Did extraterrestrial collisions capable of causing widespread extinctions pound the earth not once, but twice—or even several times?

Repeated Blows

By Luann Becker

Most people are unaware of it, but our planet is under a constant barrage by the cosmos. Our galactic neighborhood is littered with comets, asteroids and other debris left over from the birth of the solar system. Most of the space detritus that strikes the earth is interplanetary dust, but a few of these cosmic projectiles have measured five kilometers (about 3.1 miles) or more across. Based on the number of craters on the moon, astronomers estimate that about 60 such giant space rocks slammed into the earth during the past 600 million years. Even the smallest of those collisions would have left a scar 95 kilometers (about 60 miles) wide and would have released a blast of kinetic energy equivalent to detonating 10 million megatons of TNT.

Such massive impacts are no doubt capable of triggering drastic and abrupt changes to the planet and its inhabitants. Indeed, over the same time period the fossil record reveals five great biological crises in which, on average, more than half of all living species ceased to exist. After a period of heated controversy, scientists began to accept that an asteroid impact precipitated one of these catastrophes: the demise of the dinosaurs 65 million years ago. With that one exception, however, compelling evidence for large impacts coincident with severe mass extinctions remained elusive—until recently.

During the past two years, researchers have discovered new methods for assessing where and when impacts occurred, and the evidence connecting them to other widespread die-offs is getting stronger. New tracers of impacts are cropping up, for instance, in rocks laid down at the end of the Permian period—the time 250 million years ago when a mysterious event known as the Great Dying wiped out 90 percent of the planet's species. Evidence for impacts associated with other extinctions is tenuous but growing stronger as well.

Scientists find such hints of multiple life-altering impacts in a variety of forms. Craters and shattered or shocked rocks—the best evidence of an ancient impact—are turning up at key time intervals that suggest a link with extinction. But more often than not, this kind of physical evidence is buried under thick layers of sediment or is obscured by erosion. Researchers now understand that the biggest blows also leave other direct, as well as indirect, clues hidden in the rock record. The first direct tracers included tiny mineral crystals that had been fractured or melted by the blast. Also found in fallout layers have been elements known to form in space but not on the earth. Indeed, my colleagues and I have discovered extraterrestrial gases trapped inside carbon molecules called fullerenes in several suspected impact-related sediments and craters.

Equally intriguing are the indirect tracers that paleontologists have recognized: rapid die-offs of terrestrial vegetation and abrupt declines in the productivity of marine organisms coincident with at least three of the five great extinctions. Such severe and rapid perturbations in the earth's ecosystem are rare, and some scientists suspect that only a catastrophe as abrupt as an impact could trigger them.

The evidence for impacts acting as culprits in widespread die-offs is getting stronger.

Overview/*Deadly Barrage?*

- About 60 meteorites five or more kilometers across have hit the earth in the past 600 million years. The smallest ones would have carved craters some 95 kilometers wide.
- Most scientists agree that one such impact did in the dinosaurs, but evidence for large collisions coincident with other mass extinctions remained elusive—until recently.
- Researchers are now discovering hints of ancient impacts at sites marking history's top five mass extinctions, the worst of which eliminated 90 percent of all living species.

Dinosaur Killer

THE FIRST IMPACT TRACER linked to a severe mass extinction was an unearthly concentration of iridium, an element that is rare in rocks on our planet's surface but abundant in many meteorites. In 1980 a team from the University of California at Berkeley—led by Nobel Prize–winning physicist Luis Alvarez and his son, geologist Walter Alvarez—reported a surprisingly high concentration of this element within a centimeter-thick layer of clay exposed near Gubbio, Italy. The Berkeley team calculated that the average daily delivery of cosmic dust could not account for the amount of iridium it measured. Based on these findings, the scientists hypothesized that it was fallout from a blast created when an asteroid, some 10 to 14 kilometers (six to nine miles) across, collided with the earth.

Even more fascinating, the clay layer had been dated to 65 million years ago, the end of the Cretaceous period. From this iridium discovery came the landmark hypothesis that a giant impact ended the reign of the dinosaurs—and that such events may well be associated with other severe mass extinctions over the past 600 million years. Twenty years ago this bold and sweeping claim stunned scientists, most of whom had been content to assume that the dinosaur extinction was a gradual process initiated by a contemporaneous increase in global volcanic activity. The announcement led to intense debates and reexaminations of end Cretaceous rocks around the world.

Out of this scrutiny emerged three additional impact tracers: dramatic disfigurations of the earthly rocks and plant life in the form of microspherules, shocked quartz and high concentrations of soot. In 1981 Jan Smit, now at the Free University in Amsterdam, uncovered microscopic droplets of glass, called microspherules, which he argued were products of the rapid cooling of molten rock that splashed into the atmosphere during the impact. Three years later Bruce Bohor and his colleagues at the U.S. Geological Survey were among the first researchers to explain the formation of shocked quartz. Few earthly circumstances have the power to disfigure quartz, which is a highly stable mineral even at high temperatures and pressures deep inside the earth's crust.

At the time microspherules and shocked quartz were introduced as impact tracers, some still attributed them to extreme volcanic activity. Powerful eruptions can indeed fracture quartz grains—but only in one direction, not in the multiple directions displayed in Bohor's samples. The microspherules contained trace elements that were markedly distinct from those formed in volcanic blasts. Scientists subsequently found enhanced iridium levels at more than 100 end Cretaceous sites worldwide and shocked quartz at more than 30 sites.

Least contentious of the four primary impact tracers to come out of the 1980s were soot and ash, which measured tens of thousands of times higher than normal levels, from impact-triggered fires. The most convincing evidence to support the impact scenario, however, was the recognition of the crater itself, known today as Chicxulub, in Yucatán, Mexico. Shortly after the Alvarez announcement in 1980, geophysicists Tony Camargo and Glen Penfield of the Mexican national oil company, PEMEX, reported an immense circular pattern—later estimated to be some 180 kilometers (about 110 miles) across—while surveying for new oil and gas prospects buried in the Gulf of Mexico. Other researchers confirmed the crater's existence in 1991.

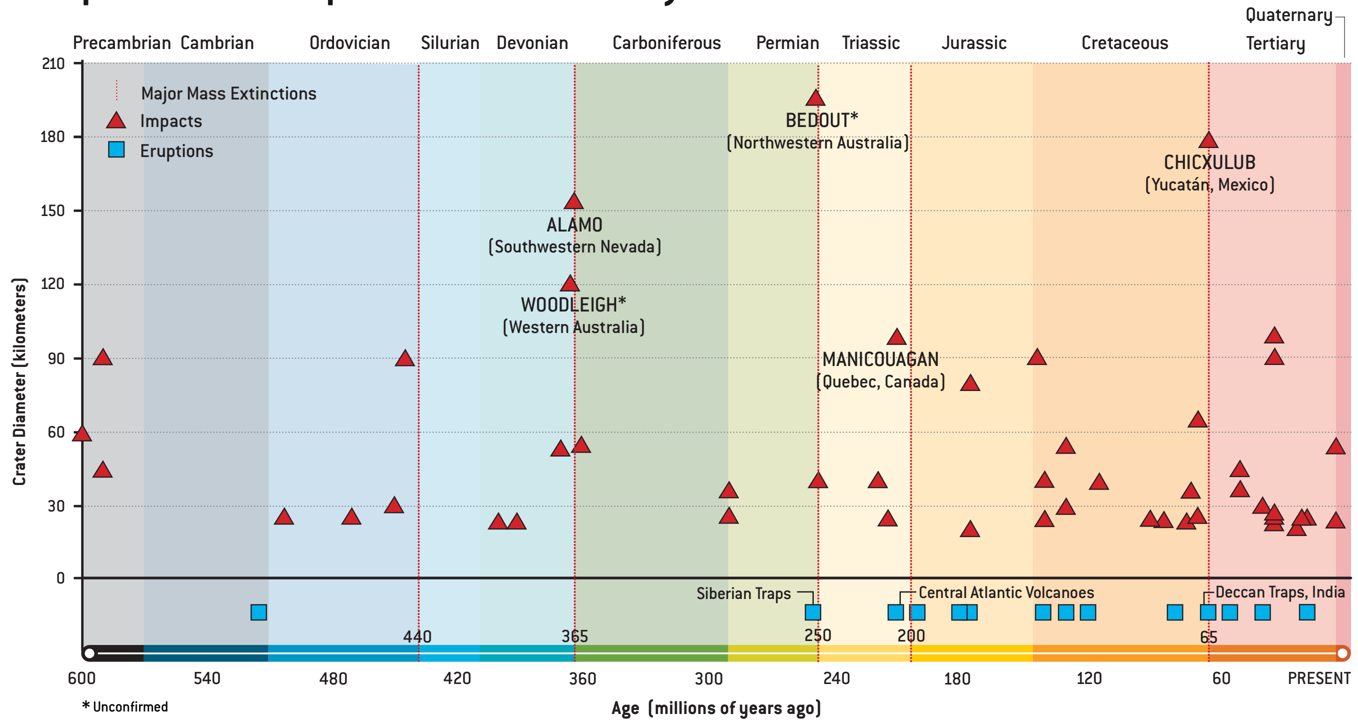
Finding a reasonable candidate for an impact crater marked a turning point in the search for the causes of extreme climate perturbations and mass extinctions—away from earthly sources such as volcanism and toward a singular, catastrophic event. Both volcanoes and impacts eject enormous quantities of toxic pollutants such as ash, sulfur and carbon dioxide into the atmosphere, triggering severe climate change and environmental degradation. The difference is in the timing. The instantaneous release from an impact would potentially kill off species in a few thousand years. Massive volcanism, on the other hand, continues to release its pollutants over millions of years, drawing out its effects on life and its habitats.

While geologists were searching for craters and other impact tracers, paleontologists were adding their own momentum to the impact scenario. Fossil experts had long been inclined to agree with the volcanism theory because the disappearance of species in the fossil record appeared to be gradual. A convincing counterargument came from paleontologists Philip Signor of the University of California at Davis and Jere Lipps,

KAMIL VOJNAR (*preceding two pages*)

AARON FIRTH (BASED ON GRAPHIC BY MICHAEL PAINE)

Impacts, Eruptions and Major Mass Extinctions



LUANN BECKER has studied impact tracers since she began her career as a geochemist at the Scripps Institution of Oceanography in La Jolla, Calif., in 1990. In 1998 Becker participated in a meteorite-collecting expedition in Antarctica and in July 2001 was awarded the National Science Foundation Antarctic Service Medal. The following month she joined the faculty at the University of California, Santa Barbara, where she continues to study fullerenes and exotic gases trapped within them as impact tracers. This summer she and her colleagues will conduct fieldwork at end Permian extinction sites in South Africa and Australia. Part of this expedition will be included in a television documentary, scheduled to air this fall, about mass extinctions and their causes.

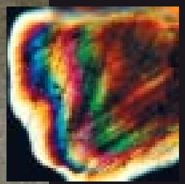
THE AUTHOR

Enduring Traces

Craters are the best evidence for an impact, but ejecta from the affiliated blast contains other clues that can settle to the earth and persist in the rock record for millions of years. Such impact tracers are especially prevalent with large, devastating collisions like the hypothetical one illustrated here: an asteroid 10 kilometers (six miles) wide slams into a coastline, transmitting temperatures of several thousand degrees and pressures a million times greater than the weight of the earth's atmosphere.

IMPACT TRACER

SHOCKED MINERALS



Extreme pressure and heat fracture quartz crystals (*left*) and metamorphose iron-nickel-silica grains.

IMPACT TRACER

DISFIGURED ROCKS

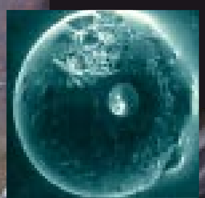
Shock waves are captured in rock as shattercones (*left*).

Bedrock fractures; some ejected debris resettles as breccia.

IMPACT TRACER

MICROSPHERULES

Tiny glass droplets form during the rapid cooling of molten rock

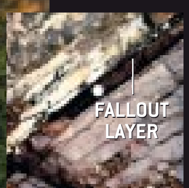


that splashes into the atmosphere.

IMPACT TRACER

IRIDIUM

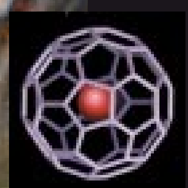
This element, which is rare in



earthly rocks but abundant in some meteorites, may be preserved in a fallout layer of clay.

IMPACT TRACER

EXTRATERRESTRIAL FULLERENES



Caged carbon molecules trap extraterrestrial noble gases in space and travel to the earth in the impactor.

IMPACT TRACER

SOOT AND ASH

Fires transform vegetation into

soot that accumulates to levels tens of thousands of times higher than normal.

INITIAL DEVASTATION

INTO ORBIT

The explosion ejects some 21,000 cubic kilometers (5,000 cubic miles) of debris, about 1,700 cubic kilometers of which is launched into orbit at 50 times the speed of sound.

CHOKED SKY

Little sunlight can penetrate to the ground for several months as ejected debris rains through the atmosphere, and temperatures drop below freezing for up to half a year.

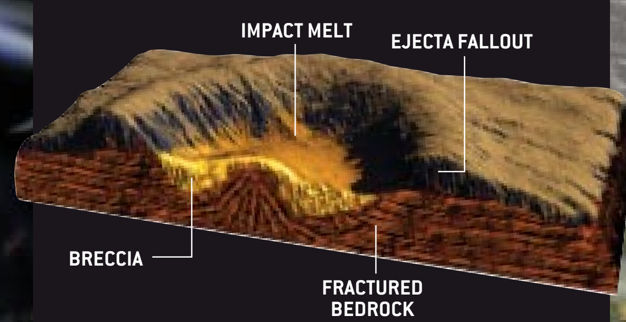
KILLER WAVES

Tsunamis as high as 90 meters (300 feet) destroy coastal ecosystems within hundreds or even thousands of kilometers of the impact.

TERRIBLE TREMOR

A magnitude 13 earthquake—a million times greater than the strongest tremor recorded in human history—courses through the planet.

DISMAL AFTERMATH



This hypothetical catastrophe excavates a crater up to 100 kilometers (60 miles) across and 40 kilometers (25 miles) deep. The nearly instantaneous release of climate-changing pollutants such as ash, sulfur and carbon dioxide kills off species and degrades environments in a few thousand years or less. This geologically rapid timing is reflected in recent scientific studies indicating that species disappear quickly during the worst mass extinctions. Massive volcanism ejects similar pollutants, but its damaging effects are prolonged over millions of years.

illustrations: DON FOLEY; SOURCE: *THE MISTAKEN EXTINCTION*, BY LOWELL DINGUS AND TIMOTHY ROWE. W. H. FREEMAN, 1998. *photographs:* ALAN HILDEBRAND (*quartz*); WALTER PEREDERY (*shattercones*); TIM CULLER *University of California, Berkeley*/ APOLLO 11 CREW/NASA (*microspherules*); W. ALVAREZ/SPL/PHOTO RESEARCHERS, INC. (*fallout layer*); WENDY S. WOLBACH *DePaul University* (*soot*)

now at Berkeley. In 1982 they recognized that the typical approach for defining the last occurrence of a given species did not take into account the incompleteness of the fossil record or the biases introduced in the way the fossils were collected.

Many researchers subsequently conducted high-resolution studies of multiple species. These statistically more reliable assessments indicate that the actual extinction time periods at the end of the Cretaceous—and at the end of the Permian—were abrupt (thousands of years) rather than gradual (millions of years). Although volcanically induced climate change no doubt contributed to the demise of some species, life was well on its way to recovery before the volcanism ceased—making the case for an impact trigger more compelling.

Extraterrestrial Hitchhikers

THE RECOGNITION of a shorter time frame for the Great Dying prompted several scientists to search for associated impact tracers and craters. By the early 1990s scientific papers were citing evidence of iridium and shocked quartz from end Permian rocks; however, the reported concentrations were 10- to 100-fold lower than those in the end Cretaceous clay. This finding prompted some paleontologists to claim that the impact that marked the end of the age of dinosaurs was as singular and unique as the animals themselves.

Other scientists reasoned that perhaps an impact had occurred but the rocks simply did not preserve the same clues that were so obvious in end Cretaceous samples. At the end of the Permian period the earth's landmasses were configured into one supercontinent, Pangea, and a superocean, Panthalassa. An asteroid or comet that hit the deep ocean would not generate shocked quartz, because quartz is rare in ocean crust. Nor would it necessarily lead to the spread of iridium worldwide, because not as much debris would be ejected into the atmosphere. Supporting an ocean-impact hypothesis for more ancient extinctions such as the Great Dying, it turned out, would require new tracers.

One of the next impact tracers to hit the scene—and one that would eventually turn up in meteorites and at least two impact craters—evolved out of the accidental discovery of a new form of carbon. In the second year of my doctoral studies at the Scripps Institution of Oceanography in La Jolla, Calif., my adviser, geochemist Jeffrey Bada, showed me an article that had appeared in a recent issue of *Scientific American* [see "Fullerenes," by Robert F. Curl and Richard E. Smalley; October 1991]. It outlined the discovery of a new form of carbon, closed-cage structures called fullerenes (also referred to as buckminsterfullerenes or "buckyballs," after the inventor of the geodesic domes that they resemble). A group of astrochemists and physical chemists had inadvertently created fullerenes in 1985 during laboratory experiments designed to mimic the formation of carbon clusters, or stardust, in some stars. Additional experiments revealed that fullerenes, unlike the other solid forms of carbon, diamond and graphite, were soluble in some organic solvents, a property that would prove their existence and lead to a Nobel Prize in Chemistry for Curl, Smalley and Harold W. Kroto in 1996.

Knowing that stardust, like iridium, is delivered to our plan-

Rough Neighborhood

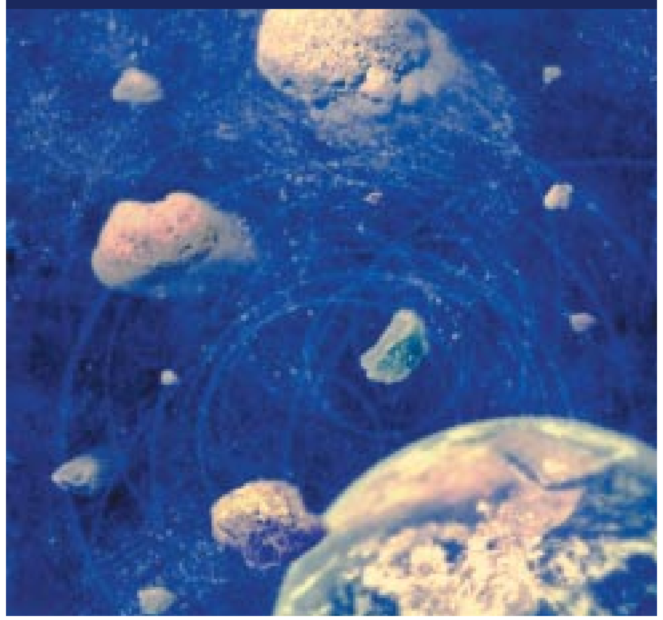
The search for Earth-crossing asteroids expands

ON JANUARY 7 a shopping mall–size rock reminded everyone just how cluttered the solar system really is. Roughly 300 meters in diameter, asteroid 2001 YB5 was small enough to escape notice until late December but big enough to carve a crater the size of a small city had it struck land. Fortunately, its closest approach to Earth was 830,000 kilometers (about twice the distance to the moon), and we are in no danger of a YB5 collision for at least the next several centuries.

But what about the 1,500 other known near-Earth asteroids? (They are so dubbed because they have broken away from the main asteroid belt between Mars and Jupiter and now pose a potential impact risk.) YB5-size space rocks fly this close nearly every year, says David Morrison of the NASA Ames Research Center, but they strike Earth only about every 20,000 to 30,000 years.

Finding hazardous objects long before they become a threat is the aim of the U.K.'s new information center on near-Earth objects, which is scheduled to debut in early April at the National Space Science Center in Leicester. Asteroid hunters at the U.K. center and a handful of other institutions worldwide are especially concerned with objects one kilometer (six tenths of a mile) in diameter, the low-end estimate for the size required to wreak global havoc. The odds of such a catastrophe occurring in the next 100 years range between one in 4,000 and one in 8,600, according to recent calculations by Alan Harris of the Jet Propulsion Laboratory in Pasadena, Calif. NASA's ongoing Spaceguard Survey, which aims to find 90 percent of the Earth-crossing asteroids this size or larger by 2008, will help sharpen this prediction.

—Sarah Simpson, contributing editor



KAMIL VOJNAR

et in the form of cosmic dust, asteroids and comets, we decided to search for these exotic carbon molecules in earthly sediments. We chose a known impact site—the 1.85-billion-year-old Sudbury crater in Ontario, Canada—because of its unique lining of carbon-rich breccia, a mixture of shattered target rocks and other fallout from the blast. (Not unlike the Chicxulub controversy, it took the discovery of shocked quartz and shatter-cones, features described as shock waves captured in the rock, to convince most scientists that the crater was an impact scar rather than volcanic in origin.)

Because fullerene is a pure-carbon molecule, the Sudbury breccia offered a prime location for collecting promising samples, which we did in 1993. By exploiting the unique solubility properties of fullerene, I was able to isolate the most stable molecules—those built from 60 or 70 carbon atoms each—in the laboratory. The next critical questions were: Did the fullerenes hitch a ride to the earth on the impactor, surviving the catastrophic blast? Or were they somehow generated in the intense heat and pressures of the event?

Meanwhile organic chemist Martin Saunders and his colleagues at Yale University and geochemist Robert Poreda of the University of Rochester were discovering a way to resolve this question. In 1993 Saunders and Poreda demonstrated that fullerenes have the unusual ability to capture noble gases—such as helium, neon and argon—within their caged structures. As soon as Bada and I became aware of this discovery, in 1994, we asked Poreda to examine our Sudbury fullerenes. We knew that the isotopic compositions of noble gases observed in space (like those measured in meteorites and cosmic dust) were clearly distinct from those found on the earth. That meant we had a simple way to test where our exotic carbon originated: measure the isotopic signatures of the gases within them.

What we found astounds us to this day. The Sudbury fullerenes contained helium with compositions similar to some meteorites and cosmic dust. We reasoned that the molecules must have survived the catastrophic impact, but how? Geologists agree that the Sudbury impactor was at least eight kilometers (about five miles) across. Computer simulations predicted that all organic compounds in an asteroid or comet of this size would be vaporized on impact. Perhaps even more troubling was the initial lack of compelling evidence for fullerenes in meteorites.

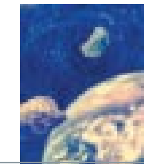
We, too , were surprised that the fullerenes survived. But as for their apparent absence in meteorites, we suspected that previous workers had not looked for all the known types. In the original experiment designed to simulate stardust, a family of large fullerenes formed in addition to the 60- and 70-atom molecules. Indeed, on a whim, I attempted to isolate larger fullerenes in some carbon-rich meteorites, and a whole series of cages with up to 400 carbon atoms were present. Like their smaller counterparts from the Sudbury crater, these larger structures contained extraterrestrial helium, neon and argon.

With the discovery of the giant fullerenes in meteorites, Poreda and I decided to test our new method on sediments associated with mass extinctions. We first revisited fullerene samples that other researchers had discovered at end Cretaceous sites. One group, led by Dieter Heymann of Rice University, had proposed that the exotic carbon was part of the soot that accumulated in the wake of the massive, impact-ignited fires. The heat of such a fire may have been intense enough to transform plant carbon into fullerenes, but it could not account for the extraterrestrial helium that we found inside them.

Inspired by this success, we wondered whether fullerenes would be a reliable tracer of large impacts elsewhere in the fossil record. Sediments associated with the Great Dying became our next focus. In February 2001 we reported extraterrestrial helium and argon in fullerenes from end Permian locations in China and Japan. In the past several months we have also begun to look at end Permian sites in Antarctica. Preliminary investigations of samples from Graphite Peak indicate that fullerenes are present and contain extraterrestrial helium and argon. These end Permian fullerenes are also associated with shocked quartz, another direct indicator of impact.

As exciting as these new impact tracers linked to the Great Dying have been, it would be misleading to suggest that fullerenes are the smoking gun for a giant impact. Many scientists still argue that volcanism is the more likely cause. Some have suggested that cosmic dust is a better indicator of an impact event than fullerenes are. Others are asking why evidence such as shocked quartz and iridium are so rare in rocks associated with the Great Dying and will remain skeptical if an impact crater cannot be found.

Whatever stimulated these mass extinctions made possible our own existence.



Forging Ahead

UNDAUNTED BY SKEPTICISM, a handful of scientists continues to look for potential impact craters and tracers. Recently geologist John Gorter of Agip Petroleum in Perth, Australia, described a potential, enormous end Permian impact crater buried under a thick pile of sediments offshore of northwestern Australia. Gorter interpreted a seismic line over the region that suggests a circular structure, called the Bedout, some 200 kilometers (about 125 miles) across. If a future discovery of shocked quartz or other impact tracers proves this structure to be ground zero for a life-altering impact, its location could explain why extraterrestrial fullerenes are found in China, Japan and Antarctica—regions close to the proposed impact—but not in more distant sites, such as Hungary and Israel.

Also encouraging are the recent discoveries of other tracers proposed as direct products of an impact. In September 2001 geochemist Kunio Kaiho of Tohoku University in Japan and his colleagues reported the presence of impact-metamorphosed iron-silica-nickel grains in the same end Permian rocks in Meishan, China, where evidence for abrupt extinctions and extraterrestrial fullerenes has cropped up. Such grains have been reported in several end Cretaceous impact sites around the world as well.

In the absence of craters or other direct evidence, it still may be possible to determine the occurrence of an impact by noting symptoms of rapid environmental or biological changes. In 2000, in fact, Peter Ward of the University of Washington and his colleagues reported evidence of abrupt die-offs of rooted plants in end Permian rocks of the Karoo Basin in South Africa. Several groups have also described a sharp drop in productivity in marine species associated with the Great Dying—and with the third of the five big mass extinctions, in some 200-million-year-old end Triassic rocks. These productivity crashes, marked by a shift in the values of carbon isotopes, correlate to a similar record at the end of the Cretaceous, a time when few scientists doubt a violent impact occurred.

Only more careful investigation will determine if new impact tracers—both direct products of a collision and indirect evidence for abrupt ecological change—will prove themselves reliable in the long run. So far researchers have demonstrated that several lines of evidence for impacts are present in rocks that record three of our planet's five most devastating biological crises. For the two other largest extinctions—one about 440 million years ago and the other about 365 million years ago—iridium, shocked quartz, microspherules, potential craters and productivity collapse have been reported, but the causal link between impact and extinction is still tenuous at best. It is important to note, however, that the impact tracers that typify the end of the Cretaceous will not be as robust in rocks linked to older mass extinctions.

The idea that giant collisions may have occurred multiple times is intriguing in its own right. But perhaps even more compelling is the growing indication that these destructive events may be necessary to promote evolutionary change. Most paleontologists believe that the Great Dying, for instance, enabled dinosaurs to thrive by opening niches previously occupied by other animals. Likewise, the demise of the dinosaurs allowed mammals to flourish. Whatever stimulated these mass extinctions, then, also made possible our own existence. As researchers continue to detect impact tracers around the world, it's looking more like impacts are the culprits of the greatest unresolved murder mysteries in the history of life on earth. SA

MORE TO EXPLORE

Impact Event at the Permian-Triassic Boundary: Evidence from Extraterrestrial Noble Gases in Fullerene. Luann Becker, Robert J. Poreda, Andrew G. Hunt, Theodore E. Bunch and Michael Rampino in *Science*, Vol. 291, pages 1530–1533; February 23, 2001.

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