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CHAPTER 4 Demise of the Dinosaurs

Why did the dinosaurs vanish? One popular account is a simplistic story of a colliding object from space as the only cause of extinction. The true story is much more complicated and much more interesting.

This Is the End

Dinosaurs ruled the earth at the end of the Cretaceous Period, about 66 Ma. They did so for more than 120 million years. During all this time, they were preeminently successful around the world. In North America, the Late Cretaceous dinosaurs included the most famous dinosaur, *Tyrannosaurus rex*, as well as the three-horned *Triceratops* and other horned dinosaurs, turtlelike armored ankylosaurs, and lots of different kinds of duck-billed dinosaurs—but very few long-necked sauropods, which we saw in the previous chapter. No sauropods are found in the Upper Cretaceous beds of Montana or Wyoming, and only the titanosaur *Alamosaurus* is known from the Late Cretaceous of the San Juan Basin in New Mexico.

In South America, there are numerous fossil assemblages of latest Cretaceous age, especially in Patagonia. These fossils are very similar to those of other Gondwana landmasses, such as India and Madagascar, but very different from those in North America. In contrast to North America and Asia, there were no horned dinosaurs such as *Triceratops* in South America. Instead of the rare sauropods that we see in North America, there were abundant titanosaurs in South America. Some, such as *Puertasaurus* and *Laplatasaurus*, were not much smaller that the gigantic *Argentinosaurus* from the middle part of the Cretaceous (about 93 Ma). There were also small titanosaurs such as *Neuquensaurus* and *Saltasaurus*, which were only about 13 meters (40 ft) long and weighed only 7 metric tonnes (8 tons), small for a sauropod. These titanosaurs closely resemble those found on other Gondwana continents. Instead of the tyrannosaurs found in Asia and North America, the dominant predators in South America were the horned abelisaur theropods, such as *Carnotaurus*.

Thus, most of the Argentinian dinosaurs were Southern Hemisphere groups that lived across the Gondwana continents, especially Madagascar and India as well as South America. But in the latest Cretaceous, for the first time since Pangea had begun to break up, there were also dinosaurs from the north that reached the Lost World. As in Mongolia and Canada, there were smaller predatory dinosaurs, such as the *Velociraptor* relative known as *Unquillosaurus*. In addition, latest Cretaceous beds in South America yield a diversity of both duck-billed dinosaurs and the turtlelike armored ankylosaurs, both typically found in Mongolia, China, and North America but never seen in South America until the end of the Cretaceous. From this, most scientists have concluded that there was some sort of land bridge between the Americas in the Late Cretaceous, allowing the first exchange between the continents in a very long time—and the last exchange for another 60 million years.

Out with a Bang . . . or a Whimper?

These are the creatures that ruled the earth 66 Ma. Let's look at three possible scenarios for what happened to them at the end of the Cretaceous.

Scenario 1

With no warning, a giant asteroid about 10 kilometers (6 mi) across came hurtling from space at speeds greater than 100,000 miles an hour (160,000 kph). It would have an energy level equivalent to 100 million megatons of TNT. As it approached the earth's atmosphere, it formed a huge fireball in the sky, brighter than the sun, that temporarily blinded the land animals that witnessed it. Shortly after it lit up the sky, the shock wave ahead of it produced a series of incredible sonic booms. Then it slammed into the earth with the energy a billion times stronger than the Hiroshima nuclear bomb. It hit in the spot where the modern Yucatán Peninsula of Mexico is located today. The impact excavated a crater over 20 kilometers (12 mi) deep and 170 kilometers (106 mi) wide, with a flash brighter than any nuclear blast.

The impact caused giant tsunamis to crash around the coastline of the Gulf of Mexico and Caribbean, leaving huge deposits of impact debris and storm waves in places from Mexico to Texas to Cuba and Haiti. Meanwhile, the "mushroom cloud" of dust and debris shot 12,000 meters (40,000 ft) up into the stratosphere, where it created a nuclear winter effect—that is, the dust-choked deep freeze associated with the aftermath of a thermonuclear explosion. The dust circulated around the global stratospheric layer and blocked the sunlight for years, chilling the planet and cutting off photosynthesis by the plants. In one version of this scenario, sulfur from the gypsum located in the Yucatán bedrock created sulfuric acid rain around the globe. Land animals quickly died off, especially the dinosaurs.

In the oceans, the darkness caused the food pyramid based on planktonic algae to collapse, wiping out many organisms higher in the food chain. Especially prominent were the ammonites, shelled relatives of squids and octopuses that looked like the living chambered nautilus. These had survived the previous great mass extinctions in the Permian and Triassic and yet succumbed abruptly at the end of the Cretaceous to the extreme stresses. Widespread death and destruction occurred throughout the oceanic realm, wiping out marine reptiles, many of the clams and snails, and other marine creatures. The end had come with a bang, and it would take much of the next 10 million years of the Paleocene for the planet to recover.

Scenario 2

The second largest volcanic eruption in all of earth history erupted from the mantle during the latest Cretaceous, about 68 Ma, then intensified about 66 Ma. Known as the Deccan lavas, they erupted mostly in what is now western India and Pakistan, in the area centered on Mumbai (Bombay). Huge floods of red-hot lava poured from cracks in the earth and flooded the landscape for more than 500,000 square kilometers (almost 200,000 sq mi), with a volume of 512,000 cubic kilometers (123,000 cubic mi). The volcanoes erupted over and over again, building up a stack of cooled lava flows over 2,000 meters (6,500 ft) thick. Immense quantities of volcanic gases were released from these mantle-derived magmas, including carbon dioxide, sulfur dioxide, and other nasty chemicals. The stratospheric dust and gases blocked the sunlight for a time and led to a global cooling event. The global cooling and dark skies produced the same kinds of death and extinction that the postulated asteroid impact might have produced.

Scenario 3

Global sea level dropped around the world, the biggest sea level drop in the entire Age of Dinosaurs. Apparently, the mid-ocean ridges that produced new oceanic seafloor abruptly began to slow down their eruption and spreading rates, which caused the volume of the mid-ocean ridges to shrink. As the ridges shrank, they displaced less water onto the land and caused shorelines to retreat and huge areas of shallow marine habitat to be exposed to the air and to the erosion of rivers. Most impressive was the loss of the great Western Interior Seaway, which ran from the Arctic to the Gulf of Mexico during the entire Cretaceous. It once teemed with marine life, especially huge mollusks, gigantic fish, and marine reptiles such as mosasaurs, plesiosaurs, and giant sea turtles. The loss of so much shallow marine habitat was devastating to marine life and led to mass extinctions.

Meanwhile, the exposed continental shelves caused a change in the reflectivity of the earth's surface, altering global temperature. There were also big changes in ocean circulation patterns and global wind patterns as the seas retreated and the land was exposed. These complex changes in climate and temperature are still poorly understood, but they meant bad news for the dinosaurs and much of the plankton that had flourished through most of the Cretaceous.

On land, coastal plains and freshwater habitats expanded rapidly as the seas retreated. This was good for freshwater fish, which thrived, but caused mass extinction in the sharks that once swam into the realm of the dinosaurs.

There are three different explanations for mass extinctions at the end of the Cretaceous. Most people have heard only of the first one, the impact scenario, and even many scientists have never heard of the other two, although all three of them are well documented and all three actually happened. Which was most important? What really killed off the dinosaurs?

Serendipity

Many people think that scientific research is about finding a problem and solving it. However, it turns out that most great scientific discoveries are made by accident. More often than not, scientists who discover something important were looking for something else and made their great discovery without planning to do so. We call these lucky accidents *serendipity,* from an old Persian tale named "The Three Princes of Serendip"—the old name for Sri Lanka or Ceylon—whose heroes make discoveries unexpectedly.

There are hundreds of examples of accidental discoveries. Alfred Nobel accidentally mixed nitroglycerin and collodium ("gun cotton") and discovered gelignite, the key ingredient for his development of TNT. Silly Putty, Teflon, Superglue, Scotchgard, and Rayon were all accidents, as was the discovery of the elements helium and iodine. Among drugs, penicillin, laughing gas, Minoxidil for hair loss, the birth-control pill, and LSD were all discovered by accident. Viagra was originally developed to treat blood pressure but later was discovered to be a cure for erectile dysfunction. Great accidents in physics and astronomy include the discoveries of the planet Uranus, infrared radiation, superconductivity, electromagnetism, X-rays, and many others. Two Bell Lab engineers who were trying to eliminate noise from their newly developed microwave antennas accidentally discovered the cosmic background radiation from the Big Bang in the process.

There are also many practical inventions that were stumbled upon by accident, such as inkjet printers, cornflakes, safety glass, Corningware, and the vulcanization of rubber. Percy Spencer was working on surplus magnetrons from World War II for Raytheon, which had built hundreds of them for the war effort and could no longer sell them. When he found that a candy bar in his lab coat pocket had melted, he accidentally invented microwave ovens.

Geologists have also found important things they were not expecting. In 1855, John Henry Pratt and George Biddell Airy were doing routine surveying for the British government in northern India. They noticed that the plumb line weight under the surveying tripod was not as gravitationally attracted to the Himalayas as they had expected, and they eventually discovered the evidence for the deep crustal roots of mountains. The marine geologists who mapped the magnetic anomalies on the seafloor were not looking for the crucial evidence that proved plate tectonics but were simply doing routine data collection of magnetic, bathymetric, and oceanographic data as their ships undertook regularly scheduled voyages of discovery. Maurice Ewing, the founder of Lamont-Doherty Geological Observatory (now Lamont-Doherty Earth Observatory) at Columbia University, gave a standing order that each ship take a deep-sea core at the end of the day, no matter where it was. Many of those cores turned out to have crucial evidence for the history of oceans and climates and the evolution of life.

Likewise, the arguments over the possible causes of the great Cretaceous extinction events were inconclusive until serendipity stepped in. For generations, scientists had been blaming the extinction of dinosaurs on all sorts of ideas, most of which could not be subjected to scientific testing. These included climate change (too warm or too cold), the evolution of flowering plants (except this happened at the beginning of the Cretaceous and may actually have spurred the evolution of duck-billed dinosaurs), mammals eating their eggs (except mammals and dinosaurs both appeared 200 million years ago, so why did they suddenly eat all the dinosaur eggs?), diseases and epidemics (no way to scientifically test this idea), and many other notions. The problem with all these suggestions was not only that they were not easy to test scientifically but also that they focused exclusively on dinosaurs. But the great Cretaceous extinctions also affected the food chain in the oceans, from the planktonic algae to the ammonites to the marine reptiles, and the food chain on land as well, from flowering plants to many other animals besides dinosaurs. Any explanation that focused on dinosaurs alone missed the point. Dinosaurs were a side effect. Clearly, dinosaurs would be affected by any event that disrupted the biosphere from the base of the food chain to the top.

The breakthrough came in 1978, when a young structural geologist named Walter Alvarez was working on some marine limestones in the Apennine Mountains near Gubbio, Italy. (I first met him when he was a postdoctoral student at Lamont, where I was a grad student in the late 1970s.) Walter wanted to find a way to estimate how quickly the sediments that spanned the end of the Cretaceous had been deposited, especially the distinctive clay layer found right at the top of the highest Cretaceous limestone and right below the lowest Paleocene limestones. This level is known as the "KPg" or "KT" boundary to geologists. (The Cretaceous is abbreviated "K" in geological maps, after *Kreide*, the German word for the Cretaceous chalks of the White Cliffs of Dover; "Pg" stands for "Paleogene"; and "T" is short for the now-obsolete term "Tertiary.")

Walter's father, Nobel Prize–winning physicist Luis Alvarez of the University of California, Berkeley, suggested that they might use the rate of accumulation of cosmic dust in these ocean-bottom sediments. If there was lots of cosmic dust, then the sediments had accumulated slowly, but if there was little dust, then it had been quicker. Walter took samples of the rocks all across the KPg boundary (figure 4.2), and they looked for a rare platinum-group metal called iridium as a tracer for cosmic dust. Iridium is relatively abundant in extraterrestrial rocks and in the earth's mantle but rare in the crust.

What they found shocked them. The iridium levels were much higher than anything that could be explained by the gentle rain of cosmic dust.

Figure 4.2. Close-up of the KPg boundary layer at Gubbio, Italy. The gray layers on the bottom are Cretaceous limestones, and those on top are from the Paleogene. The thin layer of clay with the coin on it is the iridium-rich deposit from the KPg impact event (courtesy A. Montanari).

Walter, Luis, and their collaborators Frank Asaro and Helen Michel, geochemists who had measured the iridium at Berkeley, brainstormed their puzzling results. They came up with the idea of an asteroid impact as an explanation for the iridium and extinctions. Their scientific paper finally appeared in 1980, and it has become one of the most cited papers in the history of science. It spurred a stampede of scientists into studying mass extinctions and generated thousands of other scientific papers and many books.

The paper hit the scientific community like the asteroid impact it described. At first, most geologists were skeptical, as any scientific community should be of such wild ideas. Such skepticism also was warranted because there are several ways that rare elements can be concentrated in clay layers like that at the Gubbio KPg boundary. But after finding iridium-rich layers in marine sections in Denmark and many other places, in numerous deep-sea sediment cores, and eventually even in land sections, most scientists had to agree that the Gubbio iridium spike was real and not just a bad data point. In addition, hundreds of scientists looked for additional impact evidence, and soon there were reports of quartz grains with shock features from impacts in the KPg boundary layer, plus blobs of melted crustal rock from the impact site and tsunami deposits all around the Gulf of Mexico. But throughout the controversy in the 1980s, the impact hypothesis was missing one crucial piece of data: Where was the crater?

Meanwhile, other scientists were doing detailed research on the Deccan lava flows of India and Pakistan and pointing out that they would have had many effects similar to an asteroid impact and were reliably dated to just before the KPg boundary. The controversy got to be intense and bitter as hundreds of scientific papers argued one side or another. I could see it every year as I attended the annual meeting of the Geological Society of America (GSA). The GSA meeting brings four thousand to six thousand geologists together for four days, and they give thousands of presentations. A hot topic such as the KPg extinction always guarantees dozens of intensely debated talks and posters each year.

Then, in 1990, a breakthrough occurred. The crater was found deeply buried under the jungle vegetation (and younger sediments) at a site called Chicxulub (pronounced CHICK-zoo-loob), on the tip of Yucatán. Oil geologist Glen Penfield had originally discovered it in 1978, but he did not connect it to the KPg impact idea, which had not yet been published. It took astronomer Alan Hildebrand, who was looking for just such a structure with the impact idea in mind, to track it down, and in 1990 he rediscovered the evidence buried in old oil company reports. This tipped the scales for a while, and most geologists, geophysicists, and geochemists considered the asteroid impact model the only one worth pursuing.

What Do the Fossils Say?

While some earth scientists considered the debate over, paleontologists questioned the asteroid impact model from the beginning. Paleontologists are trained not just in geology but also in biology and are accustomed to the subtle complexity of living systems, with multiple causes and effects. Even before the debate began, they knew that the pattern of extinctions at the end of the Cretaceous was complicated. The impact would produce a sharp, distinct boundary, with all the species dying out precisely at the end of the Cretaceous and not before it. But if a lot of species were declining before the impact or had vanished from the fossil record altogether before the end of the Cretaceous, then the impact model was less important, and other factors might be more influential. The gradual deterioration of the environment by the continual eruption of the Deccan lavas might prove to be more significant, as could the fall in sea level.

During the 1980s and 1990s, paleontologists continued to document the patterns of extinction in both land and marine animals and plants and to determine whether extinctions were instantaneous or followed a more complex pattern (figure 4.1). Now, four decades after the asteroid impact model was first proposed, the pattern of extinctions is far more complicated than can be explained by a single extinction event triggered by impact.

First, let's look at extinctions in the marine realm. The most important species are the plankton, which are the crucial base of the marine food chain and extremely sensitive to environmental changes. Their tiny shells can be found by the thousands in deep-sea sediment cores, so we can study their extinction in fine detail. The planktonic algae known as coccolithophorids, the algae that make chalk, did indeed have a severe crash, as would be expected if the light was dimmed by dense dust clouds, but two other kinds of algae, diatoms and silicoflagellates, which are equally sensitive to the loss of light, did not. Two groups of shelled amoebalike plankton were also studied. The group known as the foraminiferans seemed to show a crash (although some micropaleontologists argued differently), but the other group of planktonic amoebas, the radiolarians, did not. Some foraminiferans lived on the sea bottom rather than in the plankton, and they showed no extinction at all.

Moving up the food chain, we can look at the fossilized shells of the mollusks (clams, snails, and their kin) that once inhabited the Cretaceous seafloor. Some groups, such as the big, flat "dinner-plate" clams known as inoceramids (which reached 1.7 meters, or 5 feet, in diameter) and the conical reef-forming oysters known as rudistids, were extinct long before the end of the Cretaceous, so the impact is irrelevant to them. Of the remaining mollusks, 35 percent of snails and 55 percent of clams and oysters died out, but every study shows their extinction was gradual through the end of the Cretaceous.

Critical to this debate are the rapidly evolving ammonites. They had survived every previous mass extinction since the Devonian. Most studies suggested that ammonites died out slowly through the Cretaceous, with only a few species that survived to near the KPg boundary. On Seymour Island on the Antarctic Peninsula, just south of Chile and Argentina, Bill Zinsmeister has documented a long, protracted extinction in the ammonites through the Upper Cretaceous rocks there (figure 4.3).

The rest of the marine invertebrates—corals, lamp shells, bryozoans, sea lilies, brittle stars, sea urchins, and the like—show either no effect of the KPg event at all or only a gradual extinction through the interval. At the top of the food chain are the marine reptiles, especially the giant marine lizards known as mosasaurs. Their fossil record is not complete enough to show whether they were even around to witness the rock from space, but most of the data suggests that they were dying out long beforehand.

In summary, the only sea creatures that show an obvious abrupt effect consistent with the asteroid impact model are some (but not all) of the plankton. The rest of the marine realm appears to be deteriorating slowly throughout the Late Cretaceous, consistent with the effects of volcanic gases and climate change, as well as the falling sea level exposing most of the shallow marine habitat.

What about the land record? Here the answer is complex and confusing as well (figure 4.1). At the bottom of the food chain are the land plants,

Figure 4.3. William Zinsmeister of Purdue University, seen at his field tent, surrounded by ammonites, in the early 1980s. He collected huge numbers of fossil ammonites from the KPg transition on Seymour Island, Antarctica. They show a gradual pattern of extinction, not the abrupt mass extinction suggested by the impact model. (Photograph courtesy W. J. Zinsmeister.)

and there is certainly a striking change in the leaf fossils across the KPg boundary. In addition, the spores and pollen in these sediments suggest a high abundance of ferns growing in the dark, cool aftermath of the impact, consistent with some aspects of the nuclear winter model of the impact. But the rest of the land fauna shows a complex pattern. Sure, the non-bird dinosaurs vanished, but whether it was sudden or gradual is disputed because their fossil record is so incomplete. A study published just as this book went to press shows that the dinosaurs were declining long before the end of the Cretaceous, and only a few species remained to witness the asteroid. There are suggestions that many of the groups of Cretaceous birds vanished, but the fossil record is not good enough to tell whether it was abrupt and precisely at the KPg boundary or gradual.

The reptiles, especially the crocodilians, lizards, snakes, and turtles, sailed right through the impact event with only minimal extinction—and some of those crocodilians were bigger than smaller dinosaurs. If the entire planet was as hellish as the impact suggests, how did the large crocodiles survive while no dinosaurs of their body size did so? Unlike small animals, crocodiles cannot hide from the effects of the impact or go into hibernation with no warning. In fact, given the warm greenhouse climate of the Late Cretaceous, it's unlikely that crocodilians hibernated at all.

Although there was a minor extinction in sharks (consistent with the loss of marine seaways and expansion of freshwater habitats), more than 90 percent of the freshwater fish survived. The tiny shrew-sized mammals showed some changes in dominance. For example, the pouched opossum-like mammals known as marsupials were replaced by placentals in some places like Montana, and groups such as the squirrel-like egg-laying mammals known as multituberculates did fine in Montana but not in China. Nevertheless, there were only a few extinctions among the mammals. Nearly all of South America's peculiar Mesozoic mammals, including their Jurassic relicts such as the unique dryolestoids and gondwanatheres, survived well into the Cenozoic. In short, the land record does not strongly support the impact-only model of extinction. Only the land plants show a clear, abrupt effect, and the rest of the groups other than dinosaurs did just fine through the supposedly extreme climates of the nuclear winter and came right back in the Paleocene no worse for wear. This casts serious doubt on any model that is too extreme. In particular, any scenario that argues for a global bath of sulfuric acid rain can be discarded right away, because amphibians went through the KPg events without any extinctions. Yet they are extremely sensitive to even small amounts of acid in their habitat, and there would be no frogs or salamanders alive right now if the acid rain scenario were true.

What Is the Answer?

The debates over the Cretaceous extinctions are not just about what killed the dinosaurs. They reveal a bigger theme in the sociology of science and the nature of science communication today.

First, they are a classic demonstration of the problem of communicating science to the public. Nearly all science is reported as one-sided sound bites, with no details, doubts, caveats, or nuance, and crucial information is often left out. In addition, flashy science headlines often prove to be wrong once other scientists look closer and double-check the results. Yet the media rarely report that a sensational study covered years earlier has since been debunked. Consequently, the public learns only the spectacular headlines ("asteroids killed the dinosaurs") and never finds out that the story is more complex, with multiple possible causes.

In the scientific community, things are different. Scientists are capable of going behind the headlines, checking the data, and patiently waiting for years until all the studies have been done and the bad data abandoned and the answer starts to become clear. The KPg debate has brought out another interesting phenomenon: the contrast among different scientific communities. The impact advocates are overwhelmingly found among geologists, geochemists, geophysicists, planetary scientists, and especially those scientists who know no geology or paleontology at all. Many of them are used to plugging samples into a machine and getting simple yes-or-no answers in their science. They like clear-cut results—even if they might be too simplistic.

Paleontologists, on the other hand, are trained in biology, where the systems are typically complex, nuanced, and interrelated and very few things occur in a simple fashion. From the very beginning, they argued with other geoscientists that the pattern of extinction did not match the simplistic idea of a "rock from space" doing everything. Their argument has not abated even four decades later. When vertebrate paleontologists who study the dinosaurs and mammals were polled in 1985, only 5 percent agreed that the impact was the cause of the KPg extinctions. In 1997, a survey of twenty-two distinguished British paleontologists, specialists in each of the groups that lived in the Late Cretaceous, voted overwhelmingly against the impact being significant in the marine fossil record. In 2004, another survey of vertebrate paleontologists found that only 20 percent accepted the impact cause for the KPg extinctions, whereas 72 percent argued that it was a gradual process inconsistent with the asteroid model. In 2010, a paper was published in the eminent journal *Science* with multiple authors, few of whom were paleontologists, again pushing the impact as the sole explanation of the KPg extinctions. It was immediately rebutted by a paper authored by twenty-eight paleontologists that demonstrated that the impact was only a minor part of the story. Even Walter Alvarez, in his popular book *T. rex and the Crater of Doom*, conceded that the KPg extinctions had multiple complex causes.

You see the battles in the professional meetings as well. During the 1980s and 1990s, nearly every meeting of the GSA had several sessions devoted to the KPg debate. By the mid-1990s, it seemed like the impact advocates had won. The tide has shifted again, and during the 2014 GSA meeting in Vancouver, Canada, there was a daylong symposium emphasizing the importance of the Deccan volcanoes and how they better explained most of the KPg extinctions. These battles can be very tense and emotional, since many scientists are not just dispassionately arguing about events from 66 Ma. They have a lot at stake. They are deeply invested in their research program, which has meant years of study and writing and publication and thousands of dollars in grant money. It is not easy to back down from a position once you have defended it in print and in front of your colleagues for years. Thus, the extremists on both sides will continue to argue, and thirty-six years is not long enough for the battle to die out completely, even though neutral outside observers see a complex pattern of multiple causes for the KPg extinction, not the simplistic "rock from space" model.

We often forget that scientists are human. Sometimes individual scientists make their research a personal quest and even insult the other side. The scientific papers on the subject often contain direct attacks on scientific credibility and competence of opponents. At professional meetings, the name-calling was even worse. Careers were ruined by being on the wrong side of the debate, and others suffered enormously as the big boys battled it out. Luis Alvarez said, "I don't want to say bad things about paleontologists, but they're really not very good scientists. They're more like stamp collectors." On the opposite side, paleontologist Bob Bakker told a reporter,

> The arrogance of these people is simply unbelievable. They know next to nothing about how real animals evolve, live, and become extinct. But, despite their ignorance, the geochemists feel that all you have to do is crank up some fancy machine and you've revolutionized science. The real reasons for the dinosaur extinctions have to do with temperature and sea level changes, the spread of diseases by migration and other complex events. In effect, they're saying this: we high-tech people have all the answers, and you paleontologists are just primitive rockhounds.

Indeed, there is no simple final answer. The impact happened. So did the Deccan eruptions. So did the huge drop in sea level. Most of the evidence suggests that the world of the latest Cretaceous was already extreme and hellish from the effects of volcanic gases and climate changes, especially in the oceans. These events must have been too much for the inoceramids, the rudistids, the marine reptiles, and many other animals and plants that vanished well before the rock from space arrived—possibly even the dinosaurs.

When the impact occurred, it was more of a coup de grâce for some of the stressed-out survivors of the environmental deterioration. It definitely had an effect on the planktonic algae and foraminifera and on the land plants. But the impact could not have produced huge amounts of acid rain, or there would be no amphibians today. It could not have been as extreme as Scenario 1, mentioned earlier in the chapter, suggested, or there would have been some effect on the crocodilians, turtles, lizards, snakes, mammals, freshwater fish, and nearly everything else on land at the time.

When someone asks me, "Did an asteroid wipe out the dinosaurs?" I say, "Yes. And no."

The Aftermath

South America is not the place to study the KPg boundary on land, because most of the fossiliferous areas in Argentina and elsewhere were underwater at the end of the Cretaceous. There are no good fossiliferous terrestrial sections that span the KPg boundary anywhere on the continent, and the youngest Cretaceous dinosaur faunas, which are dominated by titanosaurs and *Carnotaurus*, plus immigrant duckbills and ankylosaurs from the north, lived long before the end of the Cretaceous.

Then there is the peculiar locality known as Laguna Umayo in southern Peru. When it was first studied in the 1970s and 1980s, it appeared to have dinosaur eggshell fragments and pollen from Cretaceous plants associated with Paleocene mammal fossils, including some primitive marsupial teeth and peculiar isolated molars of a hoofed mammal named *Perutherium*. Was it proof that dinosaurs survived into the Paleocene in South America before they finally vanished, long after they had disappeared in the Late Cretaceous elsewhere? The poor quality of the fossils and the difficulty of dating the locality left the question unresolved for many years. Finally, in 2004 a careful study of all the fragmentary fossils using the latest dating techniques showed that the locality was Paleocene after all, but the "dinosaur eggshells" and "Cretaceous pollen" had all been misidentified.

There are other, more fossiliferous early Paleocene localities across South America, and they give us the first glimpse into what survived the KPg catastrophe. The best known of these are near Tiupampa in Bolivia and Punta Peligro in southern Argentina. They are dominated by two of the three "Old Timer" groups that came to dominate South America through the rest of the Cenozoic, as we will see in chapters 7–9. Most of the fossils are of different groups of marsupials related to opossums. By the Eocene, these creatures would evolve to fill the meat-eater niche, with marsupials that resembled wolves, hyenas, and even saber-toothed cats. Other fossils are of very archaic hoofed mammals, much like the early Paleocene mammals known as mioclaenids from North America. These creatures would eventually evolve into the native hoofed mammal groups, the second group of Old Timers that dominated South America until about 2 Ma. The similarity between North and South American mioclaenid hoofed mammals suggests that the Late Cretaceous land bridge that allowed duckbills and ankylosaurs down from North America was still in operation in the earliest Paleocene.

This is further confirmed by the presence of fossils known as *Alcidedorbignya*, named after the early-nineteenth-century French paleontologist Alcide d'Orbigny. These specimens closely resemble fossils of a group of heavy-bodied, leaf-eating ground mammals known as pantodonts. They were mostly dominant in China and Mongolia and in western North America in the Paleocene, but apparently at least one lineage was able to migrate south to reach Tiupampa, probably via the land bridge that allowed the Late Cretaceous duckbills and ankylosaurs from North America and Mongolia to reach Argentina. These mammals were among the survivors of the great KPg catastrophe, and they formed the foundation for mammal evolution in South America for the next 65 million years.

They were not the only survivors. One group of dinosaurs also survived, and it dominated the mammals of South America for most of the next 50 million years—just as dinosaurs had done for the first 120 million years of their shared history with mammals. Who were these surviving dinosaurs? They are alive today. We know them as birds.