Snowbird II: Clues to Earth's Impact History

*At the 1981 conference at Snowbird, Utah, on the effects of large impacts, it became clear that an asteroid impact was not as outrageous an explanation for the mass extinction at the end of the age of the dinosaurs as it had seemed. At Snowbird II this October, the large impact hypothesis prevailed over cataclysmic volcanic eruptions as the cause of that mass extinction 66 million years ago (*Science*, 11 November, p. 865). But even accepting that conclusion, which everyone does not, a wealth of questions remain. To answer some of them, researchers of all sorts are having to look in unprecedented detail at the geologic record. From the new detail the answers are beginning to come.*

The First Killer Crater Looks Like a Wimp

The Manson impact structure of Iowa would seem to be the perfect candidate for the impact that caused the mass extinction 66 million years ago at the boundary between the Cretaceous and Tertiary periods. Michael Kunk of the U.S. Geological Survey (USGS) has dated this buried crater as being 66 plus or minus 1 or 2 million years old, which is indistinguishable from the age of the boundary. This coincidence of impact and boundary had a 4% probability of occurring by chance.

The Manson crater, which is buried by tens of meters of glacial deposits, is in central North America, right where some researchers were looking for the Cretaceous-Tertiary crater to be. Quartz grains shocked by an impact are found around the world at the boundary, but they are more abundant and larger in North America than elsewhere.

The link between the Manson impact and the Cretaceous-Tertiary event would seem quite promising except that the Manson crater is far smaller, 35 kilometers in diameter at most, than the 150-kilometer crater thought necessary to explain the global boundary deposit. That problem could be circumvented if Manson were one of several simultaneous impacts, but that idea encountered problems at the conference. Christian Koeberl of the Lunar and Planetary Institute in Houston and his Soviet and American colleagues reported that the leading candidate for a second impact, actually a crater pair called Kara and Ust-Kara on the Soviet Arctic Ocean shore, has an age determined by the argon-argon technique of more than 70 million years. For some researchers, none of the dating of Kara is yet convincing, so dating efforts of several sorts continue.

If it turns out that there was only one impact, Manson might still qualify, noted Peter Schultz of Brown University and Donald Gault of the Murphys Center of Planetology in Murphys, California. The 150-kilometer crater size assumes a more or less vertical impact by a 10-kilometer object although the most likely angle of impact is 45° and a low-angle, 5° impact of such an object should occur every 450 million years on average. Such a glancing blow would create a smaller crater but could have more severe environmental effects—much greater vaporization of the target, broader dispersal of hot, incinerating debris, and wider dispersal of the ricocheting impactor.

The Killer Impact Is Getting Tamed

From the beginning, the large impact explanation of the mass extinction 66 million years ago was just too much for paleontologists to swallow. The global dust cloud thrown up by the impact of a 10-kilometer asteroid was supposed to block out the sun for 3 years. How could 30% or more of species survive that?, asked paleontologists.

At the first conference at Snowbird, Utah, the persistence of the dust cloud was scaled back from 3 years to 3 months, much to everyone's relief. At Snowbird II, Curt Covey of Lawrence Livermore National Laboratory and his colleagues reported that some of the most sophisticated computer modeling yet of the post-impact climate showed less severe dust cloud effects would follow a large impact than originally envisioned.

Most noticeably, the ability of the oceans in their general circulation model to give up heat to the land, something missing in simpler models, ameliorated the dust's chilling effect. Some continents froze, such as Asia and North America, but some land areas were as warm as 10°C 20 days after the impact. All in all, it seems that it is hard to freeze over the entire Earth.

The dust cloud effects have been diminishing, but a slew of new killing mechanisms proposed in recent years has been threatening overkill once again. Death by corrosion by acid rain was competing with heavy-metal poisoning, greenhouse heat prostration, and global incineration, among others. But presentations here made it clear that there is enough uncertainty in these killing mechanisms to reduce any one to harmlessness and a combination of them to consistency with the paleontological record.

Ronald Prinn and Bruce Fegley of the Massachusetts Institute of Technology reported on their latest calculations of the amount of nitric acid generated from atmospheric molecular nitrogen by the shock of the impact. In their worst case, the impact of an ice-rich comet newly arrived in the inner solar system generates enough acid to lower the pH of rain from its natural level of 5.5 to 0 to 1 for a number of years.

But the extraterrestrial iridium found in the impact deposits could also have been delivered by a slower, less massive metal-rich asteroid. Its impact would have lowered the pH of rain averaged around the globe to only 4, which is typical of industrially polluted rain today.

The global fire supposedly touched off by the impact also looks a bit less intimidating. Edward Anders of the University of Chicago, one of the discoverers of the soot presumed to be evidence of the fire, pointed out that the proposed fire might have consumed as much as 80% of Earth's biomass, a staggering proportion seemingly at odds with the fossil record, or as little as 20% of the biomass. Whatever the case, said Anders, the fire's indirect effects would have been significant but not overwhelming.

While computer modelers and geochemists were spinning tales of hard times in a post-impact world, the paleontologists were reiterating that the pattern of extinction and survival at the Cretaceous-Tertiary boundary seems to be a complex one. David Archibald and Laurie Bryant of San Diego State University reviewed the patterns formed from 100,000 vertebrate specimens collected in eastern Montana from the Hell Creek and Tullock formations. An estimated 70% of non-dinosaurian taxa survived into the Tertiary, Archibald said. "The extinction patterns among the vertebrates do not appear to be attributable to any single cause, catastrophic or otherwise."

A catastrophe does seem to have struck the ocean, noted James Zachos of the University of Michigan and his colleagues. At Deep Sea Drilling Project site 577 in the north-central Pacific they found that, at the same geologic instant that the floating marine plankton suffered a mass extinction, marine production of organic matter, as recorded in the carbon isotopes of microfossils, took a precipitous drop. Marine productivity remained severely depressed for half a million years. "Whatever caused that," said Zachos, "must have been catastrophic."

This marine-terrestrial contrast has weakened somewhat in recent years. At the 1981 Snowbird conference, Leo Hickey of Yale University argued that the record of whole-leaf fossils was inconsistent with a global catastrophe at the Cretaceous-Tertiary boundary. Not much seemed to have happened at the boundary.

At Snowbird II, Kirk Johnson of Yale and Hickey reported that, where no catastrophe had seemed evident in their study area of North Dakota, Montana, and Wyoming, they now see a dramatic extinction event at the boundary. The difference is that whereas in their previous study they had only a thousand Cretaceous specimens previously reported in the literature, they have now collected more than 10,000 specimens.

If There Was One Killer Impact, Were There More?

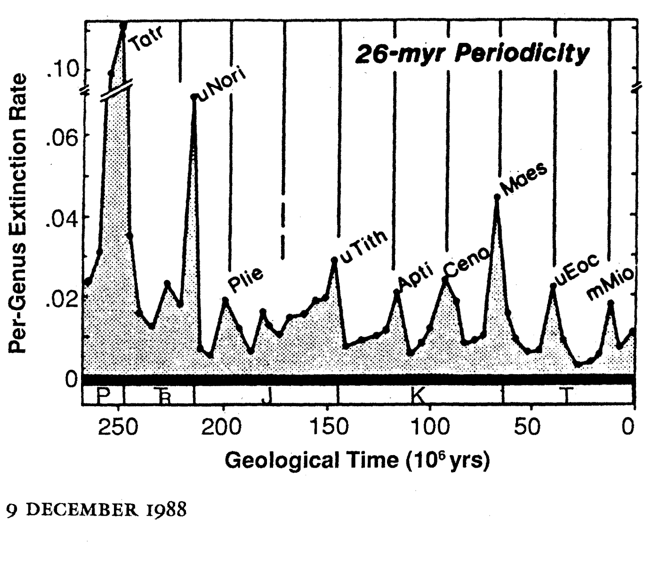
Shortly after some scientists had convinced themselves that a large impact 66 million years ago had killed off more than 50% of living species, the search was on for impacts at other major extinctions in the geologic record. Charles Orth and Moses Attrep of Los Alamos National Laboratory have been at the forefront of the search and the word from the front is not encouraging. In collaboration with geologists and paleontologists, they searched the boundaries between geologic periods as old as 600 million years for high amounts of the element iridium, a sign of an asteroid or comet impact.

After running many thousands of samples, "we find nothing compelling" older than 66 million years, said Orth. There are iridium anomalies, but they do not appear to have been deposited by an impact. A tantalizing prospect near the 91-million-year-old Cenomanian-Turonian boundary looks like deposits from mid-ocean ridge volcanism now that a similar anomaly in iridium and other elements has been found in the United Kingdom.

Not long ago, the iridium at the Cenomanian-Turonian provided one of the four possible links between extinctions and impacts (*Science*, 8 May 1987, p. 667). Intriguingly enough, those four major extinctions were the four most recent of the nine that David Raup and John Sepkoski of the University of Chicago see as recurring every 26 million years. Sepkoski reported that his latest compilation of marine animal genera still displays the 26-million-year extinction periodicity, especially during the past 120 million years when extinctions are most precisely dated.

With little support for an impact-extinction link before the Cretaceous-Tertiary boundary at 66 million years, attention has turned to these younger events. Frank Kyte of the University of California at Los Angeles reported on his analyses of 450 samples from a single North Pacific core that spans the past 70 million years. He finds nothing else like the iridium spike at 66 million years. There is no sign of broader peaks of iridium that might mark the heaviest showers of comets. Comet showers, some of which must have occurred randomly over the history of Earth (*Science*, 22 March 1985, p. 1451), have been invoked as the cause of periodic extinctions.

There is still other evidence, however, that one and perhaps both of the major extinctions since the Cretaceous-Tertiary had impacts associated with them. Billy P. Glass of the University of Delaware summarized the continuing support for two and perhaps three impacts in the late Eocene about 35 million years ago. The two impacts look real enough, but neither is associated with an unusual number of extinctions. In fact, the late Eocene extinctions in the sea seem to be spread over several million years. A full-blown comet shower might cause such a prolonged extinction event.



J. Sepkoski

The other recent major extinction, the middle Miocene extinction about 12 million years ago, will also require some more attention. Frank Asaro of the Lawrence Berkeley Laboratory and his colleagues had found a sizable iridium anomaly in a Deep Sea Drilling Program core during their methodical search of 3 million years of sediment for an impact in the middle Miocene, the time of Raup and Sepkoski's most recent periodic major extinction. Moving 10,000 kilometers away from this site near New Zealand, they searched a million years of sediment in a second core from the Weddell Sea of Antarctica. They found another, much smaller iridium peak of exactly the same age, 11.7 million years. With widely separated iridium deposits in hand, it looked like a large impact.

But then somebody changed the rules. The dating of the second core based on the record of Earth's magnetic field reversals was revised. Now the two peaks, according to the dating, occurred 1.7 million years apart. "The data are suggestive" of a single large impact, said Asaro, but now the search must be extended to the section of core indicated by the new dating.

If little else is certain, it does seem that there has been nothing else like the Cretaceous-Tertiary impact during the past few hundred-million years, making it a truly singular event in Earth history in both the geological and biological realms.

How Catastrophic Were the K-T Extinctions?

Until a large impact was suggested as the cause of the end of the dinosaur age, mass extinctions were a neglected phenomenon, dividing geologic time into convenient periods but not meriting much detailed study themselves. The subsequent dissection of these geologic boundaries, at times grain by grain, has engendered a controversy over just how species die out across a boundary viewed as a mass extinction: all at once, as if struck by a single catastrophe; gradually, as if due to a slowly changing environment; or in a number of steps, as if repeated stress was winnowing the population?

This debate was epitomized at the Snowbird conference by the presentations by Jan Smit and his colleagues at the Free University in Amsterdam and by Gerta Keller of Princeton University. Both sampled in El Kef, Tunisia, across the 66-million-year-old boundary between the Cretaceous (K) period, when the dinosaurs lived, and the Tertiary (T) period, when the mammals began their rise. A few millimeters of sediment at the K-T boundary itself contains evidence of the large impact that strewed debris around the world.

Keller reported that of 36 species of microfossil foraminifera found near the boundary, 6 became extinct 25 centimeters below the boundary, or some thousands or tens of thousands of years before the impact. Another 8 species disappeared 5 centimeters below the boundary, 12 species at the boundary, and 10 species 7 centimeters above it. The mass extinction appears to have been gradual or perhaps stepwise. Keller concluded from this site and others that "Although the onset of the mass extinction appears to have been related to global climatic changes, the K-T boundary event hastened the demise of a fauna already on the decline."

Smit could not disagree more. He found that virtually all of his 30 Cretaceous foraminifera species at El Kef continued to within 2 centimeters of the boundary. The mass extinction would thus appear to have been catastrophic and coincident with the large impact. Smit and Keller briefly discussed why one of them should see microfossils the other does not and agreed that they should get together to resolve their differences.

The debate over gradual versus instantaneous mass extinction also cropped up in discussions of land plants and marine clams and cephalopods. One conclusion was that apparent gradual extinctions well before the Cretaceous-Tertiary boundary can sometimes, but not always, be shown to be catastrophic extinctions at the boundary. It may just take lots of looking in the right places.

Peter Ward and Kenneth MacLeod of the University of Washington reported that, contrary to most earlier work, the spiraled mollusks called ammonites did not die out before the boundary. Searching beyond a classic exposure at Zumaya, Spain, around the Bay of Biscay, they found ammonite fossils, which are centimeters to up to a meter across, within 13 centimeters of the boundary. With more work and more luck, said Ward, even that gap should disappear.

On the other hand, Ward and MacLeod found that the bivalve mollusks called inoceramids disappeared over about 40 meters of sediment 120 meters below the boundary, or roughly half a million years before the impact. That is not a result of poor sampling because they found inoceramid shell fragments and prisms disappearing in deep sea cores at the same time.

Clearly, in addition to resolving questions about the boundary itself, paleontologists will have to look hard and long at many sites within a region, at many regions around the world, and over more than 1 or 2 millions years of time around the boundary in order that they can distinguish just what is unusual about mass extinctions.

■ RICHARD A. KERR

AMPTE Outfoxed by Magnetosphere

How do you lose track of 2×10^{25} lithium ions in the emptiness of space? That was the question space physicists have been asking themselves since the release of six such batches of chemical tracers near Earth in 1985. It is easy enough, it turns out, if the tracers are making their way through the complex and poorly understood magnetosphere of Earth. Recent studies suggest how things might have gone wrong.

A primary goal of the Active Magnetospheric Particle Tracer Explorers (AMPTE) mission was to show how the low-energy ions blown off the sun in the form of the solar wind can cross the barrier at the edge of Earth's magnetosphere, the teardrop-shaped enclosure formed by the magnetic field, and become energized within the magnetosphere (*Science*, 28 June 1985, p. 1519). The ions that reach the close-in radiation belts have a thousand to a million times more energy than those in the solar wind. The easiest approach seemed to be the tagging of the solar wind with some exotic, easily identified ions released by a distant satellite and the measurement of their properties by a second satellite on their arrival near the radiation belts.

Under the best of conditions, the two lithium releases sunward of and outside the magnetosphere would yield few ions to be detected near Earth, according to the best models of ion transport then available. Unfortunately, the best models were thought to be uncertain by a factor of 10. Conditions were not the best during the releases in the fall of 1984 and no lithium was detected, which was not too surprising.

More surprising was the failure to detect the ions from two barium and two lithium releases within the tail of the magnetosphere during the spring of 1985. John Cladis and William Francis of the Lockheed Palo Alto Research Laboratory have run an improved model of tracer ion behavior within the magnetic and electric fields of the magnetosphere. Their model showed that the barium clouds probably presented too small a target for the AMPTE detector satellite. Ionizing within 30 seconds of release, the barium remained at high concentrations but in such tight bundles that the detector satellite never came closer than 12,000 kilometers to the bundles in the model simulations.

All this was a bit discouraging, but from the beginning the lithium releases had looked like the best bet. Lithium took about an hour to ionize, allowing it to spread across a volume of space a few times larger than Earth. The target was certainly big enough and the simulations showed the satellite hitting the target. For the first lithium release, the simulated concentrations after the 2- to 4-hour transit time were even in the detectable range, although just barely. The fatal problem on that run may have been the natural high electron flux prevailing at the time, which created a background in the detector that swamped the lithium signal. By the time of the next release, the satellite's most sensitive detector had failed and the simulated lithium concentration was half what it was in the earlier run.

Would Cladis endorse another try at releasing magnetospheric tracers, now that the models are better? "We were very close to measuring lithium," he says, "but a repeat would not be a good idea. Even at the present time we don't have a good model of the electric fields in the deep magnetotail."

As is often the case in the data-poor field of magnetospherics, there is an opposing opinion, at least in the case of the 13 May barium release. Theodore Fritz of Los Alamos National Laboratory and his colleagues are suggesting that instead of the barium slowly diffusing toward Earth, as in the model, the strain that it created on the magnetic field formed a small blob of closed field lines containing much of the barium. From ground-based imaging of the barium and other observations, this group concludes that the so-called plasmoid promptly headed down the magnetotail toward deep space at the hefty clip of 200 kilometers per hour, taking the barium with it. Unlike Cladis, who would look to the use of a satellite-borne, repeating-ion gun to study ion transport, Fritz and his colleagues would like to see more AMPTE-like releases to tag such small plasmoids as well as the large ones that some researchers believe break off the magnetotail like drops from a dripping faucet (*Science*, 14 December 1984, p. 1298).

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ADDITIONAL READING

J. B. Cladis and W. E. Francis, "On the transport of ions released in the magnetotail by the AMPTE-IRM satellite," *Adv. Space Res.* **8**, (1)5 (1988).