# Huge Impact Tied to Mass Extinction

Radioisotopic dating has now forged the final link between the immense crater in the Yucatan and extinctions 65 million years ago, when dinosaurs disappeared and our ancestors began to flourish

A trail of clues that was first picked up almost 15 years ago in a gorge near a medieval town in the north of Italy has now ended beneath the coast of the Yucatan peninsula at the scene of an ancient catastrophe: the buried remains of a 180-kilometer-wide impact crater. The sleuthing began near the town of Gubbio, where a motley group of scientists stumbled on a thin layer of rock enriched in the exotic element iridium—a faint fingerprint just where rock from the Cretaceous period, the last age of the dinosaurs, gave way to rock from the Tertiary period. That bit of serendipity prompted them to spin a tale of cataclysm and death—of a 10-kilometer-wide asteroid that smashed into Earth 65 million years ago, opening a vast crater somewhere on the planet. In the ensuing cataclysm, the dinosaurs and many other groups died off, while the lowly mammals survived to rule the world.

In this issue of *Science* (p. 954), a group of 12 researchers presents the final proof for the first part of that story. These geochronologists and geologists have used the latest techniques in radioisotopic dating (see sidebar) to measure the age of the newly discovered crater beneath the Yucatan and the age of impact debris scattered over Earth at the geologic moment of the mass extinction. The ages are indistinguishable, demonstrating to most scientists' satisfaction that the Chicxulub crater is indeed the long-sought remains of the impact.

"It looks to me like this is the smoking gun," says geologist Walter Alvarez of the University of California, Berkeley, a coauthor of this issue's report who with his father, Nobel laureate physicist Luis Alvarez, and two nuclear chemists proposed the impact hypothesis in 1980. "This should let us stop arguing about whether there was an impact and start working on the details of the impact." The task now, says Alvarez, is to answer such questions as "What were the environmental disturbances? How could they have caused extinctions?" More skeptical researchers would add: How much of the mass extinction can be pinned on the impact, instead of on more conventional causes like climate change?

Getting down to these details has been a long-awaited, often-frustrated goal of researchers pursuing the killer impact. Time and again they had offered evidence of a huge impact only to find it wasn't sufficient to convince their colleagues. When the Alvarez group in Berkeley argued that the iridium found in a thin layer of 65-million-year-old ocean sediment must have come from an asteroid impact, because iridium is abundant in meteorites but scarce in crustal rocks, critics responded that iridium from the ocean might somehow have been concentrated in the sediments.

Then amateur geologist Charles Orth of Los Alamos National Laboratory, whose professional work involves analyzing elements like iridium in debris from underground nuclear tests, found the same iridium layer in what 65 million years earlier had been a freshwater swamp. So much for explaining away the iridium at the K-T (Cretaceous-Tertiary) boundary with ocean processes. But then skeptics pointed out that some volcanoes pour out iridium; maybe the iridium layer—which by then had been found in rocks around the world—had been laid down in a massive spasm of volcanism.

In 1984 geologist Bruce Bohor of the U.S. Geological Survey (USGS) in Denver countered with another signature of impact. A specialist in the thin layers of volcanic ash that stripe the rocks of the American West, he found quartz grains at the K-T boundary riddled by striations produced only by extreme shock pressures in the lab, at known impact craters, and in nuclear explosions. Even that didn't silence the doubters: A small but vocal group of scientists insisted that volcanoes could produce the markings. There followed 5 years of contention, with the discovery of a huge impact crater of the right age seemingly the only hope of ending it.

### Positive identification

The crater searchers followed a few false trails, but in the late 1980s cosmochemist Alan Hildebrand narrowed the search to the Caribbean. Hildebrand, who is now with the Geological Survey of Canada in Ottawa but was then a graduate student at the University of Arizona, picked up the spoor of a nearby impact in a K-T deposit in Haiti. There, at

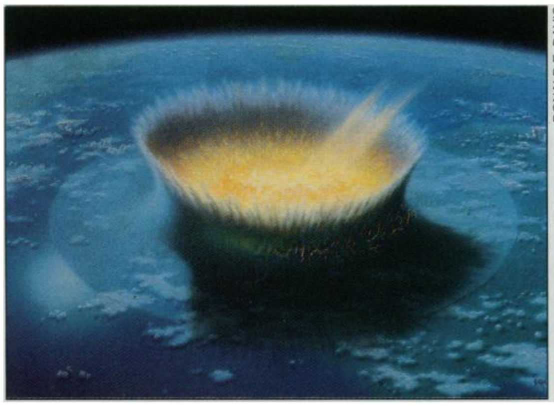
## Sniffing Out the Age of Ancient Rocks

How do geological detectives pin down the date of an ancient catastrophe? They use whiffs of argon from sand-sized grains of rock. The technique is called argon-argon dating, and finding the age of a crater that might be responsible for massive extinctions at the Cretaceous-Tertiary boundary (see main story) is only one of its triumphs. In addition, argon-argon dating is helping researchers revise the histories of human evolution, Antarctic glaciation, and plate tectonics, among other things. Glen Izett of the U.S. Geological Survey in Denver sums up his colleagues' views: "It's a fantastic jump in technology that's revolutionized geochronology."

The "jump" is actually a series of smaller leaps that began in 1966, when the technique was introduced. Like its predecessor, the potassium-argon method, argon-argon dating is a means of reading the clock that ticks away in every rock as traces of radioactive potassium-40 decay into argon-40. That clock can record dates from less than a million years ago up to several hundred million years ago. Although the two techniques share a common principle, the new one represents a sharp advance over the earlier one.

In the earlier method, investigators had to analyze two rock samples by completely different techniques—chemically processing one sample to measure the rock's content of stable potassium-39 and melting the other to extract and measure the argon-40. The potassium-39 gave a measure of how much radioactive potassium-40 the rock had originally contained (the ratio of isotopes is constant from rock to rock). That told how fast the clock was ticking. The amount of argon-40 that had built up showed how long that clock had been running. All this separate processing, however, led to unavoidable imprecision, and the accuracy of the technique depended crucially on extracting all the argon.

But the argon-argon method elegantly combined the two types of processing and eliminated much of the imprecision. By bombarding a sample with neutrons in a nuclear reactor, investigators could turn its potassium-39 into argon-39. Then the radioactive clock could be read from a sample's ratio of the two argon isotopes (40 and 39), which could be extracted in the same step and quantified by mass spectrometry. That not only streamlined the process; it also made it unnecessary to extract all the argon, since a failure to do so would not affect the ratio of the isotopes.



DONALD E. DAVIS

**Hitting home.** Forty-five seconds after the impact, lethal dust and debris begin to spread around the world.

precisely the same point in the strata as the iridium layer and the extinction, he recognized droplets of glass that had weathered to clay. Like shocked quartz, the globules could only have formed in an impact. What's more, the droplets were so large that they must have been formed nearby.

Hildebrand homed in on the crater itself after running across another clue at a planetary science meeting in Houston in 1990. Ten years earlier, Glen Penfield, a geophysicist in the oil exploration business with Intera Technologies Inc. in Houston, and Antonio Camargo of Pemex, the Mexican national petroleum company, had stumbled across a great circular structure buried beneath the north coast of the Yucatan. The structure's geophysical signature in magnetic and gravity maps suggested it was a crater. But that news never got out of the oil patch until a local reporter happened to mention it to Hildebrand at the planetary meeting. The 180-kilometer width of the ring at Chicxulub ("the devil's tail" in Mayan, by less ribald translations) would make it more than big enough for the role the Alvarez group had originally envisioned. Further work by Hildebrand, Penfield, and others eventually showed that it really was an impact crater rather than some kind of volcanic structure, but had it been formed at the right moment of geologic history?

The answer would be yes if investigators could show that Chicxulub was the source of the impact debris Hildebrand found in Haiti. And that meant applying the same dating method to both the crater and the deposit to see whether their ages were identical. The powerful dating technique called laser argon-argon dating was the obvious means of comparison. But applying it to the deposit took some luck. The clay to which the glass globules had weathered can't be dated, and conventional wisdom had it that none of the glass would have escaped alteration. But Glen Izett of the USGS in Denver chanced on a few globules of unaltered glass. His argon-argon date, as recalculated in this issue's paper: 65.06 million years, ±0.18 million years.

Pinning a date on the crater proved even more difficult. Impact craters are famously hard to date, in part because their lingering heat speeds the alteration of minerals that interferes with accurate dating. And most labs found these initial samples too altered to yield a reliable age. But two lucky groups eventually came by datable samples from one drill hole or another. One group recently submitted its results for publication; the other, headed by Carl Swisher of the Institute of Human Origins in Berkeley, renders its verdict in this issue. Swisher and 11 colleagues from seven institutions report an age for Chicxulub of 64.98 million years, ±0.06 million years. The ages of the impact, the impact debris, and the heart of the mass extinction are thus indistinguishable.

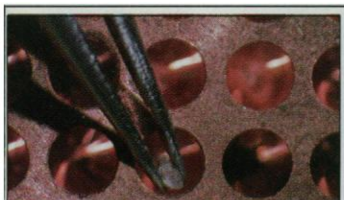
The match-up is enough to convince some skeptics that the K-T crater hunters have found their quarry. "I don't see much grounds for doubting that Chicxulub is a K-T impact event," says Virgil Sharpton of the Lunar and Planetary Laboratory in Houston. That's a bit of a turnaround for Sharpton, who initially doubted that Hildebrand and Penfield had proven the structure to be a crater, then argued that it was too old to be a K-T impact.

What brought Sharpton around is a simple analysis of the odds: Even though argon dating may not tie Chicxulub and the K-T debris to the same precise instant—the error bars do range up to a couple of hundred thousand years—"it's almost beyond imagining," he says, that one of the largest known impact craters and the impact deposits in the Caribbean could have the same radioisotopic age and not be part of the same event. He says he was also swayed by the striking similarities in the chemistry of the melted rock in the Chicxulub crater and the Haiti debris.

### How big a blow?

The new dates are impressing even some of the K-T impact theory's most skeptical critics, the paleontologists, most of whom assumed before the Alvarez hypothesis that nothing much had hit Earth in the past few billion years. "Clearly, we've been underestimating cratering rates," says vertebrate paleontologist William Clemens of the University of California, Berkeley. Even as the evidence for the impact hypothesis was building, most paleontologists gave more credence to the remaining doubts. But the steadily tightening link between Chicxulub and the K-T boundary has changed at least Clemens' view. "Impacts are part of the environment of the [past 600 million years]," he observes, and must be reckoned with at the K-T boundary.

But having accepted that, paleontologists can still ask, with Clemens, "What is the biological effect of an impact?" Answering that question will certainly occupy the next phase of research on the K-T catastrophe. For now, paleontologists are deeply split on the subject.



DAVID SMELTZER

**Load and fire.** Tiny samples are laser-heated for argon-argon dating.

That was the state of the art in the 1970s. But "what's revolutionizing the field [now] is being able to perform [argon-argon] analyses on small samples," says geochronologist Carl Swisher of the Institute of Human Origins in Berkeley, leader of the group that dated the Cretaceous-Tertiary crater at Chicxulub. That parsimony—the result of ever-more-sensitive mass spectrometers—enables daters to pick out and analyze only the freshest, least altered mineral grains in a rock sample, the ones most likely to have retained their argon since formation.

Even single grains, though, have pitfalls. For example, some argon may have diffused out of the surface layers of a grain over the millennia, resulting in a falsely young age. The solution involves using a laser or a furnace to heat the sample progressively, through 15 steps of temperature. Each step yields a separate "age" as successively deeper layers of the sample release their argon, giving the analyst the chance to discard anomalous results.

All told, these advances have boosted precision from the 3% to 5% of the potassium-argon method to the 0.1%, or 60,000-year-precision (one standard error) reported for the dating of the Chicxulub crater. And that kind of precision is shaking up some old certainties. Recently, for instance, single-grain argon-argon dating confirmed that the potassium-argon date for Earth's most recent magnetic reversal was 50,000 years too young (*Science*, 8 November 1991, p. 802). That reversal, now dated to 780,000 years ago, is a key benchmark in the recent history of plate tectonics, ice ages, and evolution.

But it's not the only benchmark of the past few hundred million years that's a lot shakier than it used to be. "The entire time scale is in flux," says Swisher. "There is no current time scale that's widely accepted; it has geologists a bit uneasy."

–R.A.K.

Invertebrate paleontologist Karl Flessa of the University of Arizona is at one end of the spectrum: "The evidence is overwhelming for an impact at the K-T and for it as the cause of the extinctions," he says. But the prevailing opinion seems to be that the impact must share the blame with more mundane perpetrators.

Anthony Hallam of the University of Birmingham speaks for most paleontologists when he says, "I may accept the story of the impact, but I think it was at most a coup de grâce. I believe a mass extinction would have taken place in the marine realm even without an impact. I like the idea of Earth-induced mass extinctions." His preferred agents of extinction are the change in sea level that took place at the K-T boundary or shortly before it, volcanism—the 2-million-year eruption of the Deccan Traps in India is centered on the K-T—and bouts of asphyxiating anoxia in the ocean brought on by changes in ocean circulation.

Sorting out just how much the impact contributed will require identifying plausible killing mechanisms for specific fossil groups: finding evidence, for example, that the impact produced abundant acid fallout, which could have killed off marine plankton by dissolving their carbonate skeletons. Blaming the impact for a group's disappearance will also take a confirmed coincidence in time between the supposed death blow and the last glimpse of the species.

So far, the evidence is uncontested in perhaps only two instances. The impact's dust-induced darkness and cold, not to mention continent-wide fires, may well have done in the plants in the western United States, given the exact coincidence of the impact debris and an abrupt shift in the flora. And the crash of the marine food chain recorded in sediments at the boundary probably cut off the spiral-shelled creatures called ammonites. As Peter Ward of the University of Washington, Seattle, has shown, these creatures—previously believed to have faded gradually—actually thrived right up to the K-T boundary and then vanished. Says Ward: "I'm convinced a meteorite ripped into the earth. It certainly, I think, killed off my beautiful ammonites." That's not the case, he hastens to add, for another extinct group he studies, the inoceramids, a group of large clams. They disappeared 2 million years before the impact, he says. "Something phenomenal happened" then, Ward says, "but it's not the impact."

To build more cases for the impact as a cause of extinctions, paleontologists and geologists will continue their detailed dissection of the millennia immediately around the K-T boundary. Most convincing of all would be the discovery of a second bona fide impact in the midst of another mass extinction. For the time being, the greatest obstacle to understanding—and accepting—the K-T event may be its uniqueness.

–Richard A. Kerr

IMMUNOLOGY

# Getting Some "Backbone": How MHC Binds Peptides

The immune system is always at war, fighting viruses, bacteria, and other pathogens that try to invade the body. In that war the class I proteins of the Major Histocompatibility Complex (MHC) play the role of informer, first having intimate contact with the enemy and then revealing the enemy's location. The MHC molecules display on the surfaces of all cells pieces of the proteins made inside the cells. If the cell is foreign or harbors a virus, some of those protein fragments, or peptides, will be foreign. They mark the cell for destruction by "killer" T cells, the immune system's hand-to-hand combat troops. By this process, the body not only fights off infection but also rejects tissue grafts, and, in cases where confused T cells take the body's proteins for foreigners, triggers the tissue destruction common to autoimmune diseases.

Researchers who study the MHC proteins have long wondered how these informers can master so many different types of military intelligence. The problem: Hundreds of different peptides are displayed on the cell surface, but each person has at most six different MHC proteins. Each protein must therefore be able to display many different peptides. What's more, the MHC proteins bind peptides tightly, and when proteins bind tightly, that usually means the fit is very specific. "The question that has been on everybody's mind for so long," says Pamela Bjorkman, a Caltech immunologist who studies MHC protein structure, "is how it is that MHC molecules bind with high affinity to peptides, and yet can bind such a wide variety."

Now, thanks to a wave of new findings from three research teams, an answer to the puzzle is at hand. And the answer is more than academic, since a better understanding of MHC-peptide binding could eventually lead to new drugs that, by blocking some MHC binding sites, could combat transplant rejection or autoimmune disease. The first team to publish its new results is that of Ian Wilson, Per Peterson, and co-workers at the Scripps Research Institute in San Diego, whose pair of papers appear on pages 919 and 927 of this issue of *Science*. Groups with similar work in press or in preparation are headed by Stanley Nathenson and James Sacchettini at Albert Einstein College of Medicine and Don Wiley and Jack Strominger of Harvard.

All three groups have independently reached the same conclusion: MHC molecules can bind a variety of peptides because they concentrate on what all peptides have in common. That is, they bind tightly to the backbone structure shared by peptides and don't bother as much with the amino acid side chains that differ from peptide to peptide. In an additional report on page 000 of this issue of *Science*, Strominger, his Oxford collaborator Andrew McMichael, and their colleagues report that they have created specific mutations in the MHC molecule and used them to confirm the importance of some of the bonds to the backbone. "It's a very pretty story," says Stanford University immunologist Hugh McDevitt of the whole collection of work. "You can really begin to see the nature of the class I binding site."

**First glimpse.** The first glimpse of that binding site came in 1987, when a team led by Wiley and Strominger at Harvard published the first structure of a class I MHC protein, as determined by x-ray crystallography. That structure revealed a groove in the protein that somehow holds the peptide, although how it holds it wasn't clear. "You could see the peptide there, but you couldn't see where the individual side chains pointed," says Caltech's Bjorkman, who was the first author on the pathbreaking paper. The peptide position was so indistinct partly because even though the MHC molecules in the crystal themselves were chemically identical, they held different peptides in their grooves. Since the structure was computed from an average of all the various MHC-peptide combinations, it was clear for the MHC molecule itself, but the peptide was a blur.

Over the next few years, several groups pushed the story further. With higher resolution structures, the Harvard group discovered pockets inside the groove, two of which seemed to tether the ends of the peptide, while others looked as if they could accommodate some of the peptide's amino acid side chains. Meanwhile, several groups found that, while MHC molecules are not terribly choosy about the peptides they bind, each one has a few requirements: for a specific amino acid, or one of a certain general size or shape, at certain positions along the peptide chain. It began to look as if the side chains of these "anchor" amino acids might sit in the pockets in the groove.

But how tightly bound were the anchor side chains in the pockets? Did they form bonds with the pocket that would help hold the peptide in place? As long as the crystals contained a mixture of peptides, these questions were difficult to answer, says Dean Madden, a graduate student who works with