T. rex

AND THE CRATER

OF DOOM
Armageddon

But it was too late. At that moment the rock quivered and trembled beneath them. The great rumbling noise, louder than ever before, rolled in the ground and echoed in the mountains. Then with searing suddenness there came a great red flash. Far beyond the eastern mountains it leapt into the sky and splashed the lowering clouds with crimson. In that valley of shadow and cold deathly light it seemed unbearably violent and fierce. Peaks of stone and ridges like notched knives sprang out in staring black against the uprising flame in Golgoth. Then came a great crack of thunder.

—J.R.R. TOLKIEN, The Lord of the Rings

REQUIEM FOR A LOST WORLD

Try to imagine a different world—different from the one we live in. Not wildly different, like the settings of science fiction stories which take place on airless planets or in giant spaceships. We are looking for a world much like our own, but different in subtle ways. J.R.R. Tolkien described such a world in The Lord of the Rings—with mountains, swamps, and plains like ours, but with a slightly different geography—much like Europe, but not quite the same. Tolkien’s “Third Age of Middle Earth” has familiar inhabitants like humans and horses, but other creatures that we know well, like dogs and cats, are missing. Middle Earth also has unfamiliar inhabitants—dwarves, elves, wizards, and hobbits. It is terrorized by the merciless, sharp-clawed goblins called orcs. Tolkien’s world seems ancestral, or perhaps alternative to ours.
The world we seek is reminiscent of Tolkien’s Middle Earth. It has mountains, deserts, forests, and oceans, arranged in a geography that is something like our Earth, yet noticeably different. It has rivers and canyons, plateaus and sand dunes. It has cloudbursts in the mountains, and glowing sunsets in the clear air after a thunderstorm. Some of the inhabitants seem familiar, though not exactly like the ones we know. Evergreen trees and deciduous trees shade the landscape, and the streams are full of fish. But the ground is bare of grass, and the animals look different. Little furry ones are recognizable as mammals. But there are also giant creatures, some placidly grazing while others hunt, with claws as terrifying as those of any orc in Middle Earth.

This world is different from ours, but it is familiar through museum reconstructions, paintings, and films. For this is not the Third Age of Middle Earth, but rather the Third Period of Middle Life. Geologists use the term Mesozoic, or Middle Life, for the Age of Dinosaurs. The third period of the Mesozoic was the Cretaceous, following the Triassic and the Jurassic periods.

More precisely, the world we are imagining was the very end of the Cretaceous, 65 million years ago. It was ancestral to our modern world, with a geography that was different but still familiar, because continental drift since then has moved the Earth’s land masses around but has not completely rearranged them. India had not yet collided with Asia to thrust up the Himalayas, but there were already mountains in western North America. Sea level was higher than today, and part of the interior of North America was covered by a shallow sea.

Not only was that world ancestral to ours, it was in some sense alternative as well. For it was a stable world. Despite the violent hunting of the carnivorous dinosaurs and the oft-depicted dramatic battles between *Tyrannosaurus rex* and *Triceratops*, life patterns and the inhabitants themselves had changed only slowly during the previous 150 million years. The dinosaurs were very successful large animals and shared their world with equally successful small animals and with plants of all kinds. There is every reason to believe that if it had remained undisturbed, the Mesozoic world could have continued indefi-
nately, with the slightly evolved descendants of the dinosaurs dominating a world in which humans never appeared.

But the Mesozoic world did not remain undisturbed. It ended abruptly, and with no warning, 65 million years ago. Vast numbers of highly successful animal and plant species suddenly disappeared in a mass extinction, leaving no descendants. This break in the history of life is so impressive that geologists use it to define the boundary between the Cretaceous, or last period of the Mesozoic, and the Tertiary, or first period of the Cenozoic. Today’s world is populated with descendants of the survivors of the mass extinction that ended the Cretaceous world.

Looking back across the abyss of time which separates us from the Cretaceous, we can somehow feel nostalgia for a long-lost world, one which had its own rhythm and harmony. We feel a special sadness when we think about its plants and animals, fish and birds—for most of the Cretaceous animals and plants are irremediably lost. We can even feel some sorrow as we imagine the sun setting over a western ocean, painting the clouds with orange and red and yellow and gold, on the last evening of that world. For the Cretaceous world is gone forever, and its ending was sudden and horrible.

**THE APPROACH OF DOOM**

Doom was coming out of the sky, in the form of an enormous comet or asteroid—we are still not sure which it was. Probably ten kilometers across, traveling tens of kilometers a second, its energy of motion had the destructive capability of a hundred million hydrogen bombs. If an asteroid, it was an inert, crater-scarred rock, dark and sinister, invisible until the last moment before it struck. If a comet, it was a ball of dirty ice, spewing out gases boiled off by the heat of the Sun, and it announced impending doom with a shimmering head and a brilliant tail splashed across half the sky, illuminating the night, and finally visible even in the daytime as Armageddon approached. Let us think of it as a comet, remembering that perhaps it was an
asteroid instead. Comets have been mistakenly interpreted by humans in times past as harbingers of doom, foretelling famine, plague, and destruction. Although no humans were there to witness the giant comet of 65 million years ago, in this case it really did portend disaster.

The Solar System abounds in comets and asteroids, some even bigger than the one which was nearing Earth on that day 65 million years ago. Most asteroids remain in a belt between Mars and Jupiter, and most comets orbit the Sun far beyond distant Pluto. Occasionally, however, an asteroid has its orbit deflected by Jupiter’s gravitational pull, or a comet orbit is altered by the gravitational tug of a passing star. A few of these asteroids and comets are diverted into orbits which cross that of the Earth. An impact occurs when such an object intersects the Earth’s orbit just as Earth happens to be at the crossing point. This is what is going on every time you see a shooting star flashing across the night sky. Those streaks of light are due to tiny fragments of comets or asteroids burning up through friction in the Earth’s atmosphere. Somewhat larger objects, the size of a fist, are too big to burn up completely in the atmosphere, but are slowed down enough to survive their impact on the Earth’s surface. These objects are the meteorites displayed in museums and studied by geologists interested in extraterrestrial rocks.¹

Large impacts can also happen, and they were frequent in the early history of the solar system, as witnessed by the ancient, crater-scarred face of the Moon. But large impacts are rare nowadays, because the debris that was abundant in the early solar system has been swept up by the planets, large Earth-crossing comets and asteroids are now rare, and Earth is a very small target. To see how small, look at Venus just after sunset, when it is the “evening star.” Venus is the size of the Earth, and from our distance it is a tiny, although brilliant, dot in the sky—a very difficult target to hit.

Earth is protected, therefore, by the fact that large comets and asteroids rarely come into the inner Solar System, and those that do are unlikely to hit something as small as our planet. So we can imagine the giant comet of 65 million years ago coming
close to the Earth again and again, over a period of centuries or
millenia, as it orbited the Sun—sometimes far from Earth, some-
times close enough to put on a spectacular display in the night
sky. A set of near misses like this must take place every now and
then in Earth history, but usually the comet hits the Sun or an-
other planet, or is deflected out of the inner Solar System. In this
particular case, however, there came a time when the invader’s
orbit intersected that of Earth just as both were approaching the
intersection point. This time there would be no escape. The
comet was aimed toward the southern part of North America—
toward the shallow seas and coastal plains which are now the
Yucatán Peninsula of Mexico.

THE MEASURES OF DESTRUCTION

It is very difficult to appreciate the impact that
was about to occur, because such an extreme event is far beyond
our range of experience—for which we can be most grateful!
One can write down the measures of what happened—an object
about 10 km in diameter\(^2\) slammed into the Earth at a velocity
of perhaps 30 km/sec\(^3\). But these measures only acquire mean-
ing when we try to visualize them, or make analogies to help
our understanding. How can we imagine a comet 10 km in
diameter? Its cross section about matches the city of San Fran-
cisco. If it could be placed gently on the surface of the Earth it
would stand higher than Mount Everest, which only reaches
about 9 km above sea level. Its volume would be comparable to
the volume of all the buildings in the entire United States. It
was a big rock, or a big ice ball, but not of a scale beyond our
comprehension.

What turned it into a cataclysmic weapon was its velocity.
The estimated impact velocity of 30 km/sec is 1,000 times faster
than the speed of a car on the highway and 150 times faster than
a jet airliner. It is about 6 times faster than the speed of seismic
waves in rock. When a collision takes place at velocities this
high, our experience is not a useful guide, and rock materials do
not behave in the ways we are used to. Instead, a shock wave is produced—a kind of sonic boom in the rock. The shock wave from such an impact crushes and compresses the impactor and target rock so intensely that after the shock passes, the decompressing rock will fly apart, or melt, or even vaporize. The concept of rocks instantaneously boiling away to vapor conveys a gut feeling for the extraordinary and violent conditions during an impact.

Scientists immediately ask about the energy of the approaching object, because energy is Nature’s currency, a measure of the ability to move things around and bring about changes. Nature runs a kind of automatic bookkeeping system for energy transfers, requiring that the energy of motion of the incoming comet be fully accounted for in all the kinds of damage done during the impact. When we do the bookkeeping, we find that the energy of motion of the comet just before impact was equivalent to the explosion of 100 million megatons of TNT, sufficient to vaporize the comet in about 1 second and to blow out a hole in the ground which was briefly 40 km deep but quickly collapsed into a broader, shallower crater 150–200 km across. To get a feeling for this quantity of energy, keep in mind that one large hydrogen bomb has a yield of about 1 megaton of TNT, and that the total nuclear arsenal of the world at the peak of the Cold War was about 10,000 such bombs. The $10^8$-megaton impact of the comet which ended the Cretaceous was therefore equivalent to the explosion of 10,000 times the entire nuclear arsenal of the world (although the impact explosion was not nuclear).

Returning to the 10-km-wide comet as it approached the Earth at 30 km/sec, we can get a feeling for how fast the event happened. An airliner flies at an altitude of about 10 km, so imagine a plane unfortunate enough to be in the way of the incoming comet. In an instant the airplane would be smashed like a bug by the onrushing body. One-third of a second later the front of the comet, carrying the insignificant aircraft wreckage, would hit the ground, generating a blinding flash of light and initiating shock waves in the comet and the ground, and after another $\frac{1}{3}$ second the back end would be passing below ground
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level. By one or two seconds after the loss of the airplane, there would be a huge, growing, incandescent hole in the ground and an expanding fireball of vaporized rock, and debris ejected by the explosion would be clearing the atmosphere on its way to points around the globe. Earth would suffer cataclysmic damage in less time than it takes to read this sentence.

Now that we have some sense of the scale of the impact that ended the Cretaceous world, let us look at our current, imperfect understanding of just what happened.

THE MOMENT OF IMPACT

The comet approaching Earth 65 million years ago first encountered the tenuous air many kilometers above the surface. About 95 percent of the atmosphere lies below an altitude of 30 km, so depending on the velocity and the angle at which the impactor approached the surface, it would have taken only a second or two to penetrate most of the atmosphere. The air in front of the comet, unable to get out of the way, was violently compressed, generating one of the most colossal sonic booms ever heard on this planet. Compression heated the air almost instantaneously until it reached a temperature 4 or 5 times that of the Sun, generating a searing flash of light during that one-second traverse of the atmosphere.

At the instant of contact with the Earth’s surface, where the Yucatán Peninsula now lies, two shock waves were triggered. One shock wave plowed forward into the bedrock, passing through a three-kilometer-thick layer of limestone near the surface, and down into the granitic crust beneath. The onrushing shock wave drove forward through the bedrock, crushing shut all cracks and pore spaces and destroying much of the orderly crystal structure of minerals.

Meanwhile, a second shock wave flashed backward into the onrushing comet. Reflecting off the back of the impactor, it tore apart the trailing edge of the comet. In the second or so it took for this to happen, the comet ceased to be recognizable as a
spherical body. With its enormous momentum driving it forward, the comet penetrated deep into the Yucatán bedrock, forcing open a huge hole and molding itself into an incandescent coating on the inside of the growing hole, which was now opening out into an expanding crater. But the comet coating on the inside of the crater did not last more than a moment before it was mostly vaporized, along with much of the original target rock.

As the rapidly vaporizing comet wreckage was carried forward into the growing crater, the shock wave curved back up to the surface and spewed out ejecta—melted blobs and solid fragments of target rock—upward and outward on high, arching trajectories that flung them through the thin outer fringes of the atmosphere and beyond. Falling back to Earth within a few hundred kilometers of the rim of the crater, this debris built up a vast blanket of ejecta.

Even this did not exhaust the pyrotechnic potential of the impacting comet. The huge cloud of vaporized rock generated at ground zero was driven outward by its own heat and pressure in a colossal fireball. The explosion of a nuclear bomb—tiny by comparison—produces a hot-gas fireball which flashes outward to a diameter of a kilometer or so, until it can push no farther against the atmospheric pressure, and then floats upward to an altitude of 10 km where it spreads out into a mushroom cloud. The incomparably greater fireball of the Yucatán impact overwhelmed the atmosphere, blowing right through the entire blanket of air, expanding and accelerating out into space and launching particles of rock into trajectories which carried them far around the Earth before they fell back to the ground.

And still the fireworks continued. Even as the scorching fireball of rock vapor blew away into outer space, it was followed by a second fireball, not as hot, but almost as dramatic. For about three kilometers down from the surface, the Yucatán was covered with a thick layer of limestone. Limestone is Nature’s way of storing carbon dioxide gas as a solid, by combining it with calcium. Shocked limestone suddenly releases its stored CO₂, and in an impact as large as this, enormous quantities of
this gas were almost instantaneously released like popping the cork on a colossal bottle of champagne. Still more rock debris was carried aloft in this second exploding gas ball as it, too, blew through the atmosphere and into outer space.

Meanwhile, the expanding crater had reached its maximum depth of perhaps 40 km. This hemispherical “transient cavity” was far too deep to be supported by the relatively weak rock of the Earth’s crust, and the center began to rise, even as the perimeter continued to expand. While the steep outer walls collapsed in giant landslides, deep rocks from the mantle, below the granitic crust, rebounding after the passage of the shock wave, rose upward faster and faster into a central peak like those preserved in many craters on the Moon. The central peak of the Yucatán crater was so large and high that it in turn collapsed downward, driving outward into a set of ringlike ridges which left a pattern resembling a bull’s-eye imprinted on the Earth to mark the site of this cataclysmic event.

**THE RING OF DEVASTATION**

In the zone where bedrock was melted or vaporized, no living thing could have survived. Even out to a few hundred kilometers from ground zero, the destruction of life must have been nearly total. Sterilized by the intense light from shock-compressed air and from the fireball of rock vapor, crushed when pores and cracks in rock were slammed shut by the passing shock wave, and bombarded by the falling debris of the ejecta blanket, little or nothing was left alive in this central area.

Out to a few thousand kilometers, into the area of modern Mexico and the United States, the Yucatán impact sent dramatic messengers of destruction. Animals living just over the horizon first witnessed a flash of light in the sky, then a last moment of calm. Then, as the ground began to shake uncontrollably from the passing seismic waves, the sky itself turned lethal. Beginning with a faint glow, the sky grew more and more intensely
red, passing into incandescence, growing brighter and brighter, hotter and hotter. Soon the Earth’s surface itself became an enormous broiler—cooking, charring, igniting, immolating all trees and all animals which were not sheltered under rocks or in holes. This fearsome phenomenon was produced by ballistic ejecta particles blasted into space by the impact, which were now falling back to Earth, reentering the atmosphere, heating up through friction with the air, and transmitting that heat to Earth as infrared light. Only places which happened to be shielded by thick storm clouds would have avoided this lethal heat. Entire forests were ignited, and continent-sized wildfires swept across the lands. The ejecta particles had barely fallen to Earth and the lethal, incandescent sky returned to normal, when the air was blackened by rising plumes of soot from fires which were consuming the forests and removing the oxygen from the atmosphere.

Even as the forests were set ablaze, another horror was approaching the coasts of the Gulf of Mexico. The impact occurred in the shallow water and coastal plains which flanked the Gulf, but it produced a huge disturbance in the waters of the deep Gulf, through seismic shaking, submarine landslides triggered by the seismic waves, and by the splashdown of the ejecta blanket. The result was a gigantic tsunami—a massive wave perhaps a kilometer high, which spread outward across the Gulf of Mexico at terrific speed. Everyday waves do not disturb the bottom of deep seas like the Gulf, which are the quietest, calmest places on Earth. But the impact tsunami was so enormous that its keel swept across the bottom of the Gulf, digging channels into the fine sediments of the sea floor, and mixing them with the impact debris which had just fallen. As the tsunami front reached the shallow water of Florida and the Gulf Coast, it was pushed up higher and higher into a wall of water that towered above the shoreline. As this deluge crashed onto the coast, it not only ripped apart whole forests, but it shook the continental margin so violently that huge volumes of sediment were mobilized into submarine landslides which flowed down into the deep Gulf, burying the impact debris which had only just fallen.
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Within hours of the impact, most of Mexico and the United States must have been reduced to a desolate wasteland of the most appalling, agonizing destruction. Where only the day before there had been fertile landscapes, full of animals and plants of all kinds, now there was a vast, smoldering netherworld, mercifully hidden from view by black clouds of roiling smoke.

Farther away from the Yucatán, the effects were less dramatic. The giant tsunami was largely confined to the enclosed Gulf of Mexico and could not reach Asia, Africa, or Europe. Ejecta particles rained down around the world, but fewer particles traveled to more remote areas, so the firestorms may not have been as intense as in North America. In contrast to the largely sterilized regions close to ground zero, distant continents may have escaped the direct effects of the Yucatán event. Tragedy would unfold more slowly in these remote areas, through the secondary effects of the impact.

THE HORSEMEN OF THE APOCALYPSE

Terrible as the immediate, direct effects of the impact were in the surrounding region, they probably would not by themselves have caused the disappearance forever of whole families of plants and animals, because survivors in remote regions would have repopulated the devastated regions in the years to come. And yet an enormous mass extinction did follow the impact, and we now understand some of the longer-term global disasters which were secondary results of the impact. Let us review these Horsemen of the Apocalypse in their order of appearance.

Within days of the impact, the immediate effects had died down. The fires were probably going out, the tsunami had spent its main strength against the coast of the Gulf of Mexico, and violent winds were settling down. But the Earth was turning cold and dark. Vast quantities of fine dust had burst through the atmosphere in the fireball and the dust was now settling through the upper atmosphere around the world, blocking the
sunlight. The land became so dark that you could not have seen your hand in front of your face, and this darkness and the accompanying cold probably lasted for a few months, until finally most of the dust had settled to the ground.\textsuperscript{8}

But after the return of light, the climate went to the opposite extreme. Two greenhouse gases—water vapor and carbon dioxide—had been released in vast quantities from the site of the impact. The water vapor was probably removed quickly from the atmosphere as rain which washed out the dust. Carbon dioxide can only be removed slowly from the air, and now it trapped the heat from the Sun, raising temperatures to sweltering levels. It was probably thousands of years before the carbon dioxide was back to normal levels.

Not only were water and dust raining out of the atmosphere, but there was also a devastating acid rain.\textsuperscript{9} Some of this may have been sulfuric acid derived from sulfur in anhydrite, a sedimentary rock interbedded with the limestones of the Yucatán. But much was nitric acid, originating from the atmosphere itself. The air we breathe is about 20 percent oxygen and most of the rest is nitrogen. Normally these occur as two-atom molecules of oxygen, O\textsubscript{2}, and of nitrogen, N\textsubscript{2}. Nitrogen forms very stable molecules which are tightly bonded together. Only when the air is strongly heated are the N\textsubscript{2} molecules broken up, allowing some of the nitrogen to combine with oxygen as molecules of nitrous oxide, NO. This happened on a grand scale during the impact event when the air was heated by shock waves, by the fireball, and by the friction of reentering ejecta. Vast quantities of nitrous oxide were formed, which reacted with oxygen and water vapor in the atmosphere to form nitric acid, HNO\textsubscript{3}, which rained out of the sky, killing plants and animals and dissolving rocks.

A world first dark and frozen, then deadly hot, a world poisoned by acid and soot. This was the global aftermath of the Yucatán impact. We wonder how anything could survive this environmental apocalypse. Yet there were survivors, and their descendants populate the world today.
VICTIMS, SURVIVORS, AND DESCENDANTS

By the time the physical devastation caused by the impact had faded, years or centuries after the event, Earth’s biosphere was changed forever. Whole groups of plants and animals had disappeared, never to be seen again. By one estimate, half of the genera living at the time of the impact perished. This was one of five great biological mass extinctions we know of in Earth’s past. It is very difficult to learn what caused the loss of any particular group of plants or animals. Some reasonable inferences have been made, but in many cases we will probably never know with certainty. It is easier to construct the list of victims and survivors.

Best known of the victims, of course, are the dinosaurs. T. rex and the other huge carnivores perished, as did the herbivorous dinosaurs, as well as their relatives who swam, like the mosasaurs, or flew, like the pterodactyls. Most paleontologists now consider that modern birds are very closely related to the dinosaurs which, in this sense, did survive the end of the Cretaceous. Yet recently discovered fossils are revealing that birds were nearly wiped out as well.

The loss of the dinosaurs is probably related to their position in the food chain, with herbivorous dinosaurs eating vegetation and carnivorous dinosaurs eating herbivores and perhaps small mammals. During the months of cold and darkness cast by the pall of dust in the atmosphere, plants would wither and the herbivores would starve, and so would the carnivores in their turn. Large animals are never abundant, especially top carnivores, so they would have been particularly vulnerable to extinction.

Many smaller land animals survived, including mammals, as well as reptiles such as crocodiles and turtles. No one really understands why these animals escaped extinction. Being smaller and thus more numerous would increase their chances of survival, and this may help explain the survival of birds as well.
Leaf fossils demonstrate that land plants also suffered a mass extinction. We expect that individual trees and bushes alive at the time of the impact would have perished in the cold and the dark. But seeds and roots should have allowed most species to reappear after the darkness ended. The extinction of many kinds of plants has not been explained.

Turning to the less familiar marine realm, we find that the impact spelled the end of the coiled-shell ammonites—relatives of the chambered nautilus—which had flourished in the seas for hundreds of millions of years. Lesser known groups of invertebrates perished wholesale at the level of genera and families. Perhaps they were the victims of food-chain collapse, or perhaps their shells were dissolved in acidified seawater, but no one knows.

Still less familiar are the microscopic single-celled plants and animals that float in the surface waters of the ocean. These tiny organisms were enormously abundant but suffered nearly complete extinction. The microscopic photosynthetic algae and the single-celled predators called foraminifera produced vast numbers of tiny platelets and miniature shells that record the mass extinction with unusual clarity. Probably vulnerable to darkness and acid, they were the base of the marine food chain, and their loss was devastating to marine animals that depended on them. Both foraminifera and photosynthetic algae were at grave peril, with many or most species perishing, but in both cases a few species survived and left descendants which abound in the oceans today.

The sudden loss of half the genera of plants and animals on Earth is a catastrophe almost incomprehensible to us. It truly marked the end of a world. And yet, the darkness eventually faded, the heat died down, and the acids were neutralized. Survivors there were, and they found themselves in a new world, tragically changed, but with boundless opportunities for the future. For 150 million years dinosaurs had been the large land animals of the planet while mammals were confined to the role of small animals. With the disappearance of the dinosaurs, there were new opportunities for mammals, and evolution rapidly
produced large ones. Our nostalgia for the lost world of the Cretaceous is tempered when we realize that it was a world that held no place for us—for large mammals. Our horror at the destruction caused by the impact that ended the Cretaceous is eased by the understanding that only because of this catastrophe did evolution embark on a course which, 65 million years later, has led to us. We are the beneficiaries of Armageddon.

JUST HOW DO WE KNOW ALL THIS?

Tolkien’s story of Middle Earth is, of course, pure fantasy. It has its own internal logic, but magical things take place in Middle Earth which could never happen in the real world. It is a wonderful story, but in order to enjoy it, you must suspend your sense of disbelief. It is not in any way intended to recount events which ever really occurred.

The story of the impact on the Yucatán which ended the age of the dinosaurs has a different purpose. It is intended to be a reconstruction, as accurate as possible, of historical events which really did happen. It asks not that its readers suspend disbelief, but that they do exactly the opposite—that they bring to it their most critical facilities, that they search it for flaws, that they test it in any way they can and try to improve its accuracy.

But how can we possibly reconstruct events which happened 65 million years ago, long before any human being was around to observe what happened and record it for posterity? We can reconstruct these events because the history of the Earth is recorded in the Earth itself. Most of the history of our planet is written in rocks. Rocks are the key to Earth history, because solids remember but liquids and gases forget. Retrieving these long-lost memories is the business of geologists and paleontologists, of people who have chosen to be the historians of the Earth.

Understanding how we decipher a great historical event written in the book of rocks may be as interesting as the event itself. Uncovering the extinction that ended the Cretaceous has been a
saga of patient detective work, of high adventure in remote parts of the world, of lonely intellectual struggle, of long periods of frustration ended by sudden breakthroughs, of friendships made or lost, of the embarrassment of public mistakes and retractions, of the exhilaration of discovery, and of delight in a wonderful emerging story. This is what we will explore in the rest of this book, as we see how the story of the Yucatán impact was uncovered and pieced together.