

TWELVE-YEAR TRAIL OF CLUES LEADS TO IMPACT CRATER FROM THE K-T BOUNDARY

The search started with a hypothesis that was literally out of this world: Could a massive comet or asteroid, perhaps 10 km in diameter, have struck the Earth about 65 million years ago, changing the climate so drastically that the dinosaurs and other creatures could no longer survive? That question was raised in 1980 by Luis Alvarez, his son Walter, Frank Asaro and Helen Michel of the University of California, Berkeley.¹ Their evidence at the time was scanty: only an anomalous concentration of iridium at the geological stratum corresponding to the era when the giant reptiles became extinct and supposedly delivered by the extraterrestrial projectile. (See the article by Luis Alvarez in *PHYSICS TODAY*, July 1987, page 24.) But the suggestion triggered a massive hunt, and geological sleuths soon gathered much substantiating evidence. The telltale crater, however, remained elusive.

Now researchers feel they have fingered the suspect: a structure 180 km in diameter submerged beneath the Yucatán peninsula and centered on the Mexican village of Chicxulub Puerto. (See the map on page 18.) In the last few years, material drilled from the Chicxulub crater has been linked chemically and geologically to pellets found in both in northeast Mexico and in Haiti, almost 2 000 km away. (See the photo below.) These

pellets are believed to be remnants of the debris that was flung thousands of kilometers as the giant asteroid or comet struck the Earth. The link between this ejecta material and the crater was all but cemented by a recent report that the Chicxulub melt rock and the pellets are coeval, all having ages consistent with 65 million years.² This age puts the possible impact at the so-called K-T boundary, the dividing line between the Cretaceous period when the dinosaurs flourished and the subsequent Tertiary period, when mammals reigned.

Following the clues

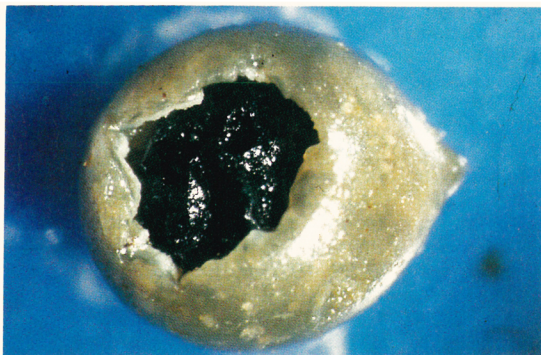
The concentrations of iridium found by the Berkeley team were hundreds of times greater in the K-T layer than they are in Earth's continental crust. Alvarez and his colleagues estimated that the bolide, or piece of solar system debris, would have to have been about 10 km in diameter to account for the iridium anomaly. Presumably the iridium was lofted into the atmosphere, along with perhaps hundreds or thousands of cubic kilometers of debris, by the fireball of hot gas resulting from the collision. From that height the iridium would have been globally dispersed before it settled out.

The iridium was suggestive but certainly not conclusive. The Alvarez hypothesis has been fiercely opposed by dissenters who contend that volca-

noes rather than extraterrestrial impacts caused the global catastrophe that befell the dinosaurs and other species. Those in the volcano school have argued that the excess iridium could have been laid down by massive volcanic eruptions. However, backers of the impact theory point out that the ratios of iridium and other noble metals in the K-T layer are more typical of those in meteorites than in volcanic gas.

A second clue was the discovery of shocked quartz grains at the K-T boundary. Bruce Bohor and his colleagues from the US Geological Survey in Denver first found such quartz at a site in Montana,³ but shocked quartz has since been found in K-T boundary layers worldwide. Proponents of the impact theory feel that the quartz seen in this layer, characterized by its multiple sets of planar shock layers, could only be produced naturally by the exceedingly high pressures that prevail during a large-scale impact. Before Bohor's find, geological samples of shocked quartz had only been seen at known crater impact sites or in the vicinity of underground nuclear explosions. Some have argued that a volcanic eruption might also generate shocked quartz, but volcanic pressures are perhaps 100 times lower, and quartz found in volcanic rocks does not have the multiple sets of planar deformations.

A third clue was the discovery of material likely to be ejecta that fell relatively close to the impact. At several K-T boundary sites in North America and the Caribbean there is a clay layer that is thought to consist of material tossed out by the impact. This layer contains very smooth-surfaced clay pellets called spherules that are shaped variously like spheres, ellipsoids, tear drops or even dumbbells. The shapes of these pellets are like those of glass-melt droplets, called tektites, formed by the fusion of terrestrial rocks during large-scale impact events. However,



Clay pellets found in Haiti may have been glass-melt droplets thrown there by the impact of an asteroid on the Yucatan peninsula. The pellet shown here, which is 1.78 mm long, has a glass core, but the rest of the glass has changed to clay. (Courtesy of Glen Izett, USGS, Denver.)

most pellets are made of a soft clay mineral rather than glass, so researchers were thus puzzled about their origin.

The puzzle was solved when several researchers found glass cores inside some of the pellets: It appears that the spherules were originally tektites but that much of the glass has now changed to clay. The discovery was made by Haraldur Sigurdsson (University of Rhode Island) and colleagues from Rhode Island, the University of North Carolina, the University of Michigan and the University of Florida,⁴ and, independently, by Glen Izett (USGS in Denver).⁵ The spherules in which the glass was found were taken from a half-meter-thick ejecta layer near the K-T boundary found by Florentin Maurrasse (Florida International University) in an outcrop in the Haitian hills near the town of Beloc.⁶ Alan Hildebrand (Geological Survey of Canada, Ottawa) had suspected the pellets of being altered tektites, and reported that conclusion together with William Boynton (University of Arizona).⁷ Izett, Brent Dalrymple (USGS, Menlo Park) and Larry Snee (USGS, Denver) subsequently found that the Haitian tektite glass were about 65 million years old.⁸

The Beloc outcrop is of special interest because it contains abundant quantities of all three materials suspected of stemming from an impact: iridium, shocked quartz and tektites. The tektites located there are larger than those found elsewhere in the world, and the ejecta layer is exceptionally thick, suggesting that an impact must have occurred nearby. Another clue to the proximity of a crater in this region is evidence of ancient tidal waves, possibly triggered by the impact.

The chemical compositions of tektite glass from both Beloc^{4,9} and a K-T boundary site near Arroyo el Mimbral in northeast Mexico¹⁰ have been carefully analyzed for clues as to the type of rock that was struck by the bolide. The glass seems to contain material typical of continental rock, with indications that the bedrock also contained considerable amounts of limestone as well as sulfur evaporite—that is, material formed by the evaporation of sea water.

Looking for the crater

The thick ejecta layer, tektites and evidence for tidal waves narrowed the crater search to North America and the Caribbean region. In 1990 Hildebrand, who was on the prowl for a crater in the area, learned from a reporter about a promising candidate. The reporter recalled that at a meet-

Chicxulub crater (red circle) is thought to have resulted from the impact of a massive comet or asteroid some 65 million years ago. Thick clay layers in Haiti (black circle) and in Mexico contain pellets possibly ejected by the massive impact.



ing in 1981, two geophysicists hired by the Mexican national petroleum company, Petróleos Mexicanos, described a very large subsurface structure near Chicxulub that had circular gravitational and magnetic anomalies. Although earlier explorers had identified the 180-km crater as volcanic in origin, Glen Penfield (then with Intera Technologies, Inc in Houston) and Antonio Camargo (then with PEMEX) asserted in their 1981 talk that the structure might be an impact crater. Hildebrand contacted Penfield and Camargo to explore the data further. They found some published gravity data and segments from a few cores.

Hildebrand, Penfield and Camargo, joined by Boynton, David Kring (University of Arizona), Mark Pilkington (Geological Survey of Canada) and Stein Jacobsen (Harvard) scrutinized the core samples. The Chicxulub material contained indications of a possible impact, such as shocked quartz, melt rock and breccia, or, roughly, rubble. The chemical composition of the melt rock bore a strong resemblance to the composition of the tektites from Beloc and Mimbral. And the age of the melt rock was estimated from biostratigraphic data to be about that of the K-T boundary. Their study supported the identification of the Chicxulub structure as an impact crater from the time of the K-T boundary.¹¹

Dating the crater

The crucial next step was to date the crater accurately. But the dating had to be done on samples of melt rock that did not seem to have been altered since they were formed. The challenge was taken on by a large team of geologists.² The participants were Carl Swisher III, Paul Renne, Garniss Curtis (Institute of Human Origins, Berkeley), José Grajales-Nishimura and Esteban Cedillo-Pardo (Mexican Petroleum Institute in Mexico City), Alessandro Montanari (Geological Observatory, Apiro, Italy), Walter Alvarez, Stanley Margolis and Philippe

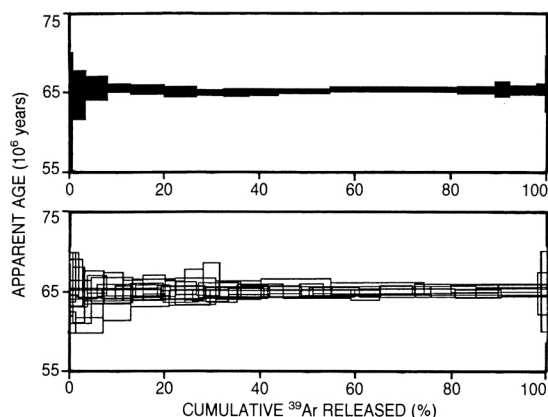
Claeys (University of California, Davis), Maurrasse, Jan Smit (Free University in Amsterdam) and Michael McWilliams (Stanford).

The method used by Swisher and his colleagues to date the melt rock and tektites is the ⁴⁰Ar-³⁹Ar incremental heating technique. Basically this technique determines the age of potassium-containing materials by measuring how much ⁴⁰K has decayed to ⁴⁰Ar. The conventional way is to measure both ⁴⁰Ar and ⁴⁰K, but potassium has to be extracted from the sample by chemical separation whereas the argon is extracted by heating. In the late 1960s researchers developed an ⁴⁰Ar-³⁹Ar method in which one irradiates the sample with neutrons to convert the ³⁹K to ³⁹Ar so that both argon isotopes can be removed by heating. This method depends only on the ratio of the two isotopes and is not dependent on the efficiency of extraction.

A further refinement is to heat the sample in successive steps. The gas extracted at each step should come from a progressively more stable location in the sample, and the age is determined separately for each step. If no argon has previously escaped, the ages from all the heating steps should be the same. The researcher thus looks for plateaus in the data—that is, ages that are stable for a successive number of heating steps.

The method requires calibration with a material of known age to determine the efficiency with which neutrons have converted the ³⁹K to ³⁹Ar. Some labs use different standards for calibration so that comparisons across labs are not always straightforward.

Swisher and his team used the ⁴⁰Ar-³⁹Ar method Swisher to date both tektites and melt rock. The figure on page 19 shows the plateaus from some samples. The weighted mean of three Chicxulub samples was 64.98 ± 0.05 million years. The overall weighted mean age of five tektites from the Mimbral and Beloc sites was 65.07 ± 0.10 million years.



Heating spectra give the ages of melt rock from the Chicxulub crater (top) and Haitian tektites (bottom). Irradiation converts ^{39}K to ^{39}Ar , and then ^{39}Ar and ^{40}Ar are extracted by heating. Age of top sample was 65.00 ± 0.08 million years, and the mean age of the nine spectra at bottom was 65.01 ± 0.08 million years. (Adapted from ref. 2.)

There is still some discrepancy among the ages measured by various research groups. The real significance of the experiment by Swisher and his colleagues is the measurement of *relative* ages: When measured by the same group with the same technique, the ages of the Chicxulub melt rock are indistinguishable within error bars from those of the Beloc and Mimbral tektites. Of course the age of the crater could still—within error bars—be separated by a hundred thousand years from the time when the Haitian tektites were deposited.

Another research team led by Virgil Sharpton (Lunar and Planetary Institute of Houston) subsequently reported a date for the Chicxulub melt rock that is consistent within error bars with that of Swisher and company.¹² In addition Sharpton and his colleagues determined the remanent magnetization of the melt rocks, finding it consistent with the direction of the Earth's magnetic field at the K-T boundary, and they discovered iridium in the melt rock.

Other craters, other causes?

In the search for K-T boundary craters, Chicxulub has not been the only candidate. Another strong contender is a 35-km-diameter crater near Manson, Iowa, that also appears to stem from the time of the K-T boundary. Michael Kunk (USGS in Reston, Virginia) told us that his agency, together with the Iowa Geological Survey, is now drilling new cores at Manson to study it and to improve the estimate of its age.¹³ There are other craters that might be of the right size and age, but none has been studied well enough to determine its origin.

While Chicxulub seems sufficient to explain existing observations, the evidence cannot yet rule out the possibil-

ity of more than one bolide impact. Izett and Eugene Shoemaker (USGS in Flagstaff) have noted that the K-T boundary layer in the western US really appears to have two layers: an upper layer where one finds the iridium anomaly and shocked quartz and a lower layer containing spherules and only a slight excess of iridium. They have speculated that perhaps the top layer was put down by the impact at Manson and the lower one by Chicxulub. Could two large bolides have struck the Earth within a few hundred thousand years of one another, perhaps because they are of related origin?

Among those who still do not believe that Chicxulub is an impact crater is Charles Officer of Dartmouth College. One of his arguments is that the crater region is overlain by limestone from the Upper Cretaceous epoch, suggesting that the melt rock predates the K-T boundary. Crater proponents make various counterarguments. Swisher feels that the few samples remaining from the drill holes are insufficient to establish the stratigraphy. Researchers hope that fresh cores can be drilled.

Although many other observers are now willing to accept the strong evidence for a massive K-T impact, they are not necessarily prepared to go further and accept it as the mechanism for the death of the dinosaurs and other forms of life. A comet or asteroid was not the only devastation to strike the Earth around that time. There were also numerous and large volcanic eruptions, a change in sea level and evolution of the oceanic and atmospheric chemistry.

The environmental effects of a large impact need to be more thoroughly explored. Originally the Berkeley group felt that particulates injected into the stratosphere by the collision would have plunged the

Earth into a deep cooling trend. Other environmental effects have been mentioned since then. One is the acid rain that would result from nitrogen oxides generated as the fireball essentially burned the atmosphere. But the largest effects may have come from the atmospheric gases spewed into the air by the impact, which happened to strike a region where there were considerable amounts of both limestone (CaCO_3) and sulfur evaporite. The sulfur dioxide could have contributed more acid rain than the nitrogen oxides, and would have produced profound cooling, as the sulfate particles reflected incoming sunlight. After a few years the sulfates would have settled out, but the CO_2 would have remained in the atmosphere to produce a warming trend.

If the impact of a large comet can wreak such havoc, perhaps we should pay attention to the comet predicted to have a 1-in-10 000 chance of hitting Earth around 2126.

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