so as well.

This establishes that the extinction was abrupt in geologic terms, but it does not establish how many years this extinction took, because it is a major accomplishment to date a rock to an accuracy of a million years. Intervals in the geologic records can be determined with precision only to within 10,000 years (.01 Myr), a period longer than the entire span of human civilization.

The duration of the mass extinction that marks the KT boundary can be estimated more precisely than this. In the deep-water limestones at Gubbio in Italy, a thin layer of clay separates Cretaceous and Tertiary sediments. The

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layer, discovered by Isabella Premoli Silva of the University of Milan, is typically about one centimeter thick. In the 1970s one of us (Alvarez) was part of a group that found the clay falls within a six-meter thickness of limestone deposited during the .5-Myr period of reversed geomagnetic polarity designated 29R. On the face of it, this suggests that the clay layer, and the mass extinction it marks, represents a span of no more than .001 Myr, about 1,000 years.

Jan Smit of the University of Amsterdam did a similar study of sediments at Caravaca in southern Spain, where the stratigraphic record is even more precise, and estimated the extinction lasted no more than 50 years. By geologic standards this is blindingly fast!

Our work on the KT boundary began in the late 1970s when we and our Berkeley colleagues Luis W. Alvarez and Helen V. Michel tried to develop a more accurate way to determine how long the Gubbio KT clay layer took to be deposited. Our efforts failed, but they did provide a crucial first clue to the identity of the mass killer. (That is what detectives and scientists need: a lot of hard work and an occasional lucky break.)

The method depended on the rarity of iridium in the earth's crust—about .03 part per billion as compared with 500 parts per billion, for example, in the primitive stony meteorites known as carbonaceous chondrites. Iridium is rare in the earth's crust because most of the planet's allotment is alloyed with iron in the core.

We suspected that iridium would enter deep-sea sediments, such as those at Gubbio, predominantly through the continual rain of micrometeorites, sometimes called cosmic dust. This constant infall would provide a clock: the more iridium in a sedimentary layer, the longer it must have taken to lay down. Moreover, iridium could be measured at very low concentrations by means of neutron-activation analysis, a technique in which neutron bombardment converts the metal into a radioactive and hence detectable form.

One scenario we considered was that the KT boundary clay layer formed over a period of about 10,000 years when organisms that secrete calcareous shells died out, and so no calcium carbonate (which makes up most of the limestone) was deposited. Most layers at Gubbio contain about 95 percent calcium carbonate and 5 percent clay; the boundary layer contains 50 percent clay. If this scenario was correct, the ratio of iridium to clay would be the same in the boundary clay as in higher and lower layers. If clay deposition had slowed at the same time as calcium carbonate deposition, the ratio would be higher than that in adjacent rocks.

In June of 1978 our first Gubbio iridium analyses were ready. Imagine our astonishment and confusion when we saw that the boundary clay and the immediately adjacent limestone contained far more iridium than any of our scenarios predicted—an amount comparable to that in all the rest of the rock deposited during the 500,000 years of interval 29R.

Clearly, this concentration could not have come from the usual sprinkling of cosmic dust. For a year we debated possible sources, testing and rejecting one idea after another. Then in 1979 we proposed the one solution that had survived our testing: a large comet or asteroid about 10 kilometers in diameter had struck the earth and dumped an enormous quantity of iridium into the atmosphere.

Since we first proposed the impact hypothesis, so much confirming evidence has come to light that most scientists working in the field are persuaded that a great impact occurred. More than 100 scientists in 21 laborato-

EVIDENCE OF GIANT IMPACT that caused the mass extinction at the end of the Cretaceous period is scattered around the globe. This map shows continents as they were at the time of the extinction 65 million years ago. Anomalous levels of iridium, which suggest a large impact, have been found in sediments from the Cretaceous-Tertiary (KT) boundary, as have impact-generated quartz crystals. The 150-kilometer crater that an impact would have made has not been found.