THE K-T EXTINCTION

by Richard Cowen

Cowen, R. 1994. *History of Life*. 2nd edition. 460 pp. Blackwell Scientific Publications, Cambridge, Massachusetts. This is a freshman-level textbook published by Blackwell Science. Copyright Richard Cowen 1994. Available from Blackwell Science, 238 Main Street, Cambridge, Massachusetts 02142, telephone 800-215-1000. Information and updates on the 3rd edition.

See also a separate essay devoted to the general topic of major extinctions, and for an outline of Richard Cowen's oral presentation.

At the Geology Department at the University of California, Davis, Richard Cowen tries to maintain other Web pages of interest:

- Updates and Web links for the essay on the KT Extinction
- New references on the KT Extinction that have appeared since *History of Life* was published.
- Updates and Web links for the essay on Extinction
- New references on Extinction that have appeared since *History of Life* was published.
- Paleontology in the News: Web pages of current interest.

The End of the Dinosaurs: The K-T extinction

Almost all the large vertebrates on Earth, on land, at sea, and in the air (all dinosaurs, plesiosaurs, mosasaurs, and pterosaurs) suddenly became extinct about 65 Ma, at the end of the Cretaceous Period. At the same time, most plankton and many tropical invertebrates, especially reef-dwellers, became extinct, and many land plants were severely affected. This extinction event marks a major boundary in Earth's history, the K-T or Cretaceous-Tertiary boundary, and the end of the Mesozoic Era. The K-T extinctions were worldwide, affecting all the major continents and oceans. There are still arguments about just how short the event was. It was certainly sudden in geological terms and may have been catastrophic by anyone's standards. Despite the scale of the extinctions, however, we must not be trapped into thinking that the K-T boundary marked a disaster for all living things. Most groups of organisms survived. Insects, mammals, birds, and flowering plants on land, and fishes, corals, and mollusks in the ocean went on to diversify tremendously soon after the end of the Cretaceous. The K-T casualties included most of the large creatures of the time, but also some of the smallest, in particular the plankton that generate most of the primary production in the oceans.

There have been many bad theories to explain dinosaur extinctions. More bad science is described in this chapter than in all the rest of the book. For example, even in the 1980s a new book on dinosaur extinctions suggested that they spent too much time in the sun, got cataracts, and because they couldn't see very well, fell over cliffs to their doom. But no matter how convincing or how silly they are, any of the theories that try to explain only the extinction of the dinosaurs ignore the fact that extinctions took place in land, sea, and aerial faunas, and were truly worldwide. The K-T extinctions were a global event, so we should examine globally effective agents: geographic change, oceanographic change, climatic change, or an extraterrestrial event. The most recent work on the K-T extinction has centered on two hypotheses that suggest a violent end to the Cretaceous: a large asteroid impact and a giant volcanic eruption.

An Asteroid or Cometary Impact?

A meteorite big enough to be called a small asteroid hit Earth precisely at the time of the K-T extinction. The evidence for the impact was first discovered by Walter Alvarez and colleagues. They found that rocks laid down precisely at the K-T boundary contain extraordinary amounts of the metal iridium (Figure 18.1). It doesn't seem to matter whether the boundary rocks were laid down on land or under the sea. In the Pacific Ocean and the Caribbean the iridium-bearing clay forms a layer in ocean floor sediments; it is found in continental shelf deposits in Europe; and in North America, from Canada to New Mexico, it occurs in coal-bearing rock sequences laid down on floodplains and deltas. The dating is precise, and the iridium layer has been identified in more than 100 places around the Earth. Where the boundary is in marine sediments, the iridium occurs in a layer just above the last Cretaceous microfossils, and the sediments above it contain Paleocene microfossils from the earliest part of the Cenozoic.

The iridium is present only in the boundary rocks and therefore was deposited in a single large spike: a very short event. Iridium occurs in normal seafloor sediments in microscopic quantities, but the iridium spike at the K-T boundary is very large. Iridium is rare on Earth, and although it can be concentrated by chemical processes in a sediment, an iridium spike of this magnitude must have arisen in some unusual way. Iridium is much rarer than gold on Earth, yet in the K-T boundary clay iridium is usually twice as abundant as gold, sometimes more than that. The same high ratio is found in meteorites. The Alvarez group therefore suggested that iridium was scattered worldwide from a cloud of debris that formed as an asteroid struck somewhere on Earth.

An asteroid big enough to scatter the estimated amount of iridium in the worldwide spike at the K-T boundary may have been about 10 km (6 miles) across. Computer models suggest that if such an asteroid collided with Earth, it would pass through the atmosphere and ocean almost as if they were not there and blast a crater in the crust about 100 km across. The iridium and the smallest pieces of debris would be spread worldwide by the impact blast as the asteroid vaporized into a fireball. If indeed the spike was formed by a large impact, what other evidence should we hope to find in the rock record? Well-known meteorite impact structures often have fragments of shocked quartz and spherules (tiny glass spheres) associated with them (Figure 18.2). The glass is formed as the target rock is melted in the impact, blasted into the air as a spray of droplets, and almost immediately frozen. Over geological time, the glass spherules may decay to clay. Shocked quartz is formed when quartz crystals undergo a sudden pulse of great pressure. If they are not heated enough to melt, they may carry peculiar and unmistakable microstructures (Figure 18.2, top).

All over North America, the K-T boundary clay contains glass spherules (Figure 18.2, bottom), and just above the clay is a thinner layer that contains iridium along with fragments of shocked quartz. It is only a few millimeters thick, but in total it contains more than a cubic kilometer of shocked quartz in North America alone. The zone of shocked quartz extends west onto the Pacific Ocean floor, but shocked quartz is rare in K-T boundary rocks elsewhere: some very tiny fragments occur in European sites. All this evidence implies that the K-T impact occurred on or near North America, with the iridium coming from the vaporized asteroid and the shocked quartz coming from the continental rocks it hit.

The K-T impact crater has now been found. It is a roughly egg-shaped geological structure called Chicxulub, deeply buried under the sediments of the Yucatán peninsula of Mexico (Figure 18.3). The structure is about 180 km across, one of the largest impact structures so far identified with confidence on Earth. A borehole drilled into the Chicxulub structure hit 380 meters (more than 1000 feet) of igneous rock with a strange chemistry. That chemistry could have been generated by melting together a mixture of the sedimentary rocks in the region. The igneous rock under Chicxulub contains high levels of iridium, and its age is 65 Ma, exactly coinciding with the K-T boundary.

On top of the igneous rock lies a mass of broken rock, probably the largest surviving debris particles that fell back on to the crater without melting, and on top of that are normal sediments that formed slowly to fill the crater in the shallow tropical seas that covered the impact area.

Well-known impact craters often have tektites associated with them as well as shocked quartz and tiny glass spherules. Tektites are larger glass beads with unusual shapes and surface textures. They are formed when rocks are instantaneously melted and splashed out of impact sites in the form of big gobbets of molten glass, then cooled while spinning through the air.

Haiti was about 800 km from Chicxulub at the end of the Cretaceous (Figure

18.3). At Beloc and other localities in Haiti, the K-T boundary is marked by a normal but thick (30 cm) clay boundary layer that consists mainly of glass spherules (Figure 18.2). The clay is overlain by a layer of turbidite, submarine landslide material that contains large rock fragments. Some of the fragments look like shattered ocean crust, but there are also spherical pieces of yellow and black glass up to 8 mm across that are unmistakably tektites. The Beloc tektites apparently formed at about 1300℃ from two different kinds of rock; and they are dated precisely at 65 Ma. The black tektites formed from continental volcanic rocks and the yellow ones from evaporite sediments with a high content of sulfate and carbonate. The rocks of the Yucatán around Chicxulub are formed dominantly of exactly this mixture of rocks, and the igneous rocks under Chicxulub have a chemistry of a once-molten mixture of the two. Above the turbidite comes a thin red clay layer only about 5-10 mm thick that contains iridium and shocked quartz.

One can explain much of this evidence as follows: an asteroid struck at Chicxulub, hitting a pile of thick sediments in a shallow sea. The impact melted much of the local crust and blasted molten material outward from as deep as 14 km under the surface. Small spherules of molten glass were blasted into the air at a shallow angle, and fell out over a giant area that extended northeast as far as Haiti, several hundred kilometers away, and to the northwest as far as Colorado. Next followed the finer material that had been blasted higher into the atmosphere or out into space and fell more slowly on top of the coarser fragments.

The egg-shape of the Chicxulub crater shows that the asteroid hit at a shallow angle, about 20°-30°, splattering more debris to the northwest than in other directions. This accounts in particular for the tremendous damage to the North American continent, and the skewed distribution of shocked quartz far out into the Pacific.

Other sites in the western Caribbean suggest that normally quiet, deep-water sediments were drastically disturbed right at the end of the Cretaceous, and the disturbed sediments have the iridium-bearing layer right on top of them. At many sites from northern Mexico and Texas, and at two sites drilled on the floor of the Gulf of Mexico, there are signs of a great disturbance in the ocean at the K-T boundary. In some places, the disturbed seafloor sediments contain fossils of fresh leaves and wood from land plants, along with tektites dated at

65 Ma (Figure 18.4). Around the Caribbean and at sites up the Eastern Atlantic coast of the United States, existing Cretaceous sediments were torn up and settled out again in a messy pile that also contains glass spherules of different chemistries, shocked quartz fragments, and an iridium spike. All this implies that a great tsunami or tidal wave affected the ocean margin of the time, washing fresh land plants well out to sea and tearing up seafloor sediments that had lain undisturbed for millions of years. The resulting bizarre mixture of rocks has been called "the Cretaceous-Tertiary cocktail."

Once Chicxulub was identified, it became possible to calculate that shocked quartz had been launched into a high-angle spray from the impact. This first hot fireball blew vaporized and molten debris (including glass spherules and iridium) high above the atmosphere to be deposited last and globally as it slowly drifted downward. The larger fragments, solid and molten, were blasted outward at lower angles, but not very far, and were deposited first and locally (about 15 minutes travel time to Colorado!). At the same time, smaller fragments, including shocked quartz, were blown upward between the hot fireball and the larger fragments, and were deposited second and regionally (about 30 minutes to reach Colorado). The impact energy, for comparison with hydrogen bomb blasts, was around 100 million megatons.

A Giant Volcanic Eruption?

Exactly at the K-T boundary, a new plume (Chapter 6) was burning its way through the crust close to the plate boundary between India and Africa. Enormous quantities of basalt flooded out over what is now the Deccan Plateau of western India to form huge lava beds called the Deccan Traps. A huge extension of that lava flow on the other side of the plate boundary now lies underwater in the Indian Ocean (Figures 18.3 and 18.5). The Deccan Traps cover 500,000 km2 now (about 200,000 square miles), but they may have covered four times as much before erosion removed them from some areas. They have a surviving volume of 1 million km^3 (240,000 cubic miles) and are over 2 km thick in places. The entire volcanic volume that erupted, including the underwater lavas, was much larger than this (Figure 18.5).

Furthermore, the Deccan eruptions began suddenly just before the K-T boundary. The peak eruptions may have lasted only about one million years (± 50%), but that short time straddled the K-T boundary. The rate of eruption was at least 30 times the rate of Hawaiian eruptions today,

even assuming it was continuous over as much as a million years; if the eruption was shorter or spasmodic, eruption rates would have been much higher. The Deccan Traps probably erupted as lava flows and fountains like those of Kilauea, rather than in giant explosive eruptions like that of Krakatau. But estimates of the fire fountains generated by eruptions on the scale of the Deccan Traps suggest that aerosols and ash would easily have been carried into the stratosphere. The Deccan plume is still active; its hot spot now lies under the volcanic island of Réunion in the Indian Ocean.

Thus there is strong evidence for short-lived but gigantic volcanic eruptions at the K-T boundary. Some people have tried to explain all the features of the K-T boundary rocks as the result of these eruptions. But the evidence for an extraterrestrial impact is so strong that it's a waste of time to try to explain away that evidence as volcanic effects. We should concentrate instead on the fact that the K-T boundary coincided with two very dramatic events. The Deccan Traps lie across the K-T boundary and were formed in what was obviously a major event in Earth history. The asteroid impact was exactly at the K-T boundary. Certainly something dramatic happened to life on Earth, because geologists have defined the K-T boundary and the end of the Mesozoic Era on the basis of a large extinction of creatures on land and in the sea. An asteroid impact, or a series of gigantic eruptions, or both, would have had major global effects on atmosphere and weather.

There is a feeling, particularly among physical scientists, that if we can show that a physical catastrophe occurred at the K-T boundary, we have an automatic explanation for the K-T extinctions. But this connection has to be demonstrated, not just assumed. We still have to ask which catastrophe, if either, caused the K-T extinctions, and if so, how?

Did a Catastrophe Cause the Extinctions?

Almost all the scientists directly involved in trying to explain the K-T extinctions are emotionally committed to one catastrophic hypothesis or the other, or are emotionally against both. This has resulted in claims that seem to overinterpret the evidence. One must be prepared to make one's own decision, and certainly all claims must be subject to close scrutiny.

SOME IMPACT SCENARIOS FOR EXTINCTION

We think we understand impacts and explosions rather well, after direct study of the Moon's surface, photographic surveys of cratered surfaces on planets and satellites, and our experience with nuclear blasts. We also know that asteroids do strike the Earth. Meteor Crater in Arizona, Manicouagan Crater in Canada, and scores of others can be seen from air photographs; indeed, about 20% of the world's nickel is mined from the Sudbury impact site in Canada, where an asteroid struck about 2000 Ma. Over geological time scales, an asteroid impact is not an unusual event.

Some general predictions of the asteroid impact theory are clear and can be used as indirect tests of its plausibility. The impact of a 10 km asteroid would blow a mass of vaporized rock and steam high above the atmosphere, forming an immense dust cloud that would slowly settle out through the atmosphere over a period of weeks, perhaps several months, perhaps several years. The blast and the cloud would spread material worldwide (Figure 18.6). The scenario has been discussed extensively because similar consequences (nuclear winter or at least nuclear fall) could result from a thermonuclear war. But realistic models are still not available, and at least some of the discussion is biased one way or another because the topic is so important politically. Nuclear fall models and K-T impact models have been so intertwined in people's minds that results from one tend to be automatically applied to the other in spite of the differences between the two.

Here is one possible impact scenario. An impact at Chicxulub, where the target rocks contain high quantities of sulfur, produces enormous amounts of sulfate aerosols in the atmosphere that act as nucleation sites for acid rains much more intense and devastating than anything we have generated from industrial pollution. One model suggests rain with the strength of battery acid! The direct effect is enough to suffocate some air breathers, to destroy plant foliage, and to dissolve the shells of marine creatures living along shores and in the surface waters of the ocean. The balance of CO_2 between air and ocean is upset, and a chain of climatic events makes ocean surface waters barren for perhaps 20 years. Among other effects of the impact, dust, smoke, and aerosols cut down the sun's rays for weeks or months, so that land plants and algal plankton in the ocean cannot photosynthesize. The dust also causes freezing air temperatures within days after the impact, and maintains them below freezing for weeks or even months. This may not be an unusual situation at a pole, and may not be a problem for an organism living deep in the ocean, but it is a catastrophe for organisms on continental land masses.

Later, once the dust and aerosols have settled out, the enormous amount of CO_2 released into the atmosphere by the impact generates a greenhouse effect that elevates temperatures on Earth for a thousand years or more.

The most extreme impact scenario could be called the microwave summer because it contrasts so much with nuclear winter. It was put together by Jay

Melosh and colleagues. In this scenario, some of the material produced in a very large asteroid impact was blasted upward at a velocity greater than Earth's escape velocity, although most of it eventually fell back into the atmosphere on ballistic trajectories after a travel time of about one hour. An asteroid of mass 1015-1016 kg would have supplied the observed iridium and spherules, in a depositional layer averaging 10 kg/sq m (about 20 pounds per square yard of Earth's surface).

One can calculate how much thermal radiation the mass of ballistic debris would have emitted as it re-entered the atmosphere. Data on nuclear weapons suggest that the radiation pulse from infalling dust would have been 1000 times more than enough to ignite dry forests.

Ejecta radiation arrives spread over time, however, not in the single radiant pulse generated by an H-bomb. Even so, when we calculate this effect, the rates of worldwide radiation were somewhere between 30 and 100 times that of full sunshine, predominantly in the form of heat.

Of course, half of the radiation was directed upward into space, and some was absorbed by atmospheric water vapor and CO_2. Nevertheless, one-third reached the Earth's surface. It would have taken most of the radiation to evaporate dense cloud, which would therefore largely have protected the surface beneath. Light cloud or no cloud would of course have given little or no shielding. Therefore, Melosh and colleagues estimate surface heating of perhaps 10 kilowatts per square meter for several hours, comparable with the heating in a domestic oven set at Broil.

This radiant heat then generated global wildfires that allegedly left soot in the K-T boundary sections. In general a surface temperature of 545℃ is needed for wood to ignite spontaneously, and the radiation could not have produced this on a worldwide basis. But the volatile gases given off by hot wood will burst into flame after 20 minutes at 380℃, which is attained in the scenario. Even local variations in received radiation would have been sufficient to begin fires.

In perhaps the most bizarre of the "What if?" scenarios, if the tropical ocean surface were to reach 50° C, hypercanes (gigantic hurricanes) might have sucked up ice and dust and blown them into the stratosphere, blocking sunlight even more and destroying the ozone layer!

What do we do with these impact scenarios? Naturally, we compare them with the evidence from the geological record. Birds, tortoises, and mammals live on land and breathe air: the evidence from the K-T boundary shows that they survived the K-T boundary event. Therefore they and the air they breathed weren't set on broil for several hours. To put it simply, these scenarios did not happen.

VOLCANIC SCENARIOS FOR EXTINCTION

We also think we know rather a lot about volcanic eruptions. Gigantic eruptions could produce results similar to those of an impact. Volcanic eruptions produce ash, but, even more important, they produce vast amounts of aerosols in the form of sulfuric acid droplets, which stay suspended longer than ash and produce long-lasting effects on climate. Eruptions can sometimes blow material into the stratosphere, where it can be carried over great areas. The eruption of Tambora in 1815 blew out 30 cubic km (7 cubic miles) of ash and dust, which caused spectacular sunsets worldwide and inspired Turner's finest paintings. The darker side of the eruption was that the dust and ash blocked off enough sunlight to cause "The Year Without a Summer" in 1816. Crops failed all over the Northern Hemisphere, resulting in widespread hunger, and even starvation in some areas. The summer was so gloomy in Europe that it depressed Mary Shelley enough to write the famous novel Frankenstein. The eruption of Toba, 75,000 years ago, is the largest documented eruption on Earth, perhaps 100 times the scale of Tambora. Yet the Toba ash is nowhere near the scale of the Deccan Traps. The possible results of the Deccan Traps eruptions include acid rain, ozone depletion, a greenhouse effect, a cooling effect, or any combination of the above: in other words, many of the same effects cited for an asteroid impact.

The Ecology of a Catastrophe

It's easy to imagine that a giant eruption or impact might have caused some kind of catastrophe at the K-T boundary. But it is not certain that it would. The problem with discussing impacts, nuclear war, and eruptions is that we don't know how much dust, smoke, and aerosols would be produced, even though it's absolutely critical to calculations of darkening and temperature change that we know those factors rather precisely. We don't know how far aerosols and stratospheric dust would be carried over the Earth, or in detail what effects they would have. Dust in the air can help absorb solar heat rather than reflect it, for example, and some models of nuclear war suggest that parts of the Earth would warm, parts would cool, and parts would stay at about the same temperature.

In some ways, some volcanic and impact scenarios are similar. For example, some calculations suggest that a Chicxulub impact could have produced hundreds of times more sulfate aerosol than the Tambora eruption in 1815, with its dramatic climatic effect.

The most persuasive scenarios of catastrophic extinction are quickly summarized. Regionally, there is little doubt that the North American continent would have been absolutely devastated. Globally, even a short-lived catastrophe among land plants and surface plankton at sea would drastically affect normal food chains. Pterosaurs, dinosaurs, and large marine reptiles would have been vulnerable to food shortage, and their extinction after a catastrophe seems plausible. Lizards and primitive mammals, which survived, are small and often burrow and hibernate; they would have found plenty of nuts, seeds, insect larvae, and invertebrates buried or lying around in the dark. In the oceans, invertebrates living in shallow water would have suffered greatly from cold or frost, or perhaps from CO_2-induced heating. But deeper-water forms are insulated from heat or cold shock and have low metabolic rates; they therefore would be able to survive even months of starvation. High-latitude faunas in particular were already adapted to winter darkness, though perhaps not to extreme cold. Thus, tropical reef communities could have been decimated, but deep-water and high-latitude communities could have survived much better. All these patterns are observed at the K-T boundary.

Doubts about Catastrophes

The problem with catastrophic hypotheses for the K-T extinctions is that the catastrophes must have been severe but not too severe, because so many creatures survived. Dust and soot must have fallen quickly (within a year) to satisfy some scenarios, but had to remain suspended longer in the atmosphere to produce other effects.

Some specific evidence shows that impacts and eruptions do not necessarily cause catastrophes. For example, a major impact formed the Ries crater in Germany at 15 Ma, throwing huge masses of boulders more than 100 km (60 miles) into Switzerland and the Czech Republic, and tektites several hundred kilometers. The Ries impact did not affect even the local mammal fauna. A major impact at 51 Ma formed the Montagnais crater in the North Atlantic, 45 km (28 miles) across, and an impact hit Chesapeake Bay at 35 Ma, causing a crater 90 km (56 miles) across, but neither of them caused an extinction.

One should beware, however, of dismissing catastrophic explanations because small events do not trigger catastrophes. There may be a threshold effect: if the event is not big enough it will do nothing, but if it is big enough it will do everything. Perhaps there has been only one asteroid impact in the last 500 m.y. large enough to cause a mass extinction (at the K-T boundary); perhaps there have been only two eruptions large enough, at the K-T boundary and/or the P-Tr boundary.

Despite the model predictions and despite reasonable evidence about the physical effects, we don't yet know whether an impact and/or an eruption would have catastrophic, severe, or only mild biological and ecological effects, or whether those effects would be local, regional, or global. In each scenario, however, the killing agent is transient: it would have operated for only a short time geologically. Clearly, if such events occur, they are rare. That does not make them impossible, only unlikely. And that means they have to be very persuasive before we accept them!

PALEONTOLOGICAL EVIDENCE FROM THE K-T BOUNDARY

The paleontological evidence from the K-T boundary is ambiguous. While many phenomena are well explained by an impact or a volcanic hypothesis, others are not. The fossils do provide us with real evidence about the K-T extinction events, instead of inferences from analogy or from computer models.

The best-studied terrestrial sections across the K-T boundary are in North America. Immediately this is a problem, because we know that the effects of the asteroid impact were greater here than in most parts of the world. Perhaps this has given us a more catastrophic view of the boundary event that we would gather from, say, comparable careful research in New Zealand. Even so, it is obvious that life, even in North America, was not wiped out: many plants and animals survived the K-T event.

Land Plants

North American land plants were devastated from Alberta to New Mexico at the K-T boundary. The sediments below the boundary are dominated by angiosperm pollen, but the boundary itself has little or no angiosperm pollen and instead is dominated by fern spores in a spore spike analogous to the iridium spike (Figure 18.7). Normal pollen counts occur immediately after the boundary layer. The spore spike therefore coincides precisely with the iridium spike in time and is equally intense and short-lived.

The spore spike could be explained by a short but severe crisis for land plants, generated by an impact or an eruption, in which all adult leaves died off for lack of light, or in a prolonged frost, or in acid rain. Perhaps ferns were the first plants to recolonize the debris, and higher plants returned later. This happened after the eruption of Krakatau in 1883. Ferns quickly grew on the devastated island surfaces, presumably from windblown spores, but they in turn were replaced within a few decades by flowering plants as a full flora was reestablished.

Evidence from leaves confirms the data from spores and pollen. Land plants in North America recovered from the crisis, but many Late Cretaceous plant species were killed off. The survivors probably remained safe during the crisis as seeds and spores in the soil, or even as roots and rhizomes.

Angiosperms were in the middle of a great expansion in the Late Cretaceous, and the expansion continued into the Paleocene and Eocene. Yet there were important and abrupt changes in North American floras at the K-T boundary. In the Late Cretaceous, for example, an evergreen woodland grew from Montana to New Mexico in a seasonally dry, subtropical climate. Changing leaf patterns indicate that the climate was slowly warming during the latest Cretaceous. At the boundary the dominantly evergreen Late Cretaceous woodland changed to a largely deciduous Early Cenozoic swamp woodland growing in a wetter climate. The fern spike represents a period of swampy mire at the boundary itself. Deciduous trees survived the K-T boundary events much better than evergreens did; in particular, species that had been more northerly spread southward. These changes could be explained in two different catastrophic scenarios: a regional catastrophe that wiped out all vegetation locally, with recolonization from survivors from the north; or a catastrophe that selectively destroyed evergreen plants.

Plants in Japan were affected less than North American ones, and Southern Hemisphere plants were hardly affected at all. Most likely, this reflects the fact that North America was hit far harder than any other continent by the Chicxulub impact.

Freshwater Communities

Some ecological anomalies at the K-T boundary are not easily explained by a catastrophic scenario. Freshwater communities were less affected than terrestrial ones. For example, turtles and a more primitive group of aquatic reptiles, the champsosaurids, survived in North Dakota while dinosaurs were totally wiped out. Freshwater communities are fueled largely by stream detritus, which includes the nutrients running off from land vegetation. It has been suggested that animals in food chains that begin with detritus rather than with primary productivity would survive a catastrophe better than others. That may be true generally and seems to be true for freshwater communities at the K-T boundary, but such communities would survive any ecological crises better, catastrophic or not.

Environmental Sex Determination

Most catastrophic scenarios are so severe that it's difficult to see how some groups of animals survived. Many living reptiles have environmental sex determination (ESD). The sex of an individual with ESD is not determined genetically, but by the environmental temperatures experienced by the embryo during a critical stage in development. Often, but not universally, the sex that is larger as an adult develops in warmer temperatures. This pattern probably evolved because, other things being equal, warmer temperatures promote faster growth and therefore larger final size (at least for ectotherms). Female turtles are larger than males because they carry huge numbers of large eggs, so baby turtles tend to hatch out as females if the eggs develop in warm places and as males in cooler places. (This makes turtle farming difficult.) Crocodiles and lizards are just the reverse. Males are larger than females because there is strong competition between males, so eggs laid in warmer places tend to hatch out as males. ESD is not found in warm-blooded, egg-laying vertebrates (birds and monotreme mammals), and it didn't occur in dinosaurs if they too were warm-blooded.

ESD is found in such a wide variety of ectothermic reptiles today that it probably occurred also in their ancestors. If so, a very sudden change in global temperature should have caused a catastrophe among ectothermic reptiles at the K-T boundary. But it did not. Crocodilians and turtles were hardly affected at all by the K-T boundary events, and lizards were affected only mildly.

High-Latitude Dinosaurs

Late Cretaceous dinosaurs lived in very high latitudes north and south, in Alaska and in South Australia and Antarctica. These dinosaurs would have been well adapted to strong seasonal variation, including periods of darkness and very cool temperatures. An impact scenario would not easily account for the extinction of such animals at both poles.

Birds

The survival of birds is the strangest of all the K-T boundary events, if we are to accept the catastrophic scenarios. Smaller dinosaurs overlapped with larger birds in size and in ecological roles as terrestrial bipeds. How did birds survive while dinosaurs did not? Birds seek food in the open, by sight; they are small and warm-blooded, with high metabolic rates and small energy stores. Even a sudden storm or a slightly severe winter can cause high mortality among bird populations. Yet an impact scenario, according to its enthusiasts, includes "a nightmare of environmental disasters, including storms, tsunamis, cold and darkness, greenhouse warming, acid rains and global fires." There must be some explanation for the survival of birds, turtles, and crocodiles through any catastrophe of this scale, or else the catastrophe models are wrong.

Where Are We?

It is clear that at least the extreme "impact winter" models are wrong. It's not clear that impact hypotheses or volcanic hypotheses can explain satisfactorily the extinction patterns we see in the fossil record. There are nagging fears that we are overstating the effects of the impact because the results are so clear in North America, close to the impact site.

OCEANOGRAPHIC CHANGE

An impact or a gigantic eruption that might otherwise have caused only a regional extinction might have caused the global K-T extinction by inducing longer-term climatic changes. These changes would be best recorded in ocean sediments and marine fossils. Tropical reef communities were drastically affected in the K-T extinctions, as were microplankton in the surface waters of the ocean. The pattern of marine K-T extinctions is consistent with a massive breakdown in normal marine ecology.

Oxygen isotope measurements across the K-T boundary suggest that oceanic temperatures fluctuated markedly in Late Cretaceous times and through the boundary events. Furthermore, carbon isotope measurements across the K-T boundary suggest that there were severe, rapid, and repeated fluctuations in oceanic productivity in the 3 m.y. before the final extinction, and that productivity and ocean circulation were suppressed for at least several tens of thousands of years just after the boundary, and perhaps for 1 or 2 m.y. afterward. These changes could have devastated terrestrial ecosystems as well as marine ones. Steve D'Hondt has suggested that climatic change is the connection between the impact and the extinction: the impact upset normal climate, with long-term effects that lasted much longer than the immediate and direct consequences of the impact.

There were survivors: hardly any major groups of organisms became entirely extinct. Even the dinosaurs survived in one sense (as birds). In particular, planktonic diatoms survived well, possibly because they have resting stages as part of their life cycle. They recovered as quickly as the land plants emerged from spores, seeds, roots, and rhizomes. The sudden interruption of the food chains on land and in the sea may well have been quite short, even if full recovery of the climate and full marine ecosystems took much longer. D'Hondt et al. suspect that normal surface productivity was re-established in the oceans after a few thousand years at most. However, it took about three million years for the full marine ecosystem to recover, probably because so many marine predators (crustaceans, molluscs, fishes, and marine reptiles) had disappeared, and had to be replaced by evolution among surviving relatives.

We still do not have an explanation for the demise of the victims of the K-T extinction, while so many other groups survived. We do not know whether it was the impact alone, or the combination of the impact and the plume volcanism, that caused the extinction, and we do not know the linkages between the physical events and the biological and ecological effects. It would be astonishing if the impact played no role, and it would be astonishing if the volcanism played no role.

The unusual severity of the K-T extinction, its global scope, and the sudden and dramatic biological features such as the fern-spore spike may have happened because an asteroid impact and a gigantic eruption occurred when global ecosystems were particularly vulnerable to a disturbance of oceanic stability. We will probably gain a better perspective on the K-T boundary as we gather more information about the Late Permian and Late Devonian extinctions. It looks increasingly probable that the Permian extinction was linked with a massive plume eruption, and this may mean that mass extinctions need either an external (impact) trigger or an internal (volcanic) one, and in addition they also require a tectonic or geographic setting that made the global ecosystem vulnerable.

Further Reading

EASY ACCESS REFERENCES

- Alvarez, L. W., et al. 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science* 208: 1095-1108. The paper that started it all.
- Alvarez, W., et al. 1995. Emplacement of Cretaceous-Tertiary boundary shocked quartz from Chicxulub crater. *Science* 269: 930-935. Why the shocked quartz overlies the rest of the impact layer.
- Alvarez, W. 1997. *T. rex and the Crater of Doom*. Princeton University Press. The best of many books on the extinction. Try to read it first.
- Bourgeois, J., et al. 1988. A tsunami deposit at the Cretaceous-Tertiary boundary in Texas. *Science* 241: 567-570.
- Chapman, C. R., and D. Morrison. 1994. Impacts on the Earth by asteroids and comets: assessing the hazard. *Nature* 367: 33-40.
- D'Hondt, S., et al. 1998. Organic carbon fluxes and ecological recovery from the Cretaceous-Tertiary mass extinction. *Science* 282: 276-279.

- Duncan, R. A., and D. G. Pyle. 1988. Rapid eruption of the Deccan flood basalts at the Cretaceous/Tertiary boundary. *Nature* 334: 841-843.
- Head, G., et al. 1987. Environmental determination of sex in the reptiles.*Nature* 329: 198-199.
- Hildebrand, A. R., et al. 1995. Size and structure of the Chicxulub crater revealed by horizontal gravity gradients and cenotes. *Nature* 376: 415-417, and comment, pp. 386-387.
- Koeberl, C., et al. 1996. Impact origin of the Chesapeake Bay structure and the source of the North American tektites. *Science* 271: 1263-1266. An 90-km crater from 35 Ma under Chesapeake Bay.
- MacDougall, J. D. 1988. Seawater strontium isotopes, acid rain, and the Cretaceous-Tertiary boundary. *Science* 239: 485-487.
- Melosh, H. J., et al. 1990. Ignition of global wildfires at the Cretaceous/Tertiary boundary. *Nature* 343: 251-254. Microwave summer.
- Morgan, J., et al. 1997. Size and morphology of the Chicxulub impact crater. *Nature* 390: 472-476.
- O'Keefe, J. A., and T. J. Ahrens. 1989. Impact production of CO_2 by the Cretaceous/Tertiary impact bolide and the resultant heating of the Earth.*Nature* 338: 247-248.
- Rabinowitz, D. L., et al. 1993. Evidence for a near-Earth asteroid belt.*Nature* 363: 704-706. These are not killers, but they are important.
- Rampino, M. R., and T. Volk. 1988. Mass extinctions, atmospheric sulphur and climatic warming at the K/T boundary. *Nature* 332: 63-65.
- Raup, D. M., and J. J. Sepkoski. 1986. Periodic extinction of families and genera. *Science* 231: 833-836.
- Schuraytz, B. C., et al. 1996. Iridium metal in Chicxulub impact melt: forensic chemistry on the K-T smoking gun. *Science* 271: 1573-1576.
- Sharpton, V. L., et al. 1992. New links between the Chicxulub impact structure and the Cretaceous/Tertiary boundary. *Nature* 359: 819-821.
- Stothers, R. B. 1984. The great Tambora eruption of 1815 and its aftermath. *Science* 234: 1191-1198.
- Turco, R. P. et al. 1990. Climate and smoke: an appraisal of nuclear winter.*Science* 247: 166-176. Revised version of their original 1983 suggestion.
- White, R. S., and D. P. McKenzie. 1989. Volcanism at rifts. *Scientific American* 261(1): 62-71. Why the Deccan Traps are so enormous.
- Wolfe, J. A., and G. R. Upchurch. 1986. Vegetation, climatic, and floral changes at the Cretaceous-Tertiary boundary. *Nature* 324: 148-152.
RETURN TO TOP

MORE TECHNICAL READING

- D'Hondt, S., et al. 1996. Oscillatory marine response to the Cretaceous-Tertiary impact. *Geology* 24: 611-614.
- Emanuel, K. A., et al. 1995. Hypercanes: a possible link in global extinction scenarios. *Journal of Geophysical Research* 100: 13755-13765.
- Finnegan, D. L., et al. 1986. Iridium emissions from Kilauea volcano.*Journal of Geophysical Research* 91: 653-663.
- Heissig, K. 1986. No effect of the Ries impact event on the local mammal fauna. *Modern Geology* 10: 171-191.
- Li, L., and G. Keller. 1998. Abrupt deep-sea warming at the end of the Cretaceous. *Geology* 26: 995-998.
- Pope, K. O., et al. 1997. Energy, volatile production, and climatic effects of the Chicxulub Cretaceous/Tertiary impact. *Journal of Geophysical Research* 102: 21645-21664.
- Rampino, M. R., et al. 1988. Volcanic winters. *Annual Reviews of Earth and Planetary Science* 16: 73-99.
- Ryder, G., et al. (eds.) 1996. *The Cretaceous-Tertiary Event and Other Catastrophes in Earth History*. Geological Society of America Special Paper 307. Papers presented at the third major international conference on the K/T event. Two previous conferences were published in the same series, volumes 190 and 247 (1990).
- Schultz, P. H., and S. D'Hondt. 1996. Cretaceous-Tertiary (Chicxulub) impact angle and its consequences. *Geology* 24: 963-967.
- Sheehan, P. M., and T. A. Hansen. 1986. Detritus feeding as a buffer to extinction at the end of the Cretaceous. *Geology* 14: 868-870.
- Sigurdsson, H., et al. 1992. The impact of the Cretaceous/Tertiary bolide on evaporite terrane and generation of major sulfuric acid aerosol. *Earth and Planetary Science Letters* 109: 543-559.
- Wolbach, W. S., et al. 1990. Fires at the K/T boundary: carbon at the Sumbar, Turkmenia, site. *Geochimica et Cosmochimica Acta* 54: 1133-1146. The assumptions in their previous papers have now become facts!
- Wolfe, J. A. 1987. Late Cretaceous-Cenozoic history of deciduousness and the terminal Cretaceous event. *Paleobiology* 13: 215-226.

RC, June 1999.