2. Disaster

Except for the confusing new data supplied by Raup and Sepkoski, our understanding of what happened *65* million years ago had seemed nearly complete. The Alvarez team and teams of other scientists around the world had painted a fairly complete picture of the disaster. There were still some details that weren't fully understood, but the broad picture can be summarized as follows.

At the end of the Cretaceous period, the golden age of dinosaurs, an asteroid or comet about *5* miles in diameter (about the size of Mt. Everest) headed directly toward the Earth with a velocity of about 20 miles per second, more than 10 times faster than our fastest bullets. Many such large objects may have come close to the Earth, but this was the one that finally hit. It hardly noticed the air as it plunged through the atmosphere in a fraction of a second, momentarily leaving a trail of vacuum behind it. It hit the Earth with such force that it and the rock near it were suddenly heated to a temperature of over a million degrees Celsius, several hundred times hotter than the surface of the sun. Asteroid, rock, and water (if it hit in the ocean) were instantly vaporized. The energy released was greater than that of 100 million megatons of TNT, 100 teratons, more than 10,000 times greater than the total U.S. and Soviet nuclear arsenals.

Before a minute had passed, the expanding crater was 60 miles across and 20 miles deep. (It would soon grow even *larger.)* Hot vaporized material from the impact had already blasted its way out through most of the atmosphere to an altitude of 15 miles. Material that a moment earlier had been glowing plasma was beginning to cool and condense into dust and rock that would be spread worldwide. The entire Earth recoiled from the impact, but only a few hundred feet. The length of the year changed by a few hundredths of a second.

The deep crater may have reached through the crust of the Earth to **the** mantle. The rock at this depth is very hot due to the natural radioactivity of trace amounts of potassium, uranium, and thorium. The hot rock had turned to liquid as soon as the weight of the rock above it was removed. Great pressure from the Earth's interior quickly filled in most of the crater with melted rock from below. It is possible that molten rock continued to flow in a great outpouring. This is not known for certain, because the impact site has not been definitely identified. One suggested location is at the Deccan traps in India, one of the greatest outpourings of deep basaltic rock that has taken place in the last billion years of the Earth's history. Two hundred thousand square miles of the Earth were covered when the Deccan traps were formed, and this is known to have taken place at about the right time, approximately 65 million years ago.

Shock waves from the impact rattled the Earth with energy much greater than that of the largest earthquakes humans have experienced, probably a million times more energetic than the one that devastated San Francisco in 1906. The shock may have triggered other earthquakes, causing aftershocks lasting for months or years. This is speculation, for we don't know enough about the crust of the Earth to say with any certainty Weak points in the Earth's crust may have opened and sprouted new volcanoes. It is impossible to guess all the effects, or how long they lasted.

Our failure to find the crater suggests either that it was obscured by the subsequent outflow of magma or that the impact occurred in the two thirds of the Earth that is covered by ocean. According to the latter scenario, the asteroid quickly punched through the water layer much as a rock would through a puddle, since in most places the depth of the ocean is less than the hypothesized 5-mile diameter of the asteroid. The splash created a great tsunami, or tidal wave, which grew hundreds of feet high as it swept toward shore. The giant wave circled the Earth many times, inundating the coastal regions. Only the interiors of the continents were spared.

Rock from the crater, mixed with vaporized comet material, cooled to several thousand degrees Celsius as it rose in a fireball up through the atmosphere. It was then about as hot and bright as the surface of the sun, the greatest fireball ever seen by living creatures. But they didn’t watch it for long, because the intense heat radiated from the glowing cloud burned everything within sight. The heat of the fireball also fused nitrogen and oxygen in the air to make nitrous oxides, a constituent of modern smog. Some of this gas later combined with water in the atmosphere to make nitric acid. Likewise, sulfur dioxide from burning plant material formed sulfuric acid, which together with the nitric acid eventually fell to Earth. This acid rain may have been strong enough to dissolve the shells of creatures that lived in the surface waters of the oceans.

Some of the material ejected from the crater flew out of the atmosphere in ballistic trajectories and, like ICBMs (intercontinental ballistic missiles), rained havoc on distant continents. Some escaped into space, perhaps to hit the Earth on an anniversary of the impact when both the Earth and the ejecta returned to the same part of their orbits around the sun. As the fireball reached the top of the atmosphere, it bobbed like a cork, floating on the cooler air beneath it, but it had nothing to hold it together and it began to spread out over the entire globe. As it spread, its color cooled from a glowing red to an impenetrable black. The surviving creatures below probably thought that night had come early, but it was a night without a moon, without stars. The dinosaurs could not see their own claws in front of their faces. Morning would not come for several months.

A few animals had avoided the initial destruction, and at first they seemed to manage surprisingly well. Most of the plant eaters could still find food, although the settling dust added a gritty texture to it all. Some of the carnivores were accustomed to hunting in the dark, although they had never experienced blackness such as this. But the ultimate source of all food, the sun, had been effectively blocked out. Without sunlight, there was no photosynthesis, no creation of sugar and starch from carbon dioxide and water. Unseen by the animals, the plants were turning from green to yellow, and then to brown. If not for the darkness, it would have been a beautiful autumn scene. The larger herbivores began to starve, followed soon afterward by the large carnivores. Similar death occurred in the oceans. Phytoplankton, the first link in the food chain for the oceans, died from the acid rain and lack of sunlight, and the higher organisms quickly followed.

Without sunlight, the temperature of much of the Earth began to drop. On much of the land the temperature soon fell below freezing. Only those fortunate few animals that had already begun to hibernate didn’t notice. Warm-blooded creatures had an advantage in their ability to endure the cold, but they also required more food. The coastal regions had temperatures moderated by the oceans, but these were the areas that had been devastated by the tsunami. Tremendous storms were generated by the great temperature differences between the oceans and the land masses. The storms rained the nitrous and sulfuric acids onto land and sea.

The tiny particles of dust high in the atmosphere began to stick to each other, agglomerating into larger particles, which fell to Earth more quickly. All over the Earth the dust settled to form a layer about a half-inch thick. (One day Walter Alvarez would puzzle over a section of this layer in an outcropping near Gubbio, Italy, where it had been brought up to the surface as the crust of the Earth folded during the creation of the Apennine mountains. He would cut a piece of it out to give as a gift to his father.)

As the dust settled, sunlight began to filter through to the Earth's surface. Virtually every animal and plant had died. The plants were probably the first to revive. Many spores and seeds had been left behind. Life is incredibly robust. For some plants, the three-month period of darkness and cold was no worse than a severe winter; these resprouted from seeds and roots. It was a miracle that any of the higher life forms made it through. Indeed, almost every land animal that weighed more than about 50 pounds had been extinguished, probably because they were most vulnerable in their high position on the food chain. The reptilian dinosaurs, both on land and in the sea, had vanished forever. The nearest relatives of the dinosaurs to survive were the birds. We don't really know why. Perhaps it was their mobility, their ability to search for warmth and food. Perhaps they were better able than other dinosaurs to feed off decaying matter and seeds. Perhaps it was their warm blood. We can't be sure because we don't even know if the other dinosaurs were warm-blooded or cold-blooded. There was no obvious pattern that explained why certain creatures had survived, and others had not. Life is very robust, and yet very fragile.

With plant life suddenly sprouting all around, the few creatures that had made it through the catastrophe found themselves in a virtual Garden of Eden. Their natural enemies were gone, and food from plants was abundant. However, their species would not continue unless they could find mates. Those that did quickly spread out over the Earth, like (much more recently) the rabbits let loose in Australia. They filled the ecological niches that had been denied them by their previously "fitter" enemies. The slate of evolution had been wiped nearly clean. Now there was plenty of room for Nature to try new inventions. In fact, the great catastrophe was marked in the paleontological record not only by the disappearance of species, but also by the great proliferation of new species that followed. Like a forest fire clearing the brush, the destruction may have been necessary to clear the world of weak creatures that had nevertheless held on to a niche simply by virtue of filling it before any other animal. In evolution, possession really is nine tenths of the law. Survival of the fittest had been hindered by an equally powerful principle: survival of the first. The catastrophe had cleared out whatever stagnation there had been in the process of evolution. Once again there was room for free experimentation.

In this picture, evolution wasn't exactly what it was once thought to be, creatures fighting other creatures to determine which were the fittest. To survive, creatures also had to be adapted to endure catastrophe. Maybe that's why the mammals made it through. They had put up with trauma for 100 million years, the trauma of attempting to live with the dinosaurs.

When Luis Alvarez's team first analyzed the climatic effects of the impact, it could not decide whether the dust surrounding the Earth would cause the surface temperature to drop or rise. The answer depended on which effects were most important. Blocking the sunlight should cause the Earth to chill, they thought at first. But high dust is better at absorbing sunlight than clouds, which reflect most of the light that hits them. If the dust became hot enough, it could radiate the heat to the surface of the Earth, warming it up. Geologist Eugene Shoemaker had pointed out that if the asteroid hit in the ocean, the injection of water vapor into the atmosphere could increase the "greenhouse effect" and warm the climate. It was hard to know which effect would dominate, whether the temperature would rise or drop. This question had interested Brian Toon, a physicist who worked at NASA'S Ames Research Laboratory in Sunnyvale, California. Toon and his colleagues were eventually led to an amazing conclusion, one that had immediate practical consequences far afield from the mystery of the dinosaurs. (A few years later this work was under extensive study by the U.S. Department of Defense.)

Toon and his colleagues recognized that the dust cloud would cause both the absorption and reemission of the solar radiation to take place at higher altitudes than usual. Normally the surface of the Earth receives light radiation from the sun and roughly an equal amount of infrared radiation from the upper atmosphere. With the dust layer stopping the direct sunlight, the land would receive only half as much energy. Normally the temperature of an object bathed in radiation is proportional to the fourth root (i.e., the square root of the square root) of the energy hitting it. Since the surface temperature of the dust-free Earth is normally about 28 degrees Celsius (300 degrees above absolute zero), a drop could be expected, on an absolute scale, of the fourth root of 2, a factor of 1.18, down to 252 degrees above absolute zero, about 20 degrees below freezing. More detailed computer simulations that took into account the fact that the atmosphere has several effective layers essentially verified the simple calculation, although the temperature drop was not quite as severe.

If snow covers a large fraction of the Earth, then even the return of sunlight may not warm up the Earth. Although it can begin to reach the ground once the dust settles, the sunlight will be reflected by the white snow before it can turn into infrared heat. It may take something external, such as another impact or a volcanic eruption that would spread dust over the snow, to make the Earth absorb sunlight again. Some paleontologists had believed that it was climate change that had killed the dinosaurs. But it now seemed likely that one was not a consequence of the other, but that in fact both had been brought about by the same cause, the asteroid impact. Perhaps a climate change *had* been the responsible agent, but it was a climate change brought about by an impact.

The impact-caused winter was a major contribution, an important new idea. But then, in a great conceptual leap, Toon and his collaborators realized that a similar effect could occur today as a result of an all-out nuclear war, if sufficient dust were lofted into the high atmosphere. It was the birth of the idea of the "nuclear winter." Toon discussed these ideas with Carl Sagan, his former thesis adviser, who had analyzed the climate effects of dust clouds on Mars and had reached similar conclusions. They realized that the major contribution to the darkening of the atmosphere would not be dust lofted in the fireball, but soot

from the extensive burning of cities that would very likely accompany an all-out nuclear war. This analysis was published in *Science* magazine, in a paper that soon became known as the TTAPS report, from the initials of the authors:
Turco, Toon, Ackerman, Pollack, and Sagan.

The TTAPS report predicting a nuclear winter hit the entire defense community like a shock wave. A few years earlier, a committee of the National Academy of Sciences, the most prestigious scientific organization in the United States, had analyzed the long-term effects of nuclear war and concluded that they might be relatively minor. Populations had sprung back from past disasters, such as the bubonic plague of 1350, with amazing resiliency and speed. But the Academy committee had never thought of the nuclear winter, which could be far more devastating than immediate blast or long-term radiation effects. Depending on the duration of the chill, it seemed possible that all higher forms of life could again be destroyed, this time in action brought on by ourselves.

Some critics of the TTAPS report said that the calculations had been overly simplified. The existence of the oceans, of storms, and of cloud formation had been neglected. The nuclear winter threat might not exist, or might be much less severe than the TTAPS report suggested. However, many sober-minded scientists felt that this criticism, although accurate, was irrelevant. The TTAPS group had shown that the best scientists in the world, in their previous thinking about nuclear war, might possibly have missed the most important, the most damaging effect. The TTAPS group might be wrong in their detailed climate calculations, but they were absolutely right in their demonstration that nuclear warfare was too large a departure from prior experience for us to have any confidence that we could predict its consequences. Nuclear winter might turn out to be right or wrong, but we had all learned a nuclear humility.

Soon after the Alvarez group published its discovery of the primordial impact, NASA commissioned a special study to figure out what to do if we discovered that an asteroid or comet was heading directly toward the Earth. One could not simply blow the asteroid to smithereens, since even a small smithereen can destroy a city. In 1908, a small piece of a comet, probably less than 100 feet across, hit the atmosphere above the Tunguska region of Siberia. It vaporized and never reached the ground, but the blast from the hot gases was equivalent to that of a 50-megaton nuclear explosion. Tens of thousands of square miles of trees were flattened. Observers flying over Tunguska a decade later reported that from the air the broken trees looked like matchsticks, with their bases all pointing back toward the place where the fragment would have hit.

The NASA study, which included Luis Alvarez as a participant, concluded that the best thing to do was to land on the asteroid, dig a hole in it, and set off a small nuclear explosion in the hole. In effect, the entire asteroid would become a rocket, with the blast of the explosion giving a thrust that would push the asteroid out of its old orbit. If you caught the asteroid early, a relatively gentle blast could deflect it enough so that it would miss the Earth Physicist Roderick Hyde figured out that it would be even easier to deflect a comet, which is largely ice and dust. Detonate the nuclear weapon a few miles above the surface of the comet core, he suggested. The blast of heat would vaporize water on the surface of the comet, and this vapor would push the comet away. If it were sufficiently spread out, the explosion would not tear the comet apart.

We are the first creatures on the Earth capable of putting up this kind of “comet umbrella.” It would be wise to practice on a few distant asteroids and comets, however, to make sure that the method works before we try it on a comet or asteroid that is headed directly toward the Earth.