The Mistaken Extinction

Chapter Five

Fatal Impact: *Evidence for the Catastrophic Impact Hypothesis*

Dissatisfaction with conventional and fanciful explanations for the extinction of dinosaurs stimulated continued scientific research. This pursuit eventually led to a key observation that, in turn, has fueled a decade-and-a-half of vigorous and often vitriolic debate.

Actually, as early as the mid-1700s, people were raising the idea that extraterrestrial events were responsible for extinctions on Earth[1]. In fact, one of these proposals by French scientist Pierre de Maupertuis in 1742 argued that impacts by comets on the Earth have caused extinctions by modifying the atmosphere and oceans. Present-day scenarios are based on this same essential concept. In 1964, René Gallant wrote an essay on the geological and biological effects of meteorite impacts. He discussed the possibility that such impacts could be the cause of mass extinctions as a result of associated changes in the Earth's rotation and environmental damage. In addition to impacts, an explosion of a nearby supernova was proposed by Dale Russell of the Canadian National Museum of Natural Sciences and Wallace Tucker of Center for Astrophysics at Harvard College Observatory as the cause of dinosaur extinction in 1971[2]. The scenario involved organisms being exterminated by lethal levels of radiation generated by the explosion. However, these early ideas involving extraterrestrial causes for extinctions on Earth had no tangible geologic evidence to back up the claims. They were just hypothetical scenarios, and as a result, none were taken very seriously.

Since the end of the 18th century and beginning of the 19th century, the primary strategy that geologists have used to gain an understanding of Earth history has been to use the “present as a key to the past.” In other words, those geological processes that we can see acting on the Earth today are most likely responsible for any evidence that we see preserved in the geologic record of the past. In general terms, this doctrine has become known as the principle of uniformitarianism.

The story of how uniformitarianism became the dominant school of geological thought is an interesting and informative one that continues to be debated and discussed two centuries after the fact. The story also has close ties to the contemporary debate between proponents of more catastrophic, extraterrestrially based scenarios and those favoring more

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gradual, terrestrially based ones. For, it was at the end of the 16th century and the beginning of the 17th century that the geological schools of catastrophism and gradualism actually arose[3-5].

The chief proponent of the catastrophic school was the influential French anatomist, Georges Cuvier of the Paris Museum of Natural History (fig. 5.01). Working in the earliest decades of the 1800s, his meticulous studies of the fossil faunas in rock layers of the Paris Basin led him to conclude that repeated catastrophes had been inflicted on the Earth and it's biota. He was not sure what caused these catastrophes, but he was sure that he could document the effects of them. The ideas and evidence are laid out in his *Essay on the Theory of the Earth,* the third edition of which was published in 1817.

Cuvier used a previously developed geological principle called the law of superposition. This principle generally states that rock layers are deposited sequentially one on top of the other, so that lower layers are older than higher ones. Cuvier noted that the kinds of fossil organisms preserved in the different layers of rock changed dramatically as one moved from a lower layer into the next higher layer of the sequence. He interpreted these changes to mean that each layer represented a distinct period of earth history with its own distinctive fauna. The boundaries between the layers represented catastrophes that wiped out all the previously existing organisms. Subsequently in the next higher layer, a new set of organisms appeared.

Modern students of Cuvier's work disagree over how he viewed these catastrophes. Some, such as William Berry of UC Berkeley, interpret Cuvier's writings to suggest that he believed that at each catastrophe all of the previously existing organisms suddenly became extinct, and a complete new set of organisms was created[7]. Others, such as Anthony Hallam[5], have suggested that Cuvier believed the new faunas might have migrated into the area from other continents or seas. Part of this interpretive problem appears to be tied up with understanding Cuvier's leanings in relation to the prevailing religious beliefs of the time. Across the Channel in England many people interested in geological issues were also clergymen and devout believers in the literal translation of the great biblical flood. In fact, in the earliest translation of Cuvier's seminal work into English from French, the most recent of Cuvier's catastrophic episodes was thought to represent the flood documented in Genesis. Cuvier's work was, therefore, of great interest to these clergymen because it could be easily rationalized with the religious teachings of the day. Whether Cuvier believed this himself is debated today[5,7]. Whether he did or not, he was convinced of the sudden and catastrophic nature of the biologic turnovers he saw in the geologic record.

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During the same general time period, a distinctly different view of what the biologic changes between different rock layers meant was being developed in England and Scotland by other contemporary geologists. Beginning in 1780s, James Hutton, a Scottish farmer and dedicated collector of fossils, brought into focus the idea that natural geological laws could be derived from studying modern geological processes and the deposits that these processes generated (fig. 5.02).
In essence, he proposed that ancient geological deposits resulted from the same geological processes which we can see operating on the Earth today. His concepts were outlined in a talk to the Royal Society of Edinburgh in 1785 and eventually published as a book entitled *Theory of the Earth* in 1795. There, he stated, "In examining things present, we have data from which to reason with regard to what has been; and from what has actually been, we have data for concluding with regard to that which is to happen hereafter."[6] Hutton traveled to many locations across the British Isles in search of fossils. As he did, he paid keen attention to the geologic processes that he could observe in operation. Although others had previously noted the same basic concept, Hutton is usually given credit for laying the foundation of this principle of uniformitarianism.

Hutton concluded that the geologic record had been generated by long episodes of rock formation and uplift, followed by erosion and the formation of younger layers of rock from previously existing rock. His observations were summed up in his statement that "The result, therefore, of our present inquiry is that we find no vestige of a beginning, no prospect of an end."[7] Hutton's concept of an immense expanse of geologic time and history flew in the face of the prevailing religious doctrine. According to the authority of Bishop Ussher's religious dictates, the Earth was only 6,000 years old--it having been created by God in the year 4004 BC. Hutton died two years after his work was published in its most expanded form. Not suprisingly, his ideas were severely criticized by the religious establishment.

Nonetheless, his themes were carried on in the ensuing early decades of the 1800s by a friend and colleague, John Playfair, a Professor of Mathematics at the Univeristy of Edinburgh, as well as, by Charles Lyell, a Fellow in the Geological Society of London (fig. 5.03). Lyell's *Principles of Geology*, first published in three volumes between 1830 and 1833, did much to influence the geological community's view of how on-going geologic processes could be used to interpret past geologic deposits and events[8]. In more detail than Hutton, Lyell extensively documented the processes of erosion and deposition to illustrate the uniformity of natural geological processes through time. He concurred

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with Hutton's conclusion that the expanse of geologic time was much longer than the prevailing religious doctrines allowed. Because of the popularity of his text book, Lyell is often cited as the father of uniformitarianism.

In writing the *Principles of Geology*, Lyell appears to have had two primary items on his agenda. He wanted to counter the more catastrophic vision of earth history embodied in the work of Cuvier, which had been adapted by some of his English colleagues for support of literal biblical rationalizations. Also, he sought to establish geology as a testable science based on empirical natural laws.

In attempting to counter Cuvier, Lyell argued that observable modern geologic processes operated at relatively constant or uniform rates rather than at varied rates that would generate catastrophic episodes of change. In essence, he argued that if the processes of volcanism, uplift, erosion, and deposition were allowed to operate constantly throughout the expanse of geologic time, they could easily explain the geologic structures and landforms found both on the Earth today and throughout the geologic past. No appeal to sudden catastrophes was required. By the time of his death in 1875, his goal had been fairly successfully accomplished.

Thus for two centuries, the principle of uniformitarianism has dominated our thinking, ever since the seminal work of James Hutton, Georges Cuvier, Charles Lyell, and others laid the foundation to transform geology into a testable science. Recent reviews of Lyell's brand of uniformitarianism have focused a critical light on some of his arguments. Steven Jay Gould of Harvard University played an instrumental role in this reevaluation when he recognized that the concept of uniformitarianism actually represented two different ideas[9]. Few geologists today agree with Lyell's conclusion, now termed substantive uniformitarianism, that geologic processes have operated at constant rates throughout geologic history. On the other hand, the other aspect of Lyell's uniformitarianism, termed methodological uniformitarianism, forms the cornerstone for all geological research. Basically, it states that natural geological laws have applied throughout the Earth's history so that no hypothetical unobservable processes need to be invoked to explain the existing geologic record.

Because geologists have long focused almost exclusively on earth-based observations and processes during their research, students have been cautioned to consider as bunk any catastrophic, extraterrestrial causes for geological phenomena observable on our planet. But the dawn of the Space Age in the latter half of the twentieth century called such Earth-centered approaches into question. Missions to the moon and planets produced a wealth of new data, including the undeniable effects of impacts on many objects in our solar system. In a very visceral and hyper-real sense, this exploration confirmed the Earth's relation to other bodies in the solar system and the universe. In effect, it became increasingly clear that impacts of asteriods and comets on the Earth could be legitmately considered to be methodologically uniformitarian.

Then, in the late 1970s when we were entering Berkeley as graduate students, several geological clues were discovered that provided the first compelling evidence for a plausible extraterrestrial culprit in the extinction of dinosaurs. In a sense, history had turned on itself, and the old arguments between the catastrophists and the uniformitarianists (or gradualists) were once again ignited into a cacophony of scientific conflict.

In a figurative sense, a meteorite had impacted just one floor above our offices in the Department of Paleontology, as a sensational new catastrophic extinction scenario was formulated and published by a group of researchers in the Department of Geology and Geophysics [10]. They were led by a Nobel-laureate physicist, Luis Alvarez, and his son Walter, a Professor in the Department of Geology and Geophysics.

In both marine and terrestrial rock layers, or sequences, many of the plants and animals that went extinct at or near the end of the Age of Dinosaurs drop out of the record abruptly as one moves from lower, older rocks documenting the end of the Age of Dinosaurs up into higher, younger rocks representing the beginning of the Age of Mammals. Such an abrupt disappearance of many forms of single-celled plankton in the marine limestones near Gubbio, Italy led Walter Alvarez and his colleagues to wonder how long those extinctions really took[11].

Between the white limestone representing the end of the Age of Dinosaurs and the pink limestone representing the start of the Age of Mammals lies a 3/8 ths of an inch-thick (one-centimeter-thick) bed of clay (fig. 5.06). Alvarez discussed this problem with his father and several of his father's associates. In the end, they felt that they might get some idea of how long it took to deposit this layer of clay by looking at the concentration of an element called iridium. Iridium (Ir) is one of the platinum group elements which has an atomic number of 77.

Iridium is not common in the rocks of the Earth's crust. It is a relatively heavy element that tended to sink toward the Earth's core as the planet cooled and differentiated into its aforementioned layers of different composition and density at an early stage in its history. Most of the iridium present at the formation of the Earth appears to be combined as an alloy with iron and is now concentrated in the core. However, iridium is found in higher concentrations in some meteorites and comets, where the original chemical composition of the solar system is preserved.

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These smaller bodies were not large enough to go through the same process of chemical differentiation that our planet did.

Nonetheless, small amounts of iridium continue to be deposited on the Earth's surface in microscopic meteorites which continually bombard the Earth (fig. 5.07). One estimate suggests that the mass of the earth is increased, on the average, by 12,100 tons (11,000 tonnes) per year as the result of this constant cosmic bombardment[12]. While falling through the atmosphere, most meteorites burn up. However, a small percentage survive the descent to impact on both land and sea. By measuring how many of these small meteorites fall to Earth over a given period of time in our modern world, scientists can estimate how much iridium is brought in because they know the concentration of iridium in the meteorites. Then, by measuring the amount of iridium in the boundary clay, the Alvarez team felt that it could estimate how long it took for the clay to be deposited, assuming that the rate at which small meteorites hit the Earth today is similar to the rate at which they hit the Earth at the end of the Age of Dinosaurs. In retrospect, it's extremely ironic to realize that this experiment represented a classic uniformitarian approach to solving the problem. The Alvarez team looked to the modern world for help in interpreting the ancient geologic record. Yet, their experiment led to a very non-uniformitarian conclusion.

Based on the amount of iridium measured in the boundary clay exposed in the outcrops at Gubbio, Italy, the calculations made by the Alvarezes and their colleagues suggested a disturbing result. A period of about one million years would have been required to deposit the boundary clay. This contradicted the amount of time available based on a conflicting line of evidence suggested by reversals of the Earth's magnetic field. The interval of geologic history containing the last dinosaur fossils occurs within a period in which the Earth's geomagnetic poles were reversed. In other words, the poles were opposite the way they are oriented today. This interval, known as Chron 29r (for the 29th reversed interval before the present), was thought to have lasted only a half a million years. If so, the deposition of the boundary clay could not have lasted one million years (fig. 5.08)[15]. Another estimate suggested that the amount of iridium present in the boundary clay was 30 times that which could be expected by the normal rate of gradual accumulation of small meteorites[14].

Examined the same problem another way, the average, present-day concentration of iridium in seawater (11 x 10^{-12} grams per 10^{-3} cubic cm) implies that it would have required the Earth's oceans to be over 435 miles (700 km) deep to have precipitated out the observed amount iridium in the boundary clay under normal natural conditions[13].

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However, the deepest known part of today's oceans is found in the Mariana Trench, a subduction zone between plates near Guam. There, the depth is less than 7 miles (11 km). So, extraordinarily high concentration of iridium seemed to require a special explanation.

At first, the Alvarez team proposed that the explosion of a nearby supernova had generated the iridium. However, within a year, contradictory evidence had been found in the boundary clay[10]. Consequently, the Alvarez team regrouped and hypothesized that a large asteroid, about 6-9 miles (10-15 km) across, must have collided with the Earth releasing the equivalent of about 10^{23} joules of kinetic energy. This is 100 times more than the amount of internal energy released each year from the Earth in the form of heat and earthquakes[16], and 1000 times the energy that would be released if all of the world's nuclear weapons were detonated simultaneously[14]. The fall-out resulting from that impact created the boundary clay.

As many people both inside and outside the ensuing debates have noted, this was a strikingly bold and professionally risky proposal, especially in view of geology's long history of excluding extraterrestrial events as one of its accepted uniformitarian processes. But the coincidence of the high iridium concentration with the biologic changes at the K-T boundary in Italy was difficult to dismiss as being purely coincidental. The most noteworthy effect of the hypothesis was to spawn a storm of multidisciplinary research around the world. What the Alvarez team had contributed to the debate over the cause of dinosaur extinction was a sensational hypothesis with predictive elements that could, at least to some degree, be tested both in the field and in the laboratory, and that's exactly what the scientific community set out to do.

The new theory contrasted markedly with the conventional wisdom long held in the paleontological community that the extinction of dinosaurs was brought about by more gradual, Earth-based processes. Consequently, the level of interest in both the Paleontology Department and the Geology and Geophysics Department at Berkeley was high. Interest quickly spread to other departments, especially as a rising wave of publicity in both the popular and scientific press began to win over members of what had been a deeply skeptical scientific audience.

In the interest of exploring this new hypothesis, a seminar was initiated involving the Alvarez group and a group in the Paleontology Department led by Professor William Clemens (fig. 5.04). For over a decade, Clemens had conducted a program of paleontological and geological field research in the most famous fossil locality documenting dinosaur extinction--the Hell Creek and Tullock Formations--which form the picturesque Missouri Breaks of east-central Montana. In 1980, Lowell was the senior graduate student helping to manage that research program.

In the beginning, this interdepartmental seminar seemed to symbolize the best that a multidisciplined academic environment could offer. We discussed the strengths and weaknesses of both the impact hypothesis and more gradualistic scenarios. A program was devised for how we might test the predictions of the impact hypothesis during our next field season in Montana. This initial spirit of cooperation led to the joint discovery of the first evidence for an impact ever identified in sediments that document the K-T transition in a land-based habitat that contained remains of dinosaurs (fig. 5.05). The evidence for impact consisted of an anomalously high concentration of iridium, similar to the one found between the marine limestones in Italy. This was a tremendously invigorating and intellectually intoxicating time. We were fully aware that our work was poised on the cutting edge of science.

However, as the months passed, the atmosphere of cooperation between some of the participants in the seminar began to deteriorate. A series of public debates between proponents of the impact and those favoring Earth-based scenarios served to polarize our positions. Some exchanges even took on a rather unpleasant personal pitch. From a personal point of view, we often found ourselves arguing toe-to-toe with a Nobel-laureate over issues involved in the debates. As new graduate students yet to pass our orals, this was an intimidating situation. At times, we wondered what effect it might have on our subsequent careers. In retrospect, these seminars set the tone for a decade-and-a-half of dissension between proponents of catastrophic, extraterrestrially triggered extinction and generally more gradual, terrestrially based volcanic scenarios associated with the retreat of the seaways. In a very real sense, the debates took on the atmosphere and intolerance of wars--the "Iridium Wars."

At various times during this period, one side or the other has claimed victory. Yet, still the polemics continue. Why is this? Why, after fifteen years of research and over 2,500 scientific publications, is the mystery not resolved to everyone’s satisfaction? To understand, we need to examine the principal lines of evidence in the debate.

Associated Environmental Effects of the Impact

The initial calculations and scenario proposed by the Alvarez team suggested that the impact kicked up a globally distributed cloud of dust and water vapor that cut off light from the Sun for a period of several months to a few years. This cloud inhibited photosynthesis, which killed off many plants. Consequently, the herbivorous dinosaurs died out, and then the carnivorous dinosaurs perished.

The Alvarez team's original proposal eventually led to a contentious discussion of whether dinosaurs could have survived the several months of darkness posited by the original impact hypothesis. To try and test this scenario, paleontologists focused their attention on Cretaceous dinosaur sites located near the north and south poles.

One site called Dinosaur Cove, located in southern Victoria, Australia, was the focus of work done by Pat Vickers-Rich of Monash Univeristy and Tom Rich of the Museum of Victoria--two of our predecessors at UC Berkeley. Dinosaur Cove preserved evidence of a thriving community of dinosaurs that lived about 100 million years ago as far as 80-85 degrees south latitude. Their home was well inside the Antarctic Circle, nuzzled up against the great cold continent of Antarctica (fig. 5.09)[17]. The fossils were preserved in sediments laid down by rivers that ran through floodplains in a rift valley that formed as Australia was beginning to separate from Antarctica through the actions of plate tectonics. Based on data provided through an analysis of oxygen isotopes, the mean annual temperature was thought to have ranged between 32 degrees F (0 degrees C) and 46 degrees F (8 degrees C). However, an analysis of the flora, which included ferns, ginkgoes, conifers, and horsetails, suggests a higher mean annual temperature of about 50 degrees F (10 degrees C).

The kinds of animals present in the area around Dinosaur Cove incorporate a broad swath of dinosaurian diversity. These include a small meat-eating carnosaur that stood no more than six feet (two meters) high; a member of the bird-mimic dinosaurs called ornithomimids; and a new, plant-eating hypsilophodontid, named *Leaellynasaura*. Because of the extreme southern positioning of this region 100 million years ago, it was concluded by paleontologists working on the fauna that these dinosaurs would have had to survive three-month-long periods of darkness on an annual basis. This period would have constituted their winter, when the Earth's axis rotated into a position where the sun never illuminated this region. These conclusions left questions in the minds of the paleontologists as to why an impact-generated period of darkness would have extinguished groups of dinosaurs who were apparently well adapted to living in the cold and dark for periods of several months.

At the opposite end of the earth on the north slope of Alaska (fig. 5.10), paleontologists, including Williams Clemens, focused their collecting efforts on a 76-66 million year old, Late Cretaceous dinosaur community. It included large, herbivorous duckbill dinosaurs, as well as carnivorous forms, such as a tyrannosaur and the diminutive *Troodon*[18]. Because of its younger age near the K-T boundary, an analysis of the conditions under which this fauna lived is more pertinent to the extinction debate than the situation at Dinosaur Cove. The north slope

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sites, located along the Coleville River, were deposited by streams and rivers that built a floodplain delta extending out into the Arctic Ocean. At the end of the Cretaceous, this area is thought to have been situated between about 70 degrees and 85 degrees north latitude. These coordinates would have put the site within the Arctic Circle and subjected the fauna and flora to an annual winter darkness of about three months. Analysis of fossil pollen and spores indicates the presence of both ferns and deciduous conifers (similar to the dawn redwood *Metasequoia*) in a mild- to cold-temperate forest. Based on this flora and the absence of more temperate-adapted vertebrates, such as crocodiles and amphibians, the mean annual temperature is thought to have ranged between 35-46 degrees F (2-8 degrees C), similar to the temperature range of present-day Anchorage.

The resulting debate between proponents of volcanic and impact extinction scenarios centered on whether these high-latitude dinosaurs migrated south for the winter where the sun always rises throughout the winter months. However, Clemens and his colleagues argued that the presence of juveniles in the high latitude sites constituted evidence against this, because it would have been difficult for these young animals to survive such a long and rigorous trip. Most scientists involved in the extinction debate now concede that darkness alone was probably not responsible for causing dinosaur extinction, but many other potential "killing mechanisms" have been proposed for the impact.

Another "killing mechanism" posited that the impact caused extreme episodes of acid rain[19]. The intense, initial, atmospheric heating generated by the impact would have created temperatures of several thousands of degrees at the sight of the impact and locally raised temperatures to broiling levels immediately after the impact. Such extreme heat would have caused the formation of nitric acid as nitrogen and oxygen reacted with water vapor. The resulting acid rain would have increased the acidity of the ocean's surface water, killing up to 90% of the microscopic organisms, such as planktonic foraminifera and coccoliths, that form the foundation of the food chain. Second, the impact may have set off wildfires around the globe as the result of the heat and falling debris generated by the impact[20]. Third, the impact was alleged to have dropped surface temperatures on continents to near or below freezing for a period of several months to a year when the dust and water vapor in the globally distributed cloud of debris cut off sunlight and killed plants needing sunlight to photosynthesize[21]. Fourth, the impact significantly raised global temperatures over the longer-term, possibly tens of thousands of years, as a result of the "greenhouse effect." This rise in temperatue was driven by a two- to five-fold increase in the atmospheric concentration of carbon dioxide[22]. Finally, the extensive extinctions of microscopic marine organisms would reduce the release of a chemical compound called dimethylsulfide, thereby inhibiting cloud formation and raising global temperatures more than 11 degrees F (6 degrees C)[23]. This disruption of the food chain and climate was, in turn, hypothesized to have annihilated the dinosaurs and other organisms over a period of less than 50 years[24].

Evaluating the Evidence

There are really several separate questions involved in trying to scientifically test this scenario with the evidence available in the rock and fossil records. The first is, "Did an impact occur?" The second is, "If so, which killing mechanism extinguished each particular group of organisms?" And a third is," Can we really tell time well enough to distinguish between short-term, catastrophic events and long-term, gradual events?"

Boundary clays with high concentrations of iridium have now been reported in over 100 continental and marine sequences around the world (fig. 5.11)[25]. In terrestrial sequences, these clay beds are situated between the youngest plant fossils representing the Age of Dinosaurs and the oldest plant fossils representing the Age of Mammals. They're also about six to ten feet (two to three meters) above the highest or youngest-known dinosaur fossils that have not been reworked into younger layers.

To critics of the impact scenario, such as William Clemens and David Archibald of San Diego State Univeristy [26,27], this "gap" between the youngest dinosaur fossils and the iridium-rich clay suggests that dinosaurs were extinct before the alleged impact occurred. Such an interpretation derives from a "strict translation" or literal reading of the fossil record. Proponents of the impact hypothesis, including Luis Alvarez, have responded that dinosaur fossils are not preserved as often as the pollen spores representing the plants, so it is highly improbable that any dinosaur fossil will be found immediately under or at the same level as the boundary clay[26]. Others, including Archibald, have argued that fossils were originally in the several feet of sediment immediately underlying the boundary, but that these fossils could have been leached out by percolating ground water[27]. In any event, extensive searches for such fossil skeletons have thus far proved fruitless, although fossil footprints of dinosaurs have now been found within 15 inches (38 cm) of the boundary in New Mexico[27]. Rare reports of unreworked dinosaur

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fossils found above the level of the boundary clay remain controversial and only poorly substantiated by geologic evidence.

Advocates of the impact hypothesis argue that, in addition to the iridium, many other lines of geologic and chemical evidence suggest an impact-origin for the boundary clay. However, early on in the debate, critics proposed Earth-based mechanisms rather than an impact in an attempt to explain the same evidence. In an effort to determine whether an impact really occurred, let's now review the disputed scientific evidence involved in these arguments:

A High Concentration of Iridium

As in any murder investigation, fingerprints of the potential culprits can play a major role. In the context of the K-T extinctions, the ratios of different atoms in the boundary can serve as geological "fingerprints," pointing to a probable source for the minerals in the boundary clay. Much of the geologic detective work done to establish whether rock layers resulted from impacts or volcanic events involves painstakingly detailed chemical analyses to measure the concentrations of rare elements contained within the rocks.

As mentioned earlier, the unusually high concentration of iridium found by the Alvarez team in the K-T boundary clay, estimated to total 500 million tons globally (450 million tonnes)[28], originally seemed to represent strong and unequivocal evidence in favor of the impact scenario. Within months, a number of iridium "anomalies" were found around the world at the paleontologically recognized boundary. Although such enrichments are termed "iridium anomalies," because the concentration of iridium in the boundary clay is 100-1000 times higher than that in the surrounding rock layers, these anomalous concentrations actually record only a few parts per billion of iridium (fig. 5.12). This means that for every billion atoms present in the boundary clay, less than ten are atoms of iridium.

In 1983, the idea that high concentrations of iridium represented definitive evidence for impacts was called into question by William Zoeller and his colleagues at the University of Maryland. They studied the gases emanating from a large volcano in Hawaii[29]. During their field work, these researchers inadvertently measured the amount of iridium contained in the airborne particles erupted from Kilauea (fig. 5.13). Although the amount of iridium in the dark basaltic rock formed from the lava of Kilauea is low, the iridium concentration in the airborne particles emitted by the volcano was 17,000 times higher. This raised the possibility that large eruptions of lava and gases could explain the high concentration of iridium in the K-T boundary clay. Zoeller's study noted that the volcanic gases generated by Kilauea contain abnormally high

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concentrations of another element, fluorine. The researchers noted that Kilauea was a hot spot volcano whose magma probably rose from deep within the Earth's mantle. Fluorine-rich gases are found exclusively at volcanoes whose magma came from deep within the Earth, rather than from shallower regions. Intriguingly, the other volcanic vents listed in the study as producing magma with high fluorine concentrations are at Helka in Iceland, which is associated with the Mid-Atlantic spreading center that some volcanologists believe began as a hot spot during the K-T transition.

The previously mentioned extensive episode of volcanic activity at the end of the Age of Dinosaurs, especially the basaltic fissure floods in India, made it plausible that some or all of the iridium was generated by volcanism rather than impact. Most geologists agree that the tremendous amount of material erupted in the Deccan Traps is still not enough to explain the amount of iridium that would have been contained in the globally distributed fallout layer. However, as noted in previous chapters, there are several other hot-spot eruptions that may have begun during the K-T transition. Proponents of the volcanic extinction scenario, such as Charles Officer, Charles Drake, and Anthony Hallam argued that these may have contributed some or all of the iridium in the boundary clays [32-34].

This idea was reinforced by more measurements taken at Piton de la Fournais[30]. As mentioned in the last chapter, this is a volcano on Reunion Island in the Indian Ocean. It represents the remnant of the hot spot generated by the plume of magma that was responsible for the eruptions that created the Deccan Traps and the undersea plateau around the Seychelles Islands between 68.5 million and 64.9 million years ago. Geologists Jean-Paul Toutain of the Osservatorio Vesuviano in Italy and Georges Meyer of the Institut de Physique du Globe de Paris conducted chemical analyses of the gases and associated compounds emitted from that volcano. They documented iridium concentrations as high as 7-8 parts per billion. These researchers also concluded that the iridium was associated with fluorine-based minerals in the gases, confirming that iridium is preferentially released by hot spot volcanoes which exhibit high fluorine contents in their magmas. Such a composition could signify that the magma feeding the eruptions at Piton de la Fournaise arose from regions deep within the Earth's mantle. Calculations done by these researchers suggested that, given the amount of iridium emitted from Piton de la Fournaise (0.25 ± 0.03 parts per billion), the earlier eruptions that produced the Deccan Traps would have produced more than enough iridium to account for the concentrations found in K-T boundary clays.

The Overall Chemical Composition

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The overall chemical composition of the boundary clay was noted by the Alvarez team, and especially Miriam Kastner of the Scripps Institution of Oceanography, to be very similar to the composition of a certain type of meteorite called a type I carbonaceous chondrite[31]. These are among the most primitive known bodies in our solar system in terms of age and chemical make-up. This similarity in composition was based on the analysis of several elemental ratios present in the boundary clay, such as platinum/iridium and gold/iridium. Frank Asaro, one of the original members of the Alvarez team, working with George Bekov of the Institute of Spectroscopy in Moscow, discovered that the relative abundances of ruthenium, rhodium and iridium were more similar to those found in meteroites that in terrestrial rocks. Atomic analyses eventually led to a debate within the community of impact proponents over whether the extraterrestrial body that hit the earth was an asteroid, as the Alvarez team had originally proposed, or a comet, as suggested by some other analyses[41,44]. The iridium concentration in comets is thought to be about ten times less than that for iron meteorites.

Critics, such as the late Anthony Hallam of the University of Birmingham in England, pointed out that multiple impacts would probably need to have occurred in order to explain the observed iridium concentration[32]. This possibility and associated problems are discussed in a later section. In addition, several contradicting points were raised by proponents of a terrestrial origin for the iridium, as noted in a paper by Vincent Courtillot[33]. A sampling follows.

Researchers, including W. Crawford Elliot of Case Western Reserve University, did chemical detective work on the boundary clay preserved at Stevns Klint in Denmark. They concluded that the clay was composed of an unusual kind of smectite (a type of clay mineral), which indicated that it represented a weathering product of volcanic ash. A study by Jean-Marc Luck of the Institut de Physique du Globe de Paris and Karl Turekian of Yale Univeristy indicated that the ratio of the elements rhenium and osmium in the clay resembled the ratio found both in meteorites and the Earth's mantle. Charles Officer and Charles Drake noted that the iridium concentration of boundary clays from different areas of the globe is rather variable, which suggested to them that the source was not a globally distributed dust cloud of constant composition. They also noted that the ratios of other elements differed from that of chondritic meteorites[34]. Finally, as Zoeller and his colleagues pointed out, enrichments of other rare atoms in the emissions from Kilauea, such as antimony, selenium, and arsenic, suggested that hot spot volcanism may have played a role in creating the elemental concentrations found in the boundary layers[35].

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Proponents of the impact hypothesis, such as Walter Alvarez and Frank Asaro, countered by arguing that the osmium concentration of the boundary layer seems to suggest a source exclusive of continental rocks[36]. In terrestrial rocks, the isotope of osmium that contains 187 protons and neutrons is much more abundant than the isotope of osmium that contain 186, but this is not what is seen in the boundary clay. In fact, the reverse is true, suggesting a source from extraterrestrial meteorites or volcanic rocks from deep within the mantle. The work of Turekian and Luck was crirtical in establishing this point. Also, an analysis of the concentration of rhenium in the boundary clay provides further support for this interpretation.

As Richard Grieve of the Geological Survey of Canada has summarized[44], the chemical composition of some boundary layers suggested that the extraterrestrial body slammed into continental rocks. However, the chemical composition of a few layers yielded contradictory results, suggesting that the object may have slammed into a more basaltic material such as the floor of an ocean. A possible solution to this problem is discussed in the next chapter.

All of these factors led proponents of the impact hypothesis, such as Frank Kyte of the University of California at Los Angeles and his colleagues, to rationalize that any chemical inconsistencies between the boundary clay and extrterrestrial bodies were the result of natural variations[37]. Inconsistencies could have been caused when the fall-out from the impact was mixed with the variety of materials found in different environments around the world in which the fall-out deposited and buried to form sedimentary rocks like the boundary clay. In addition, impact proponents argued that different geochemical processes could have altered the composition of the boundary layer after it was originally deposited. However, skeptics, such as Charles Officer and Charles Drake, argued that the compositional differences probably represented the result of natural variation in terrestrially based volcanic ejecta[38].

Minerals Fractured by the Shock of the Impact

At more than 30 localities around the world, beds of the boundary clay have been found to contain microscopic grains of quartz with small fractures planes running in multiple directions through the crystal structure (fig. 5.14)[39]. Under the microscope, these crystals appear to have a cross-hatched pattern. The leader of these research efforts has been Bruce Bohor of the U. S. Geological Survey. The first place that such "shocked" crystals were discovered was at Meteor Crater in Arizona (fig. 5.15). This was where a meteorite slammed into sandstone target rock between 50,000 and 25,000 years ago.

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The sequence of events that create these fractured crystals during an impact have been described by Richard Grieve[40]. Recall that we are dealing with a body traveling between 50,000 and 150,000 mph (80,000 and 250,000 km/hr)[41] and weighing as much as 1 trillion tons (900 billion tonnes)[42]. The energy of the speeding meteorite is translated into powerful, high-pressure shock waves that travel out from the point of impact. These shock waves are initially thought by some to be as strong as 100 billion pascals. To give you some idea of this force, a pascal is equal to applying a force of one newton per square cm. A newton represents the force required to constantly increase the velocity of a one kilogram object at a rate of one meter per second. In terms of miles per hour, this would be roughly equal to constantly increasing the velocity of a two pound object at a rate of about two mph. The force of the impact was about 100 billion times greater. Another estimate of the impact force suggests that the shock would have been about 1,000,000 times that exerted by the Earth's atmosphere[41]. These tremendous forces generated by the impact vaporize, melt, and fracture the rock near the point of impact. Fracturing occurs at the lowest temperatures and pressures, whereas melting and vaporization occur at the highest.

The impact excavates a crater in the shape of a bowl into which much of the damaged material falls. Consequently, much of the surface of the resulting crater is formed by shocked and fractured rock material, some of which is melted. In addition, smaller pieces of this pulverized material are ejected from the crater by the impact and fall as debris over a large surrounding area. In impacts as large as the one thought to have occurred at the K-T boundary, a central area of uplifted bedrock is surrounded by one or more rings of down-dropped material, as will be discussed in more detail in the next chapter.

At many localities where the K-T boundary clay is present, it contains microscopic crystals of quartz that are fractured along planes that are oriented in several different directions. Many, including Bohor and the Alvarez group, feel that these multiplanar fracture patterns in the shocked quartz crystals represent unequivocal evidence in favor of the impact scenario. These proponents argue that the fractured texture could only have been created at the tremendous temperatures and pressures generated by an impact (between 10 and 40 GPa). In general, the number of different planar orientations of the fractures tends to increase with increasing shock forces. Some quartz crystals contained in exposures of the boundary clay have been claimed to have as many as seven different sets of planar fractures.

However, volcanic proponents, including Courtillot, Officer, Drake, and Hallam, noted that similar fracture patterns have been recognized in

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minerals of some rare volcanic rocks, like those from Toba, a volcano in Indonesia[43]. It must be pointed out, however, that, instead of having fractures oriented in more than one plane, the fracture pattern in these volcanic minerals is restricted to a single directional plane. Nonetheless, proponents of the volcanic extinction scenario maintain that theoretical modeling of the St. Helens eruption suggests that it might be possible to generate the necessary temperatures and pressures to create the multiplanar fracture pattern during large explosive volcanic eruptions. Until more definitive evidence is produced to demonstrate that multiplanar shocked quartz can be formed during volcanic eruptions, the presence of these crystals appears to be accepted by most geologists as good geologic evidence for an impact.

Additionally, shocked quartz crystals have been analyzed through a technique called cathodo-luminescence by Michael Owen of St. Lawrence Univeristy and Mark Anders, one of Walter Alvarez's former students[45]. This has revealed that the shocked quartz present in the K-T boundary layers exhibits a range of luminescent colors not found in quartz erupted from volcanoes but more similar to the colors present in impact-altered quartz.

Along related lines, there are several different ways in which the atoms that make up quartz crystals, which contain one atom of silicon for every two atoms of oxygen (SiO_2), can be arranged into different mineralogical structures. Under intense pressures (beginning at 85 kilobars), the common crystal structure of quartz, in which the atoms are arranged in a four-sided tetrahedron, can be modified into a structure in which the atoms are arranged in an eight-sided octahedron. In the resulting eight-sided crystals, the atoms of silicon and oxygen are more densely packed together, so the mineral is given a new name--stishovite. Like iridium, stishovite is very rare in the Earth's crust. However, it is commonly found to be associated with debris in and around impact craters. Its presence has been documented by John McHone of Arizona State University and his colleagues in the boundary clay at a site in New Mexico[44].

Finally, another mineral indicative of impact conditions, microscopic crystals of spinel with a high concentration of the atom nickel, have also been found by Bohor in the boundary clay at Caravaca, Spain (fig. 5.16)[46]. No known spinel crystals of volcanic origin have nickel content even approaching the concentration of those found in the boundary clay. However, the amounts and ratios of the elements iron, chromium, and nickel in these spinel crystals are similar to the concentrations of these atoms found in minerals from fractured rocks below impact craters located in Germany, France, and Russia.

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Glassy Spheres

Proponents of the impact scenario have noted the presence of extremely small spheres in the boundary clay at more than 60 sites (fig. 5.17)[47]. Such spheres were discovered in the boundary clay at Caravaca, Spain in 1981, by Jan Smit of the Free University in Amsterdam. More were separated from the boundary clay in Italy by Alessandro Montanari, another of Walter Alvarez's students at UC Berkeley[31]. They argue that these represent cooled drops of molten rock that were ejected into the atmosphere by the impact.

Critics, such as Officer, Hallam, Courtillot, and Drake, countered that these may instead represent fossilized algae, volcanic ejecta, or microscopic meteorites not associated with a large impact or organic remains. They noted that similar spheres were found in clay beds other than the boundary clay[48].

More recently, some spheres with glassy cores contained within a rim of clay have been identified from the K-T boundary layer in Haiti. Several researchers, led by Haraldur Sigurdsson of the University of Rhode Island and Virgil Sharpton of the Lunar and Planetary Institute in Texas, have analyzed the chemical composition of the glass and reported that it was chemically distinct from the glass produced by volcanoes, especially in terms of its ratios of oxygen isotopes[49]. Additionally, the chemical composition of some of these spheres has been found to be very similar to the composition of a spot on the Earth's surface where an impact is thought to have occurred during the K-T transition, as will be discussed shortly.

Soot

Chemical analyses have revealed a lot of soot and charcoal in the boundary clay at Denmark, New Zealand, and several other localities--concentrations of carbon thousands to tens of thousands of times higher than normal levels (fig. 5.18)[50]. Some advocates of the impact theory suggest that this carbon enrichment came from massive global forest fires ignited by the fallout or the heat of the impact itself. Wendy Wolbach of the University of Chicago has been instrumental in promoting and reporting on this evidence and hypothesis. Additionally, complex and elegantly constructed molecules called fullerines, comprised exclusively of carbon atoms bonded into a structure reminiscent of the structure found in geodesic domes and soccer balls, have been found in some exposures of the boundary clay[51]. These have also been interpreted by Dieter Heymann of Rice University and his collaborators to have formed as the result of wildfires caused by the impact and its fallout.

Overall, these impact generated wildfires are estimated to have created 77 billion tons (7×10^{16} grams) of soot, which would have initially added to the opaque dust cloud that dramatically dropped temperatures. Eventually, these particles would have contributed to the "greenhouse effect" by raising global temperatures about 16 degrees F (9 degrees C).

However, David Archibald of San Diego State University argues that the soot could represent only the normal amount contributed by forest fires set by natural causes including volcanic activity[52]. If the clay layer took a long time to become deposited, as opposed to the several months or a year as called for by the single impact hypothesis, soot from natural or volcanically triggered fires could be expected.

Diamonds in the Boundary Clay

Detailed analyses of the mineralogical composition of the iridium-bearing boundary clay in Alberta, Canada during the early 1990s revealed some additional clues. After collecting about one ounce (20 g) of the boundary clay at Knudsen's farm in Alberta, David Carlisle of Environment Canada and Dennis Braman from the Tyrrell Museum took it back to the lab and dissolved all the clay and coal out of the sample with hydrofluoric and hydrochloric acid[53]. After further chemical procedures and washing, they were left with a whitish sludge that based on X-ray analysis under a scanning electron microscope turned out to be 97% carbon, the only element that makes up the crystal structure of diamond. Of course, carbon is also the only component of graphite, the material that makes up pencil lead, so more definitive tests were needed to establish the identity of the mineral in the white residue. Using another X-ray procedure similar to the way one can shine sunlight through a prism and generate a rainbow of colors, the researchers discovered three lines in the material's spectrum that matched those which would be expected for diamonds. In addition, under a transmission electron microscope, the crystals in the white sludge were found to have an eight-sided octahedral shape--again, the same as would be expected for diamonds. So, they concluded that the material they had separated from the boundary clay was indeed minute diamond crystals.

Now, before you run out to stake your claim on the closest exposure of the K-T boundary clay, please realize that these diamonds are only nanometers (a millionth of a millimeter) in size. Nonetheless, when the concentration of the diamonds was compared to that of iridium, the results were very close to the concentration of diamonds to iridium found in meteorites called carbonaceous chondrites. Furthermore, the ratios of the carbon isotopes making up these diamonds was found to be very close to that of interstellar dust, suggesting that the diamonds were made from star dust and not made from material on the Earth[54].

Amino Acids

Two scientists at the NASA Ames Research Center, Kevin Zahnle and David Grinspoon, did additional geochemical analyses on the boundary clay from Denmark. These resulted in the identification of two amino acids that are common in the same kind of meteorites but are very rare on Earth [55]. Critics pointed out, however, that these two amino acids were in fact present on Earth, so that a terrestrial origin could not be ruled out[56]. Further research on the boundary clay in Alberta by Carlisle revealed the presence of 18 amino acids that are present in meteorites but not found on Earth. Furthermore, the ratios of these amino acids to iridium is about the same as that found in meteorites, suggesting an extraterrestrial origin for the amino acids in the boundary layer[56].

Tsunami Deposits

In the late 1980s, Joanne Bourgeois from the University of Washington and her colleagues conducted field work along the Brazos River in Texas. That sequence of rocks, which contained an iridium anomaly and the characteristic paleontological signature of the K-T boundary, also contained an unusual layer of sandstone that appeared to represent a deposit generated by a "tidal wave," or more accurately, a tsunami (fig. 5.19)[57]. The sandstone directly underlies the iridium anomaly, as well as the disappearance of marine fossils used to mark the end of the Cretaceous Period. Most of the layers of rock near the boundary are composed of mudstone that was deposited along the middle to the outer edge of the then-existing continental shelf in the Gulf of Mexico. The site is thought to have been about 62 miles (100 km) from the shoreline, and the water is thought to have been between 164 and 328 feet (50 and 100 m) deep.

There is only one layer of sandstone in the sequence near the boundary, and it is slightly over three feet (one m) thick. The base of the sandstone layer contains a chaotic mixture of coarse sand grains jumbled together with shell fragments, fish teeth, pieces of fossilized wood, rounded chunks of limy mudstone, and angular hunks of mudstone. The latter are commonly as large as two inches (five cm) across and occasionally as large as three feet (one m) across. Further up in the layer, smaller sand grains, silt, and mudstone show evidence of current action in the form of rippled bedding surfaces.

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Calculations based on the size of the larger chunks of mudstone suggest that current velocities between six inches and 39 inches (15 and 100 cm) per second would have been required to rip the chunks of mudstone out of their original beds and redeposit them as part of the sandstone layer. The researchers concluded that a tsunami was the only kind of depositional event that could have been responsible for creating this deposit on the continental shelf. Because these deposits were located immediately below the iridium anomaly and the K-T paleontological signature, they proposed that the tsunami deposits were the result of gigantic waves generated by the impact. Based on the size of the ripped-up chunks and the estimated depth of the water, they suggested that the wave was 164-328 feet (50-100 m) high when it reached this area--about as high as a 16-33 story skyscraper. It is thought that the whole layer of sandstone may have settled out of the disturbed waters of the Gulf of Mexico in as little as one day.

Earlier estimates of the tsunamis generated near the point of impact suggested that they could have been as high as 13,000 feet (4000 meters) if the impact had occurred in a deeper part of a major ocean basin. Mount Whitney, the highest peak in the continental United States, is slightly over 14,000 feet in elevation. That would have been as high as a stable water wave could have been. However, water in the Gulf region was much more shallow.

Scientists led by Florentin Maurrasse from Florida International University found similarly suspicious deposits in northeastern Mexico, Haiti, and Arkansas, where blocks as large as 16 feet (five m) were incorporated into a tsunami deposit that totaled 65 feet (20 m) in thickness[58]. In sediments deposited in troughs on the bottom of the Caribbean near what is now Cuba, a chaotic layer as much as 1500 feet (457 m) in thickness contains jumbled blocks as large as five feet (1.5 m) across that were apparently swept off the lowlands. In addition to having sedimentary structures that were interpreted to be the result of deposition and scouring by gigantic waves, some of these rock layers also contained particles interpreted to represent altered droplets of melted rock from the impact.

Not all scientists agree with these interpretations, however. Some of the proponents of volcanically based extinction hypotheses, including Charles Officer, argue that these distinctive beds represent the normal deposition and scouring of large underwater debris slides, called turbidity currents. Officer argues that they began on the continental slope of the Caribbean and traveled on out into deeper parts of the basin[59]. Also, it has been argued that if these beds represent tsunami deposits they should contain no evidence of burrowing by bottom dwelling marine organisms[52]. Some, at least, appear to contain burrows that are cut off at the same stratigraphic level. This suggests that in these instances an episode of erosion removed the upper part of the burrows before sediment was once again deposited. One would not expect such gaps during the rapid deposition of sediment after a tsunami.

In the 1980s thousands of scientists from numerous disciplines joined the debate on one side or the other. As a result of this interdisciplinary cross-fertilization, a plethora of new ideas spun off from the original impact hypothesis. However, our ability to successfully test these ideas scientifically has been limited, as the following example illustrates.

Periodic Extinctions

Paleontologists David Raup of the Field Museum of Natural History and Jack Sepkoski of the University of Chicago proposed that episodes of mass extinction occur every 26 million years[60]. Their effort to sort through the fossil record of the last 500 million years was used to identify five or six episodes of "mass extinction" at the end of the Cambrian, Ordovician, Devonian, Permian, Triassic, and of course the Cretaceous Period (figs. 5.19 and 5.20). Walter Alvarez and Richard Muller of UC Berkeley reported that impact craters appeared to be produced in a 28.4 million year cycle, within the error margins of the 26 million year mass extinction cycle[60].

There are three hypothesized causes that have been proposed to link such cycles to extraterrestrial impacts. One was put forward by Marc Davis of UC Berkeley, Piet Hut of the Institute for Advanced Study in Princeton, and Richard Muller. Their idea is that the Sun either has a dwarf twin star, appropriately christened Nemesis, orbiting around it[61]. Every 26 million years, this twin disturbs a cloud of comets in the distant reaches of the solar system called the Oort Cloud, sending a swarm of them speeding on collision courses toward the Earth. A similar proposal by Daniel Whitmire from the Univeristy of Southwestern Louisiana and his colleagues suggests that a yet to be discovered planet, also appropriately identified as Planet X, resides in the outer reaches of the solar system beyond Pluto and disturbs the Oort Cloud in the same way[62]. These ideas are very controversial in themselves, and astronomers are actively searching for such a star or planet--so far without success. A third idea is that, as the solar system periodically moves through the plane of our Milky Way Galaxy, dense gas clouds that reside near the galactic plane disturb the comets in the Oort Cloud altering their orbits and sending them toward the Earth[63]. This idea was proposed by Michael Rampino of

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New York Univeristy and Richard Strothers of the NASA Goddard Institute for Space Studies, as well as by Richard Schwartz and Philip James of the University of Missouri.

Critics have offered several arguments to counter the proposed idea of periodic extinctions. One is that, since iridium concentration of comets is about ten times less than that of iron meteorites, as many as 50 impacts may have been required to provide the observed amount of iridium in the boundary clay at Italy[64]. To the critics, like Anthony Hallam, this seems rather improbable. He suggests that a series of volcanic eruptions might be more plausible in explaining the high concentration of iridium.

Also, the body of statistics and paleontologic data used to argue for periodic extinctions has been vigorously questioned. Is the fossil record really complete enough to document all the episodes of mass extinction? Do we know the age of the extinctions precisely enough to demonstrate that they are happening every 26 million years? Many scientists do not believe that we do. For example, opponents such as Antoni Hoffman of the University of Warsaw [65] have argued that the age of the Period boundaries were arbitrarily chosen to fit the desired temporal pattern. In the process, some conflicting paleontologic evidence was simply eliminated from consideration in the studies purporting to document periodic extinction. The conclusion of some of these critics is that there is no periodicity among these extinction episodes. Instead, the extinction events are argued to exhibit a pattern of random occurrence. Hoffman's criticism was, in turn, rebutted by a response from Seposki and Raup, among others[65]. Other pessimists, including Stephen Stigler and Melissa Wagner from the University of Chicago, contend that the periodicity coming out of the recent research is simply a statistical artifact[66]. In essence, these skeptics argue, particular kinds of measurement errors can artificially generate a cyclic pattern in the data or force a false periodic signal to emerge from data that is not truly cyclic. Jennifer Kitchell and Daniel Pena of the University of Wisconsin argue that the spacing and magnitude of mass extinctions over the last 250 million years is best explained by a random model[66].

Finally, paleontologists Colin Patterson and Andrew Smith of the British Museum of Natural History have noted the dependence of the periodic extinction results on the way new species, genera, and families have been established and described in the literature[67]. These paleontologists limited their study to animals with which they are especially familiar and utilized a method of systematically organizing organisms called cladistics (see Part 2 for a detailed explanation). Their results showed that only about 25% of the alleged extinctions of fish and echinoderms (sea urchins, starfish, etc.) were confirmed to have really happened. In fact, a few paleontologists, like John Briggs at the University of South Florida, have recently taken an even more extreme position. Briggs argues that, because of such problems in interpreting the fossil record, no mass extinctions have actually ever happened[68]. This represents a return to an extremely gradualistic view of the mode of evolution.

In all, a lot of geologic evidence has been cited by advocates of the impact hypothesis as documentation for an extraterrestrial impact, but most of these lines of evidence have been countered by proponents of the volcanic extinction hypothesis. In our role as geologic detectives, it would be nice to have *unequivocal* evidence in order for us to decide once and for all whether an impact really occurred during the K-T transition. To provide that, impact advocates would have to find the crater left by the impact itself--the "smoking gun" as it has been called. The search for that evidence is the subject of the next chapter.

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Figure Captions for Chapter 5

fig. 5.01

In the early 1800s, Georges Cuvier interpreted the sequence fossil faunas in rocks of the Paris Basin to represent a series of catastrophic extinction events. This marked the beginnings of the "catastrophic" school of biological changes.
(from...

fig. 5.02

The English geologist James Hutton is commonly credited with establishing the priciple of uniformitarianism. This idea argues that ancient geological deposits were created by the same geological processes that one can see operating on the Earth today.
(from...

fig. 5.03

Charles Lyell, often acknowledged as the father of modern geology, laid out the detailed geological evidence supporting uniformitarianism in his book entitled *Principles of Geology*. (from...

fig. 5.04

Participants in the extinction seminar at UC Berkeley posed for a picture early in their discussions. Seated (left to right) are Kevin Steward, Helen Michel, and Dale Russell. Standing (left to right) are Lowell Dingus, Alessandro Montanari, Luis Alvarez, Frank Asaro, William Clemens, Walter Alvarez, and Mike Greenwald. (from photo by Saxon Donnelly in Cal Monthly, ...)

fig. 5.05

The thin, light stripe of clay near the center of the photo represents the first evidence ever discovered in a terrestrial section of rocks for the Ir-rich fallout layer from the K-T impact. It is found at the boundary between the Hell Creek and Tullock Formations near Jordan, Montana.
(from L. Dingus slide in Norell, M., E. S. Gaffney, and L. Dingus, 1995, Discovering Dinosaurs, Knopf, New York, p. 65.)

fig. 5.06

The first Ir-rich layer ever discovered was in marine limestones exposed near Gubbio, Italy. The coin is laid on the caly layer containing the fallout from the impact.
(from Stanley, S., 1987. Extinction, Sci. Am. Library, W. H. Freeman, New York. p. 134)

fig. 5.07

This microscopic photo shows a glassy tektite--one of millions of small meterorites that fall through the Earth's atmosphere to land on the ground and in the seas. Such objects are enriched in iridium. (from Stanley, S., 1987, Extinction, Sci. Am. Library, W.H. Freeman, New York, p. 143; originally from Keller, G., et al., 1983, Science, v. 221, 150-152.)

fig. 5.08

These charts illustrate the elevated levels of iridium found at four different sites spanning the K-T boundary. Such "anomaolus" concentrations of iridium have now been found at over 100 sites around the world. (from Courtillot, V., October 1990, A volcanic eruption, Sci. American, p. 91)

fig. 5.09

Dinosaur Cove in Australia has produced fossils of dinosaurs that lived on the continent about 100 million years ago when Australia occupied a position much nearer the South Pole than it does today. (from Rich, P. and T. H. Rich, July 1993, Australia's ploar dinosaurs, Sci. American, p. 52)

fig. 5.10

Near the north Pole, another asssemblage of dinosaurs has been uncovered along exposures cut by the Colville River. Along with those found at Dinosaur cove, these fossils raise questions about whether dinosaurs would have been decimated by long periods of darkness and cold. (from Clemens, W. A. and L. G. Nelms, 1993, Paleoecological implications of Alaskan terrestrial vertebrate fauna in the latest Cretaceous time at high paleolatitudes, Geology, v. 21, pp. 503-506.

fig. 5.11

This map illustrates the global distribution of geological evidence used to support the impact hypothesis for dinosaur extinction. (from Alvarez, W. and F. Asaro, October 1990, An extraterrestrial impact, Scientific American, p. 79)

fig. 5.12

On this chart, the concentration of iridium is plotted against distance from the K-T boundary in marine limestones of Italy. Notice how the concentrations are low, less that one part per billion, in the Cretaceous limestone at the botttom of the section. The higest concentrations, about 8 parts per billion, are found in the boundary clay.

(from Alvarez, L., 1983, Experimental evidence that an asteroid impact led to the extinction of many species 65 million years ago, Proc. Nat. Acad. Sci., USA, p. 630)

fig. 5.13

An eruption rages at Kilauea on Hawaii. (from Decker, __ and Decker,___, 199_, Volcanoes, W. H. Freeman, New York, plate 1.

fig. 5.14

This photograph of a quartz crystal from the boundary clay in Wyoming was taken under a microscope. Although it is less than one mm in length, it shows the multiple planes of fracturing that most scientists believe resulted from the impact near present-day Yucatan. (from Bohor, B. F., 1990, Shocked quartz and more; impact signatures in Cretaceous/Tertiary boundary clays, Geol. Soc. Am., Sp. Pap., 247, p. 336)

fig. 5.15

Meteor Crater in Arizona is about 3/4 (1.2 km) mile in diameter. It is thoght to have been formed by the impact of an iron meteorite between 75 and 180 feet (25-60 m) in diameter, which created an explosion equivalent to between 4 and 60 megatons of TNT[40]. (from Press, F. and Siever, 1978, Earth, W.H. Freeman, New York, p. 531)

fig. 5.16

This scanning electron microscope photos of spinel crystals brom the boundary clay at Caravaca, Spain is thought by many scientists to represent evidence for impact.
(from Bohor, B. F., 1990, Shocked quartz and more; impact signatures in Cretaceous/Tertiary boundary clays, Geol. Soc. Am., Sp. Pap., 247, fig. 3).

fig. 5.17

These microscopic spheres and globules, about 2-3 mm in diameter, are thought by proponents of the impact hypothesis to represent the molten droplets of rock blasted out of the Chixulub Crater by the impact. (from Bohor, B. F., 1990, Shocked quartz and more; impact signatures in Cretaceous/Tertiary boundary clays, Geol. Soc. Am., Sp. Pap., 247, fig. 4)

fig. 5.18

Photographs taken by a scanning electron microscope show soot and carbon particles thought to have resulted from wildfires ignited by the impact and its fallout.

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(from Wolbach, W., et al., 1990, Major wildfires at the Cretaceous/Tertiary boundary, Geol. Soc. Am., Sp. Pap., 247, p. 392; Stanley, S., 1987, Extinction, W. H. Freeman, New York, p. 167)

fig. 5.19

The peaks on this graph document the episodes of mass extinction in the geologic past. (from Hallam, A., 1989, Catastrophism in geology, In Alvarez, W., et al., Catstrophes and Evolution: Astronomical Foundations, Cambridge Univ. Press, Cambridge, p. 37)

fig. 5.20

The peaks on this graph illustrate how major episodes of extinction in the fossil record might correlate with a periodicity of 26 million years.

(from Hallam, A., 1989, Catastrophism in geology, In Alvarez, W., et al., Catstrophes and Evolution: Astronomical Foundations, Cambridge Univ. Press, Cambridge, p. 39)

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