The Mass Extinctions of the Late Mesozoic

by Dale A. Russell

One of the most striking events in the record of life on our planet is the simultaneous disappearance at the end of the Mesozoic era, some 65 million years ago, of many kinds of reptiles, certain kinds of marine invertebrates, and certain kinds of primitive plants. For generations scholars have sought unsuccessfully to explain this event. New evidence, however, has led to a novel hypothesis: the disappearances were the result of a catastrophic disruption of the biosphere by an extraterrestrial agency.

Catastrophism is not a new doctrine in efforts to account for episodes in the history of the Earth, but it has not been a particularly popular one. Early in the nineteenth century, when geology was in its infancy, the French anatomist Georges Cuvier suggested that the past had been marked by a series of environmental “revolutions,” or catastrophes. In his view, such disruptions would account for three animal disappearances: that of the mammoths at the end of the ice age, that of the many primitive mammals fossilized in rocks lying deeper than the ice-age gravels, and that of the giant reptiles fossilized in chalkbeds lying deeper still. In the decades that followed, however, the work of such pioneer geologists as Charles Lyell made it apparent that the processes of change in Earth history were of far greater duration than Cuvier had believed. Catastrophism fell from favor, to be replaced by the doctrine of gradualism. For more than a century now, paleontologists have generally agreed that whatever may have caused the disappearances at the end of the Mesozoic era, it could not have been a worldwide catastrophe.

The principal casualties among the reptiles were the dinosaurs. As an example, late in the Cretaceous period, the closing chapter of the Mesozoic, at least 15 separate families of dinosaurs, possibly representing between 50 and 70 distinct species, inhabited North America. In the rocks that were formed immediately after the Cretaceous, not one dinosaur skeleton has been found. That is why the end of the Mesozoic is generally characterized as the time when the dinosaurs became extinct. The dinosaurs were not, however, the only organisms to disappear. Among the 33 other families of reptiles that inhabited North America late in the Cretaceous were the following losses: all four of the families of marine turtles (although three of the four survived elsewhere); one of the three families of crocodilians, the Goniophoridae; two pterosaur (flying reptile) families,
the Ornithocheiridae and Azhdarchidae; two ichthyosaur (marine reptile) families; and all three of the plesiosaur (also marine reptile) families, the Elasmosauridae, the Polycotylidae, and the Cimoliasauridae; and, finally, two of the eight families of lizards, the Polyglyphanodontidae (primitive skinklike land forms) and the Mosasauridae (large marine forms).

What happened? Was there a gradual or a catastrophic extinction? My own interest is primarily in the larger reptiles of the Mesozoic in North America, and so the examination of these questions I undertake here will focus mainly on the disappearance of those animals. Among the many hypotheses put forward to account for their disappearance are disruptions of the food chain, both at sea and on land; a general alteration of the environment as the sea level began to drop at the end of the Mesozoic; a sharp rise in temperature; a fall in temperature caused by volcanic dust in the atmosphere; and so on. None of these phenomena, however, would seem, by itself, to be a convincing cause of the reptilian extinctions.

In 1979, paleontologists interested in the problem were presented with a new possibility. A group of workers at the University of California at Berkeley—the geologist Walter Alvarez, his father, the physicist Luis W. Alvarez, and two physical chemists, Frank Asaro and Helen V. Michel—announced the discovery of abnormally large traces of the heavy element iridium in a marine formation near Gubbio in the Apennine mountains of Italy. The iridium was concentrated in a layer of clay, one-half to three-quarters of an inch thick, that separates marine limestone of late Cretaceous age from an overlying marine limestone of early Paleocene age. The limestone below the clay contains fossil marine organisms typical of the latest part of the Cretaceous. No organisms are preserved in the clay. In the limestone above the clay, the Cretaceous organisms are absent; they have been replaced by other organisms typical of the Paleocene.

Iridium is one of several elements geologists call siderophiles, “iron lovers.” It is rarely present in the rocks of the Earth’s crust but is comparatively abundant in meteorites. The steady rain of micrometeorites on the surface of the Earth (more than 70 percent of which fall into the oceans) results in modest concentrations of iridium and other siderophilic elements in the sediments that accumulate in the ocean basins.

In 1977, Walter Alvarez was working with an international group of scholars, including the paleontologist Isabella Premoli Silva of the University of Milan, who were examining the marine strata near Gubbio that include the layer of clay. Because the infall of micrometeoritic material is thought to be more or less constant, Luis Alvarez suggested that by measuring the amount of iridium in the clay it would be possible to calculate how much time had passed during the deposition of the layer. When Asaro and Michel did so, they discovered to their surprise that the iridium in the clay layer was 30 times more abundant than it was in clays from adjacent limestone strata.
Layer of clay in this photograph is about 3/4 of an inch thick. It separates two beds of marine limestone exposed near Gubbio in the Apennine mountains of Italy. The white limestone below the clay is late Mesozoic in age and the grayish limestone above it is early Cenozoic. Analysis of the clay showed it to be 30 times richer in the heavy element iridium than the clays from adjacent marine strata. This had led the geologist Walter Alvarez, his father, physicist Luis W. Alvarez, and two chemists, Frank Asaro and Helen V. Michel, all of the University of California at Berkeley, to the hypothesis that the surplus of iridium came from an extraterrestrial object, perhaps an asteroid-sized meteorite, that crashed into the Earth at the end of the Mesozoic. The Alvarez group further hypothesized that the collision was the cause of the many extinctions of marine and terrestrial organisms at that time. The coin is the size of a 25-cent piece.

If this excess of iridium had somehow been derived from terrestrial sources, the clay should have shown comparable enhancements in the other elements normally associated with the minerals that form clay. The Berkeley group's analysis disclosed a different pattern of enhancement, closer to that of the relative abundances of the elements found in meteorites. Could the surplus iridium have come from the oceanic reservoir of elements derived from micrometeorites, suddenly precipitated by some chemical event? Evidently not; neither above nor below the clay stratum was there any evidence that the normal rate of siderophile accumulation had fallen off as it should have if a precipitation had occurred. In this connection, Charles J. Orth of the Los Alamos Scientific Laboratory and his collaborators have found a similar surplus of iridium at the top of Cretaceous
sedimentary strata that are continental in origin; precipitation from an oceanic reservoir cannot, of course, have caused this.

By the time its report was published in 1980, the Berkeley group could add to the Gubbio datum the discovery of strata containing surplus iridium in late Cretaceous marine rocks in Denmark, Spain, and New Zealand. (They were later able to add to the list iridium anomalies in deep-sea cores from both the Atlantic and the Pacific.) The report concluded with the suggestion that at the time of the mass extinction of certain marine microorganisms (and by inference at the time many reptiles disappeared), some 500 billion tons of extraterrestrial material had been abruptly deposited on the surface of the Earth.

Where might the material have come from? The question is pertinent to further elaboration of the Berkeley group's hypothesis. If, on the one hand, the influx came from within the solar system, the mechanism of its arrival on the Earth can be sought in the large body of data on this region of space. If, on the other hand, it came from outside the solar system, where there is comparatively little data on an enormous range of environments, the search for a mechanism would call for much speculation.

Consider the possibility that the extraterrestrial material was produced outside the solar system by a gigantic stellar explosion: a supernova. In support of such a hypothesis, Malvin A. Ruderman of Columbia University and James W. Truran, Jr. of the University of Illinois at Urbana-Champaign have proposed that a gigantic burst of gamma rays from such an explosion could have blown micrometeoritic material off the surface of the moon, and the Earth could have swept it up. They subsequently noted, however, that gamma-Jones flashes from supernovae have yet to be observed, and furthermore that the transfer of iridium to the Earth by such a mechanism would probably fall short of the required amount.

Another potential source of support for the supernova hypothesis is a continuing study being done by Paolo Maffei of the Astrophysical Observatory at Catania in Italy. Maffei is evaluating astronomical evidence for a gigantic explosive event some 1,000 light-years distant from the solar system at the end of the Mesozoic. The hypothesis is considered unlikely, however, by Wallace H. Tucker of the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory. In his opinion, the interstellar material swept up by even a very large supernova would not accumulate in sufficiently dense concentrations to account for the amount of iridium in the zone of siderophile enhancement that caps late Mesozoic strata.

The sequence of events in a supernova explosion begins with an initial implosion. In the course of this collapse, the nuclei of heavy elements at the core of the star rapidly cap-
ture neutrons. Among the new nuclear species formed is plutonium-244. The subsequent explosion distributes this radioactive isotope throughout an enormous volume of space. The chemists in the Berkeley group searched for Pu-244 in the iridium-rich clay, reasoning that if the iridium had been produced by a supernova, the plutonium should be present in detectable amounts. None was found.

They further reasoned that the two isotopes of iridium, Ir-191 and Ir-193, would be produced in different proportions by different supernova explosions because of variations in neutron fluxes and reaction times. When they analyzed the iridium-rich clay, they found that the two isotopes were present, not in any exotic proportion, but in the proportion that is typical of iridium in the solar system. The same is true of the proportion of the two isotopes of osmium, as has been discovered by workers in two separate laboratories: J. Hertogen of the University of Louvain in Belgium and Ramachandran Ganapathy of the J.T. Baker Chemical Company in Phillipsburg, N.J. Therefore, it seems improbable that the extraterrestrial material present in the clay stratum was the product of a supernova explosion (other than the one that may have been responsible for the formation of the solar system).

If the material came from within the solar system, how did it reach the surface of the Earth? Two possibilities immediately suggest themselves: an encounter with a meteorite of asteroid size or an encounter with a comet. Concerning the first possibility, the Berkeley group has estimated that the amount of exotic material in the iridium-rich stratum worldwide could have been contained in an asteroid some 6¼ miles in diameter. One problem with the asteroid hypothesis is that material of terrestrial origin in the iridium-rich stratum is not present in the large amounts that should have been gouged out of the Earth's crust by the impact of a body of that size. Richard A. F. Grieve of the Canadian Department of Energy, Mines and Resources, has suggested a way around this problem. The iridium could have been deposited after the impact in the form of a fallout of relatively pure meteoritic material rejetted into the stratosphere by the force of the collision. Both the Berkeley group and Jan Smit of the University of Amsterdam, a geologist who has studied late Mesozoic limestone strata in Spain, see still another way around the problem. If the asteroid fell into the sea, which is statistically likely, only a small amount of crustal material would have been excavated by the impact.

As for the possibility of an encounter with a comet, comets are low-density bodies composed largely of water ice. It is, therefore, estimated that a comet containing siderophiles in quantities large enough to account for the observed enrichment would have to be twice as massive as the hypothetical asteroid and, therefore, very much larger. This, of course, raises the excavation problem again. To counter it, Frank Kyte of the University of California at Los Angeles and his colleagues Zhiming Zhou and John Wasson have proposed that as the hypothetical comet approached the Earth, it was disrupted by grav-
Itional forces. The Earth would then have been showered with cometary debris that would not have excavated any major crater or craters.

Either of these hypothetical events might cause extreme short-term stresses within the biosphere. For example, S. V. M. Clube and William M. Napier of the Royal Observatory in Edinburgh estimate that the shock wave generated by the impact of such a big asteroid on land would not only destroy all the Earth's forests but also kill all the larger land-dwelling animals. And if the impact were at sea, it would generate tidal waves five miles high.

Extreme stresses such as these, in the opinion of Walter Alvarez and the other members of his group, might not have been enough to have caused the late Mesozoic extinctions. They suggest that the impact would also have injected an enormous quantity of dust-size particles into the stratosphere. These, the Alvarez hypothesis proposes, would render the atmosphere much less transparent and strike at the very foundations of the biosphere by diminishing photosynthesis.

How much light does the fossil record throw on this new hypothesis? A considerable amount; but it must be remembered that the fossil record contains a limited quantity of information, which is not easy to interpret. For example, although paleontologists have been collecting the remains of Mesozoic animals for more than a century, the total number of known fragments of dinosaur skeletons is only about 5,000. This is largely owing to simple economics: the high cost of collecting dinosaur bones. As a comparison, much useful environmental information can be gleaned from the study of Mesozoic plant pollens. It costs about $500 (including a week's working time) to extract 20,000 pollen grains and mount them for microscopic examination. To collect and prepare the same number of dinosaur bones would cost about $400 million (including a million weeks' working time).

The point is relevant to an important factor in the study of biological extinctions: sample size. For example, one of the most recent Mesozoic dinosaur assemblages, the remains of animals that roamed the interior plains of the United States and Canada some 65 million years ago, is characterized by large, horned herbivores, such as the genus *Triceratops*, and giant carnivores, such as the genus *Tyrannosaurus*. Strata that are 12 million years older, at Dinosaur Provincial Park in Alberta, have yielded a far greater variety of dinosaurs than the more recent rocks.

Does this mean, as some have suggested, that the dinosaurs were declining in variety as the end of the Mesozoic approached? Were they already heading for extinction millions of years before the hypothetical catastrophe? Not at all. The Alberta fossils show a greater variety because many specimens have been collected there: more than 300, compared with fewer than 75 and even as few as six or seven at the more recent locales.
The fact is that the diversity of dinosaurs in Europe as the end of the Mesozoic drew near remained about the same; in Mongolia, the diversity actually increased. In other areas of the world, the samples are too small to reveal trends. In summary, evidence of a long-term decline in the diversity of dinosaurs before the time of extinction is simply not available.

Nowhere else in the world has the fossil record of land organisms over the final 1.75 million years of the Cretaceous been as fully sampled as it has in the 328-foot-thick exposures of grayish-brown sediments around the southern edge of the Fort Peck Reservoir in northeastern Montana. The lower, earlier half of the formation is dominated by river-deposited sands, the upper, later half by alluvial silts and clays. The change in depositional patterns presumably reflects environmental changes that would have caused a change in the distribution of the animals, dinosaurs included, that inhabited this former coastal plain. In the lower levels, the large predatory genus *Tyrannosaurus* and the duck-billed herbivorous genus *Edmontosaurus* predominate. In the upper levels, the herbivorous genus *Triceratops* and small, browsing dinosaurs of the genus *Thescelosaurus* are more abundant. Similar changes in the plant community are documented by studies of fossil spores and pollen by Robert Tschudy of the U.S. Geological Survey.

An extraordinary pattern of change seems to occur at the top of the 328-foot formation. Here, along one horizon, the relative abundances lower in the sequence are reversed, and the remains of large dinosaurs locally outnumber those of small ones. Large animals normally have lower birth and death rates than small animals. Hence, an imbalance of this kind, with more large dinosaurs preserved as fossils than small ones, suggests some kind of mass death.

Above this horizon, near the top of the formation, the sediments begin to take on a more laminated appearance. The only dinosaur bones are a few fragments that appear to have been eroded from older strata and deposited secondarily in stream beds. At first there is no comparable change in the plant community. Then, at a level about 16 feet above the horizon that holds the last unredeposited dinosaur skeletal material, the fossil pollen and spores become poorly preserved. David M. Jarzen of the National Museum of Natural Sciences in Ottawa has studied the plant evidence. He and I estimate that the 16-foot interval represents a depositional period several tens of thousands of years long.

Above the level of poor plant preservation, beds of low-grade coal alternate with laminated siltstones. This separation of the highest occurrence of dinosaurs from the lowest occurrence of coal was first observed some years ago by William A. Clemens of the University of California at Berkeley. Tschudy, who has also studied the spores and pollen in the coal-bearing strata, reports that these evidences of plant life are only a third as abundant as they were in the dinosaur-bone strata below. The age of mammals had begun.
Sequence of events at two land sites in North America and a marine site in Spain at the close of the Mesozoic and the opening of the Cenozoic is presented in this table. The presence of the same replacement foraminiferan, Globigerina pseudobulloides, in North Dakota and Spain in the Cenozoic suggests a coincidence of marine and terrestrial extinctions.
The limestones Smit and his colleagues have been studying in Spain record a remarkable series of events. They were deposited on the floor of an open tropical sea that intruded into southern Spain in late Mesozoic times. The formations are composed almost entirely of the calcium carbonate shells and platelets of tiny foraminifera: free-floating protozoan members of the sea's zooplankton. Here, for more than 10 million years, planktonic productivity remained high, and there was no significant change in the character of the organic debris deposited on the sea floor.

Then within a layer of rock less than a quarter-inch thick (representing less than 200 years of deposition) nearly 90 percent of the foraminifera species found lower in the formation simply vanish. Those protozoans that survived attained only a tenth the size of their predecessors. As the rain of shells and platelets nearly ceased, so did the burrowing activity of bottom-dwelling invertebrate animals. A blanket of laminated red and green clays accumulated on the sea floor, reaching a thickness of about 4 inches. Conditions apparently remained stable for perhaps 20,000 years; by then, all but one species of the surviving foraminifera had dwindled to extinction.

Thereafter, life began to proliferate once more. The deposition of sediments resumed, and the ocean floor was once again plowed by bottom-dwelling invertebrates. A new assemblage of foraminifera arose and was soon followed by another, characterized by the presence of, among others, the species *Globigerina pseudobulloides*. The resurgent protozoans inhabited the ancient Spanish sea for the next 2 million years.

Half a world away, in what is now North Dakota, a great interior sea spread westward at this same time, flooding a delta area where the remains of *Triceratops* had become fossilized and had been covered by coal-bearing strata. The marine siltstones that were laid down on top of the coal hold the shells of foraminifera species belonging to the same *G. pseudobulloides* assemblage that appeared in the Spanish sea after the great foraminiferan extinction. Given the uncertainties in estimating elapsed time from the thickness of sedimentary deposits, it seems possible that the story told by the sediments here, at Fort Peck Reservoir and in southern Spain, is the same. If that is the case, the extinction of the dinosaurs on land and of the foraminifera at sea would have coincided.

The foraminifera were not the only marine organisms to die out at the end of the Mesozoic. As I noted above, so did a number of marine reptiles. So did various mollusks: the coiled-shell cephalopods known as ammonites, the squidlike cephalopods known as belemnites, and the peculiar coral-like bivalves known as rudists. Most of the major families of marine animals survived, but they lost many genera and species.

The fossil record at this crucial boundary is not as well understood with respect to larger marine animals as it is with respect to the microfauna such as the foraminifera. The reason is that the larger animals are numerous and diverse and the number of paleontolo-
gists is finite. As one example, even in such relatively well-studied formations as the chal-ks of Denmark, the survival rate among such important animal groups as sponges, lampshells, marine snails, and crustaceans remains uncalculated. As another example, the record of animal life in the tropical regions of the globe at this time is still poorly known. In view of the paucity of data, it is no wonder that the issue of gradualism versus catastrophism is so vigorously debated.

A crude tabulation is helpful in suggesting the magnitude of the extinctions. Compare the number of animal genera in the fossil record some 10 million years before the end of the Cretaceous with the number of genera in the record in a comparable period after the crisis. It is obvious how insecure these numerical values are. Nevertheless, the numbers appear to reflect a 50 percent decline in generic diversity worldwide. When one repeats this numbers game, counting the number of species recorded for certain plant and animal genera before and after the crisis, the result is similar. In a sample that includes mammals as representative land animals, chitinous marine algae as representative plants, and sand dollars, starfishes, and oysters as representative marine animals, the decline in species during the extinction interval is from about three species per genus to one and a half. Therefore, it seems reasonable to estimate that the biological crisis associated with the extinction of the dinosaurs also caused 75 percent of the previously existing plant and animal species to disappear. Indeed, this estimate is probably somewhat conservative.

The record of extinctions shows certain anomalies. For example, no land animal weighing more than about 55 pounds survived, and many of those that disappeared were considerably smaller. Again, the terrestrial plants of the northern regions of the Temperate Zone suffered more losses than those farther south. Yet the plants and animals of freshwater communities were scarcely affected. Much the same was probably true of deepwater marine mollusks, in the opinion of Arthur H. Clarke of Ecoserech, Inc., Mattapoisett, Massachusetts. Shallow-water marine life, however, particularly the fauna of tropical reefs, was much more profoundly altered.

Even animals that shared the same environment were not identically affected. As Eric Buffetaurt of the University of Paris has pointed out, crocodiles that occupied shallow marine waters survived the extinctions whereas the mosasaurs that occupied the same habitat did not. Whatever the agents of biological stress were, disturbances in food chains included, the ability of the biosphere to resist them was evidently varied.

What is the significance of the apparently dual nature of animal and plant extinctions at the end of the Mesozoic? Were the extinctions truly separate events, with the land animals dying out first and the plants second? If they were, was the second extinction the result of stresses as severe as those that caused the first, or was it simply a quasi-successional phenomenon of biology? Whatever the answer to these questions is, humankind
may have been the long-term beneficiary of the evident catastrophe. As the Mesozoic
drew to a close, certain small carnivorous dinosaurs had achieved the ratio of brain
weight to body weight that is characteristic of early mammals. If these presumably more
intelligent reptiles had survived, their descendants might conceivably have continued to
suppress the rise of the mammals, thereby preempting our own position as the brainiest
animals on the planet.
The Yucatan Impact and Related Matters

by Gregory S. Paul

Within a year after the 1990 essay by Courtillot and Alvarez and Asaro appeared in the pages of *Scientific American* came a major—and rather unexpected—discovery: the identification of the enormous Chicxulub impact crater underlying the Yucatan peninsula of southern Mexico. The crater, buried under Cenozoic sediments—half under water and half on land—had been tentatively discovered a number of years before but was forgotten until researchers realized the connection between the circular geological structure and the end of the Mesozoic. At 60 to 100 miles across (depending upon competing estimates), Chicxulub is among the larger craters known in the solar system. Its formation at a location that is readily accessible is a stroke of scientific luck. It was definitely made at the K/T boundary; indeed, its effects contributed to forming the boundary. In the surrounding region, the super-waves created as the meteorite hit the then-shallow waters appear to have created extensive deposits that had long perplexed geologists. Made by a comet or asteroid about 6 to 8 miles across (the size of Mt. Everest), Chicxulub has preempted all other craters as the probable "dinosaur killer." The extraterrestrial impact hypothesis is now far and away the leading candidate for the K/T extinction. Even so, questions still surround what happened and why.

It is interesting that, despite the hard work of geologists, impacts have not been correlated with most other mass extinctions, including the Permian extinction, which, if anything, was more extensive than the later Cretaceous event. On the other hand, a number of large land animals survived the P/T (Permian/Triassic) extinction, unlike the K/T (Cretaceous/Tertiary) disaster. Various theories that comet swarms—initiated by a "Nemesis" star or other cyclical extraterrestrial patterns—have caused mass extinctions on a 30 or so million year schedule have not been supported by new evidence. Nor has the notion that a short series of impacts killed off the dinosaurs step by step. Therefore, the terrestrial mechanisms that probably lie behind the great majority of mass extinctions remain poorly understood. As it is, we have only the one major K/T event to consider in terms of extraterrestrial intervention.

At this time, four super-impact events are known from the Mesozoic before the K/T Chicxulub event, and one is known from the Cenozoic. Of these, it is possible, but not yet certain, that three of the impact events—a possible multiple impact before the end of
the Triassic, another at or near the J/K (Jurassic/Cretaceous) boundary, and a linked pair of craters from the middle Cenozoic (one of which formed the Chesapeake Bay)—were about as energetic as the K/T explosion. The Mesozoic-through-Cenozoic crater survey is also incomplete. Most of the craters should have excavated the deep ocean floor, where they lie undetected, or more probably were destroyed by tectonic subduction. The last 250 million years' worth of sediments have not been carefully surveyed in search of reentry debris associated with big impacts—the K/T layer was found only because people were intensely interested in that particular zone. It is, therefore, possible that we do not know about Mesozoic and Cenozoic impacts approaching or even surpassing the scale of Chicxulub. At the same time, a recent survey of the K/T crater indicates it may not have been as extremely large as some thought.

In general, the hypothesis has been that the largest extinction of the Mesozoic was so bad because it was associated with the biggest impact of the age. An obvious problem with this premise is that the K/T impact may not have been unique after all. The other problem is that the other super-impacts did not produce correspondingly extreme extinctions of dinosaurs or other large creatures. The Late Triassic Manicouagan impact (Quebec) may or may not have been associated with some minor extinctions, but there is no evidence that dinosaurs suffered any lasting effects. The Late Jurassic, Morokweng impact (South Africa)—which possibly exceeded the power of Chicxulub—may have been associated with dinosaur and pterosaur extinctions at the J/K boundary, but these were at most modest. The well-dated middle Cenozoic Popigai-Chesapeake impact (Siberia/United States) does not closely coincide with a major extinction. This leads to an obvious question: If dinosaurs and other large land animals survived a number of super-impacts with few or no losses, why did they fail so totally when yet another piece of space debris hit planet Earth?

An important assumption about most K/T extinction scenarios is that dinosaurs were relatively easy to kill off, mainly because they were big. To understand why, we must take a look at how animals reproduce. Organisms can be sorted into two basic reproductive types: K-strategists, and r-strategists. The latter are those that produce large numbers of young, which experience high rates of mortality. Classic r-strategists are many insects and most small mammals. These are "weed" species, in that their high rates of reproduction allow them to achieve very high rates of population growth and dispersal when conditions are favorable enough to let a large percentage of juveniles survive. Because of this reproductive potential, r-strategists can quickly recover from population losses. The r-strategists are, therefore, very hard to kill off, as anyone who has targeted cockroaches and mice for extermination knows too well.

K-strategists reproduce slowly and try to keep juvenile mortality to a minimum, often via intense parental care. Large mammals are classic K-strategists. Because they cannot
churn out numerous young, maximum population growth rates are rather low even under the best of circumstances. Also, big animals are always relatively few in number because each individual eats so much. Another problem for K-strategist mammals is that the young cannot survive without parental care, especially during the nursing phase. This means that a lot of adults must care for a limited number of young.

Dinosaurs were r-strategists par excellence. As far as is known, dinosaurs of all types and sizes laid large numbers of eggs, a dozen or more per season. Therefore, rates of population recovery should have been very high. Although some may have fed their young, especially when they were small nestlings, dinosaurian parental care as a whole was not as intense as in K-strategist mammals and birds. This implies that just a few hundred adults of any particular dinosaur species needed to survive to reestablish their population over a short period. What is extraordinary is that this was true of giant dinosaurs as well as small ones. Ergo, even the biggest dinosaurs were weed species, whose survival and recovery potential was probably far superior to that of giant mammals.

The r-strategy reproduction of dinosaurs helps explain why they were so successful for so long. It is notable that few major dinosaur groups went entirely extinct before the end of the Mesozoic—exceptions being prosauropods and stegosaurs. Otherwise, dinosaur history was a story of accumulative increase in diversity, with older groups continuing to live alongside the new. At no time was there a major “size squeeze,” in which most or all of the large dinosaurs went extinct at the same time, to be replaced by an entirely new set of large forms revolved from small-bodied stock. Sauropods were persistently enormous and diverse for 130 million years. In contrast, K-strategist mammalian giants have not been so successful to date. Uintatheres, arsinootheres, titanotheres, indricotheres, and megatheres have all come and gone within brief spans. Even proboscidians (elephants and extinct related forms) have been extant for only 40 million years.

Another common tacit assumption about dinosaurs is that they were more vulnerable to climatic disruption than mammals. This is a holdover from the traditional view of dinosaurs as reptiles. The presence of dinosaurs in polar regions where reptiles were sometimes absent is especially important in this regard, because it implies that the archosaurs' ability to cope with a postimpact winter should have been better than often assumed. Nor is there reason to believe that the thermoregulation and energetics of the dinosaurs of the end of the Mesozoic were grossly inferior to those of the mammals and birds that survived. Because their energy intake was probably somewhat less than birds, the vulnerability of terrestrial dinosaurs to environmental pollutants should have been less. The large brains and sophisticated sensory systems of advanced theropod dinosaurs offered them the mental agility to adjust to new and adverse conditions. Birds did enjoy an advantage over land-bound dinosaurs. Their ability to fly allowed them to move away from bad local and even regional conditions in search of less odious venues.
There never were dinosaurs like these! But there might have been if just a few of the nonavian examples had not died out 65 million years ago. Perhaps horned dinosaurs would have evolved from surviving protoceratopsids to thunder across the American plains, accompanied by hadrosaurs with the square-tipped bills ideally suited for
cropping the new grasses. All to be hunted by long-legged tyrannosaurs that had lost their useless arms. Horned rodents peer from their burrows, a small ornithopod tries to stay out of the its big relative's way, and geese head north for the summer.
The rapid reproduction and/or sophisticated thermoregulatory abilities of dinosaurs may have been an important reason that they survived a number of Mesozoic super-impacts in good order. Which returns us to events at the K/T boundary. The immediate global result of a super-impact explosion on the scale of Chixculub is the projecting of debris cloud at suborbital velocities around the entire planet within 40 minutes. As the debris reenters en masse, it produces an incandescent, high-altitude pyrosphere that heats up the surface as hot as a kitchen oven for some minutes. This not only has adverse effects upon exposed animals, but it initiates mass forest fires. The atmosphere is massively polluted, a thousand times worse than the harshest modern smog. Sunlight is blocked out for many months, shutting down plant growth and causing a global winter that brings snow to the Equator. Acid rain—especially severe when the impact releases materials locked up in a sulfur-rich carbonate shelf—is so intense that it is corrosive; airborne toxic metals are lethal to nonburrowing animals. Water is also polluted, hence the marine food chain collapses. As the skies clear, high levels of carbon dioxide—again the result of disruption of a carbonate shelf—cause a greenhouse effect that drives global temperatures far above even the Mesozoic norm. Major droughts ensue. Where the K/T impact was most different from other Mesozoic meteoritic explosions was where it occurred. The crater was dug into a sulfur-rich carbonate shelf, a statistically rare event. The extremely high level of atmospheric acidification and the carbon dioxide boost that should have resulted may have distinguished the Chicxulub event from impacts of similar power.

Such conditions should crush animal life. And that is the problem with the scenario. The projected conditions are too severe; things could not have been so bad. We know this because had such conditions been prevalent everywhere, virtually every tetrapod would have been wiped out. Yet viable populations of reptiles, some of them large-bodied, as well as amphibians, mammals, and birds did survive, all around the planet. The survival of amphibians and birds is especially significant. The former are exceptionally sensitive to environmental toxins because their thin skins easily absorb whatever they contact. As for birds, their high metabolic rates have two effects. First, they must constantly breathe large volumes of air and eat lots of food, so their intake of any environmental toxins is rapid and high. Also, they starve quickly when denied food. Birds and amphibians are, therefore, considered key indicators of environmental degradation, whether in mines or the biosphere as a whole. That thin-skinned amphibians and hyper-energetic birds survived the K/T impact shows that the environmental toxin and acid load was not consistently intolerable, and that there was food to be found.

There is additional evidence that the K/T crisis was not as awful as some estimate. In North America, a K/T “fern spike” indicates that almost all of the shrubs and trees were wiped out, to be replaced for a period by colonizing ferns. This may have been the result of the continent being down-range of the majority of blast—a consequence of the
Chicxulub meteorite impacting at a shallow angle from the south. Half of the world’s forests may have burned. But the glass-is-half-full view observes that half of the world’s flora did not burn. Especially in the Southern Hemisphere, where relatively little of the blast was directed and where there is no evidence of significant floral extinctions at the time. The simple presence of heavy cloud cover would have provided an effective local thermal shield against the short-lived pyrosphere, and subsequent rains would have put out many of the fires.

The combined evidence shows that the postimpact environment was not so harsh as to be unsurvivable, and that refuges in which to survive were available for large numbers of tetrapods. Those dinosaurs that happened to be shielded by heavy cloud cover should have survived the initial pyrosphere. Postimpact pollution levels unable to destroy all hypersensitive amphibians and birds should have harmed dinosaurs even less. Sophisticated thermometers were available to cope with unusual climatic fluctuations. Enough flora apparently survived to support viable fauna populations of dinosaurs. Even if most or all r-strategist dinosaur species were nearly decimated, only a few hundred individuals of a given species needed to survive in order to lay the foundations for rapid recovery. It is understandable that some or even most dinosaur species succumbed to the aftereffects of the Chicxulub impact, especially in the Northern Hemisphere where the habitat degradation was most severe. What is not yet explicable is why every single species of terrestrial dinosaur in every part of the world failed to survive when Southern Hemisphere forests survived largely intact. The small birdlike dromaeosaurs and troodonts, big-brained and anatomically sophisticated, could have hunted the small mammals and lizards that survived the catastrophe. Had just a few dinosaurs managed to hang on into the early Cenozoic, they could have been the seeds for a new radiation of terrestrial dinosaurs.

What are the alternatives? Super-vulcanism is superior to an impact as an extinction agent in that its effects are extended over time, causing an attrition effect. On the other hand, repeated extinction events are similar to repeated applications of pesticides: victims tend to develop resistance. In this case, those species that are best able to survive the first event do so, and are not likely to succumb to the next—others occurred without having a marked effect on dinosaurs.

Disease as an explanation for mass extinction of dozens of species suffers from the same problem as repeated eruptions or impacts—the classic Darwinian phenomenon of resistance. It is quite difficult to kill off even all of a single species with disease; the resistant individuals that almost invariably survive are well positioned to make a comeback. Over the last half-millennium, mortality rates among various human (e.g., Amerindian) and animal (wildebeest-rinderpest epidemic) populations have often exceeded 90 percent, but no species has yet gone extinct, and full recoveries have often occurred. Killing off
even a fraction of the dozens or hundreds of dinosaur species via this mode may well be impossible. Besides, birds had been flying across and between the continents and spreading disease among themselves and between other tetrapods for tens of millions of years without disastrous results.

Supposedly, diseases spread like wildfire at the end of the Cretaceous because a global drop in sea level allowed mixing of previously separated faunas. The Mesozoic, especially the Cretaceous, was an era of unusually high sea levels, and the K/T regression was a strong one by the standards of the time. The severity of the drop has caused it to be proposed as the primary cause of the extinction. The problem here is that increasing the total area of land for dinosaurs and birds to live on would probably have helped their fortunes, not hurt them. Some local populations might have been adversely impacted, but arguments that terrestrial dinosaurs collapsed because of continental expansion are too convoluted and based on too few analyses of a few lowland populations to be convincing.

A reproduction-extinction link starts with the observation that some reptiles, including crocodilians, have temperature-dependent sex determination: the sex of the embryo is determined by the temperature at which a particular egg is incubated. Some researchers have concluded that dinosaur sexes probably were temperature-sensitive. They further suggested that fluctuating temperatures at the end of the Cretaceous skewed the sex ratios so badly that these dinosaurs went extinct. The problems with this hypothesis are legion. In many reptiles and birds, sex is genetically determined, and it is entirely possible that the same was true of some or all dinosaurs. But even if dinosaur sex ratios were temperature-dependent enough to be disrupted, it is hard to see how this problem would suddenly wipe out every single dinosaur species after they had been spawning successfully for 150 million years—especially since crocodilians and turtles with temperature-sensitive sex determination survived any temperature fluctuations at the K/T crisis!

This brings us to the matter of climatic change. Climatic change is the classic dinosaur killer, invoked by many a paleontologist since the 1800s. If this notion is so popular, why has it never been accepted as the premiere killing agent? The climate was changing throughout the Mesozoic—one example is the sudden and sharp drop and subsequent rebound in temperature that appears to have occurred well before the end of the Cretaceous, at a time when dinosaurs were increasing in diversity—and the weather change at the end of the era was by no means extreme. There was no onset of an ice age, or long-term super-heating that left even the poles hot in the winter. For that matter, Mesozoic climates were not quite as universally warm and balmy as is usually thought. Winters were probably quite chilly in continental interiors, and there may have even been modest continental glaciation at the south pole. Dinosaurs and birds had long been living and reproducing in climates ranging from polar to tropical, wet forests to desert. As explained earlier in the book, they appear to have had well-developed thermoregulatory
Things were different after the dinosaurs disappeared. This scene shows New Mexico about 7 million years after the great extinction, when mammals were starting to become fairly large. A primitive carnivore, Ancalagon emerges from its burrow as its partner dines on a small crocodilian. Hardwoods formed dense forests for the first time, and the small predator Criacus climbs a trunk while the insectivore Deltotherium scampers along a branch.
systems. Dinosaurs had the option of moving if changing climate in a particular location became a problem. Climatic change appears ill suited to explain the entire collapse of the Dinosauria.

Were dramatic floral changes responsible for the K/T debacle? In the Late Cretaceous, flowering angiosperms displaced conifers, cycad relatives, and ferns as the dominant land flora, but the change had been well underway for tens of millions of years before the end of the Mesozoic. If anything, the new plants were better food sources than the old. They tended to reproduce more rapidly, grow faster, and produce more palatable leaves, larger seeds, and more nutritious fruits. A whole array of dinosaurs and birds evolved along with the new flora, and birds would continue to thrive in the new forests and grasslands of the Cenozoic.

Finally, there are the more exotic, and perhaps crucial, implications of information-processing theory, complexity theory, and chaos theory. Computer simulations of evolutionary trends and processes suggest that chaos-driven instability causes complex species communities to periodically experience self-initiated mass extinctions. It has been shown that a nonlinear response to environmental perturbation, which by itself is insufficient to directly cause a mass extinction, can initiate a runaway effect that does result in the latter. It is the ultimate combination of Murphy’s Law and the snowball effect, in which things quickly go from bad to worse to catastrophic.

Conclusions

Dinosaurs were such a large, diverse, and reproductively potent group that their total extinction at a time when numerous other tetrapods survived remains amazing. To date, the extraterrestrial impact hypothesis is at best incomplete, in that a viable mechanism by which the aftereffects of the impact could destroy the entire Dinosauria—except one branch of Aves—has not yet been demonstrated. Lacking such a mechanism for total extermination, and without confirmation that the Chicxulub event was uniquely powerful, the impact hypothesis cannot be considered wholly verified, although it remains superior to the alternatives. It is possible that it was the combination of events at the time that conspired to do the job. Super-vulcanism and increased disease vectors may have reduced the numbers of dinosaurs. Then an impact that would not have killed off an entire healthy dinosaur population caused the population to crash to minimal levels, leaving a battered remnant that teetered on the edge of extinction or survival, until chaotic instability wiped out the last breeding individuals.