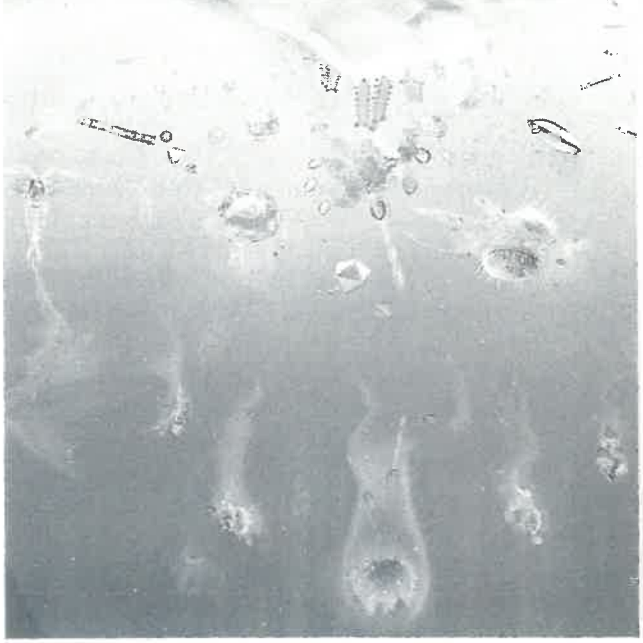
CHAPTER 13

Biodiversity through Earth History



Key Questions

- How and why has the diversity of life changed over the history of Earth?
- How can the fossil record be used to elucidate this history?
- What caused the massive losses of global diversity that have occurred at least three times over the past half-billion years of Earth history?

Chapter Overview

This chapter discusses changes in biodiversity, the variety of life forms, through geologic time. *Paleontologists* (scientists who study ancient life) use many methods to reconstruct this history. Shelly marine organisms (those with the most robust fossil record) appeared abruptly about a half-billion years ago. Their diversity rose rapidly (geologically speaking), reaching a level that persisted for a few hundred million years. Then, about 252 million years ago, Earth experienced a dramatic loss of species diversity: perhaps 95% of all species living at that time went extinct. A subsequent event, occurring some 65 million years ago, led to the extinction of the dinosaurs. A rich body of evidence supports the theory that this most recent mass extinction was a direct result of the collision of a 10-km-diameter meteorite with Earth. (We use the term *meteorite* liberally to mean a comet or asteroid that impacts Earth. Formal usage, however, would require us to refer to such objects as *meteoroids* until they strike Earth, at which point the materials that remain are referred to as meteorites.) The environmental consequences of this event were severe and clearly capable of annihilating most life on Earth at the time. Evidence for asteroid or comet impact at the other extinction boundaries is equivocal; during these events, extreme volcanic activity and its environmental consequences may have played a direct role. Nevertheless, there is a distinct periodicity in the extinction record that suggests extinction has an extraterrestrial pacemaker.

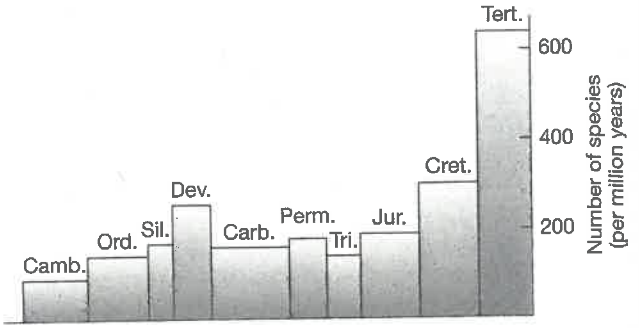
THE FOSSIL RECORD OF BIODIVERSITY

In Chapter 9 we considered the diversity of life one of its key indicators of the health of the planet. In anticipation of the forthcoming discussion of how human activity is impacting global biodiversity (Chapter 18), we here explore how the diversity of life has changed over Earth history, what the causes of those changes have been, and, in particular, how the Earth system has responded to sudden reductions in global biodiversity.

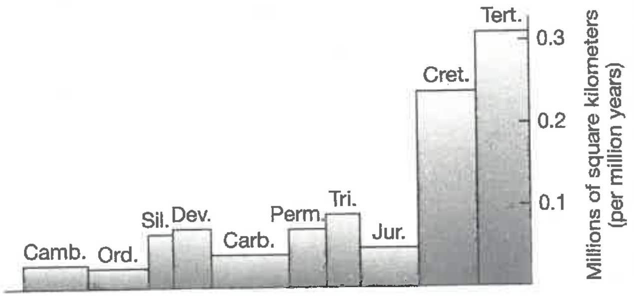
Phanerozoic Diversity Patterns

The best evidence for past changes in global biodiversity comes from the fossil record. Biologists have traditionally defined species on the basis of the ability of individuals to interbreed. This criterion obviously cannot be applied to fossils nor to organisms such as bacteria that do not reproduce sexually. Thus, paleontologists have used similarities in *morphology* (body shape) to group fossils into species. More than a hundred years of paleontological research have been laboriously compiled in an effort to determine how the diversity of life has changed over Earth history. This effort was undertaken in the 1970s and 1980s by the late Jack Sepkoski of the University of Chicago. Although the compilation has recently been updated and reanalyzed (see the following text), many of the fundamental features revealed in his compilation remain.

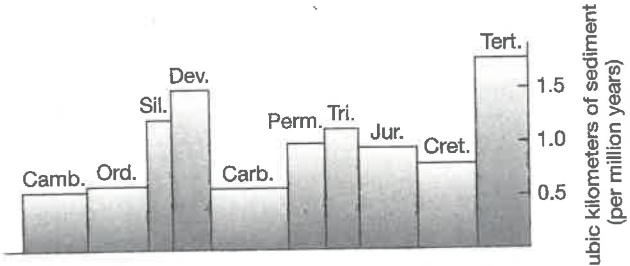
Paleontologists have cataloged the presence or absence of thousands of species of fossilizable organisms (primarily those with hard parts, i.e., skeletons, shells, or teeth). These observations reveal that, to the extent that fossil diversity reflects the diversity of all forms of life, global biodiversity has generally increased over the past 500 million years but there have been significant fluctuations (Figure 13-1a and bias-corrected curve Figure 13-2; see below). Note that in Figure 13-1a the number of species has been normalized to what we would find if rocks representing exactly 1 million years of Earth history were investigated. This normalization has been done because the geological periods are of uneven duration. Longer periods would otherwise appear to be overly diverse. Diversity rose rapidly in the Cambrian (Camb.), an event that has been called "The Cambrian Explosion." Diversity stabilized in the Ordovician (Ord.) and remained stable for much of the rest of the Paleozoic (the era from the Cambrian through the Permian), with drops at the end of the Ordovician and in the Late Devonian (Dev.). The greatest diversity drop of the entire Phanerozoic occurred in the Late Permian (Perm.), when up to 95% of all species went extinct (best seen in Fig. 13-2). Following this event, diversity recovered rather gradually, beginning an upward trend that continued for the rest of the fossil record, with two abrupt interruptions at the end of the Triassic and at the end of the Cretaceous.



(a) Apparent Species Diversity



(b) Geologic Map Area



(c) Estimated Volume of Sediment

FIGURE 13-1 (a) The fossil record of apparent species diversity of marine organisms, compared with the (b) outcrop area and (c) the volume of sedimentary rocks of the same age. All values are normalized to a million-year interval of Earth history. (*Source:* P. W. Signor, *Annual Review of Ecology and Systematics* 21, 1990, pp. 509–539.)

Biases in the Fossil Record

Unfortunately, paleontologists don't have great confidence in the species-level diversity curve shown in Figure 13-1a. The upward trend certainly is consistent with our realization that diversity must have increased over the past 3.5 billion years. However, our confidence in these data is weakened by the observation that the outcrop area (the area of rocks exposed at Earth's surface; Figure 13-1b) and the volume of sedimentary rocks (Figure 13-1c) that contain the fossils of various ages display essentially the same pattern. Particularly troubling is the anomalously high abundance of Devonian and Tertiary species (see the geologic time scale in Chapter 1), outcrops, and sediment volume. Geologists recognize that these patterns, especially the increased volume and outcrop area of the youngest rocks, are consequences of erosion: older rocks have been subject to a longer interval of erosion, so their volumes and outcrop areas are reduced. Because the number of species discovered by paleontologists depends on the availability of rocks to study, we are forced to conclude that the fossil record of species diversity is not a true reflection of the trend through Earth history. The higher species diversity of more recent times could be more apparent than real. In particular, the marked apparent increase in species diversity toward the modern is likely largely an artifact of the higher abundance of rocks and outcrops, a phenomenon called *the pull of the recent.*

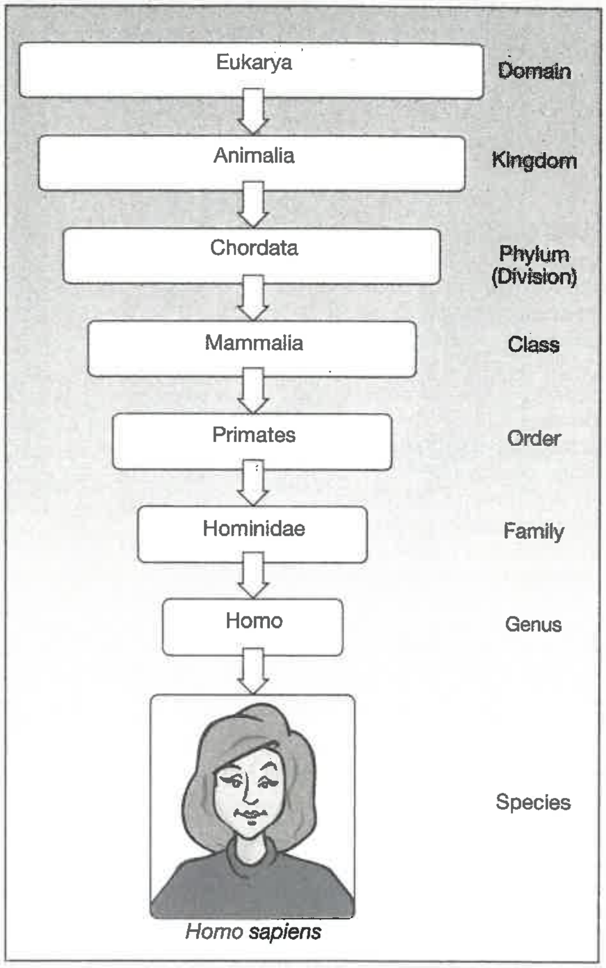
A strategy paleontologists have adopted to minimize this sampling bias is to group their fossil data into increasingly higher levels of taxonomy. **Taxonomy** is the systematic organization of living or fossil organisms into a hierarchy (see the Box "Useful Concepts: Taxonomy"). The occurrence of a single specimen of a species confirms the existence of its higher taxonomic levels: *genus, family, order, class, phylum* (for animals and some protists) or *division* (for bacteria, fungi, plants, and some protists), *kingdom,* and

USEFUL CONCEPTS

Taxonomy

Given the millions of species that exist on Earth today and the thousands of distinct fossils recognized in the geologic record, a system of organization is clearly needed. Hence the field of taxonomy (from the Greek *taxis*, meaning arrangement or order) was born. Two approaches are possible: one based on evolutionary, genetic relationships, and the other based on discernible physical similarities. The former is theoretically more satisfying, but the latter is usually more practical, especially for extinct organisms observable only as fossils. Species of extant (currently living) organisms are differentiated on the basis of their inability to interbreed. Higher levels of groupings (Box Figure 13-1) into genera (the plural of genus), families, orders, classes, phyla (the plural of phylum) or divisions, kingdoms, and domains are based on the degree of dissimilarity in all detectable characteristics between taxa (plural of **taxon**, an individual taxonomic group). For example, all families within an order should share some similarity that is distinct from all other orders.

Biochemists and evolutionary biologists are currently working feverishly to reveal the genetic sequences of a number of organisms, including both humans and bacteria. These investigators are finding that the established taxonomy based on morphology is in need of revision. Organisms that once seemed distant relatives are now surprisingly closely related on the "Tree of Life" (see Chapter 10). Moreover, there has been considerable transfer of genetic material across lineages, making the distinctions among groups a bit fuzzy. Finally, we have long known that the genetic makeup of the mitochondria of eukaryotes (including us) is distinct from the rest of the body's genetic sequences, probably indicating that eukaryotes evolved from an early symbiotic relationship among different bacteria (the "endosymbiosis" hypothesis of the origin of eukaryotes).



BOX FIGURE 13-1 A taxonomic tree for our species, *Homo sapiens*..

domain. No other species in any of these other taxonomic levels need be found. Thus, it is less likely that a higher taxonomic level will be unrepresented in the fossil record of a time when it did indeed exist. Paleontologists generally agree that the diversity record at the genus level and above, for marine organisms with well-preserved skeletons and shells and for data for which sampling biases have been removed, is reasonably robust.

Fossil Biodiversity with Bias Removed

In the most recent compilation of the fossil diversity data (Figure 13-2), paleontologists have gone to great lengths to rid the data of various biases that are associated with the processes of fossilization, subsequent erosion of the rocks hosting the fossils, and sampling. The new data are presented at the genus level and are lumped into bins with an average duration of 11 million years. This record, published in 2008 by scientists associated with the Paleobiology Database initiative (http://paleodb.org), differs significantly from earlier compilations and has yet to be fully interpreted. It displays some trends that have been recognized for a long time, including the large increase in biodiversity throughout the Cambrian (Cm) and Ordovician (O) periods. (Note the most of the genera shown in the earliest Cambrian bin arose during the earliest Cambrian, so there is an abrupt increase, not shown, during the earliest Cambrian.) The data also show major decreases in biodiversity in the latest Permian (P) and at the end of the Triassic (Tr); these decreases are associated with well-known extinctions. However, unlike the data in previous compilations (Figure 13-1a), the Cm–O diversification continues well into the Devonian (D), and then declines

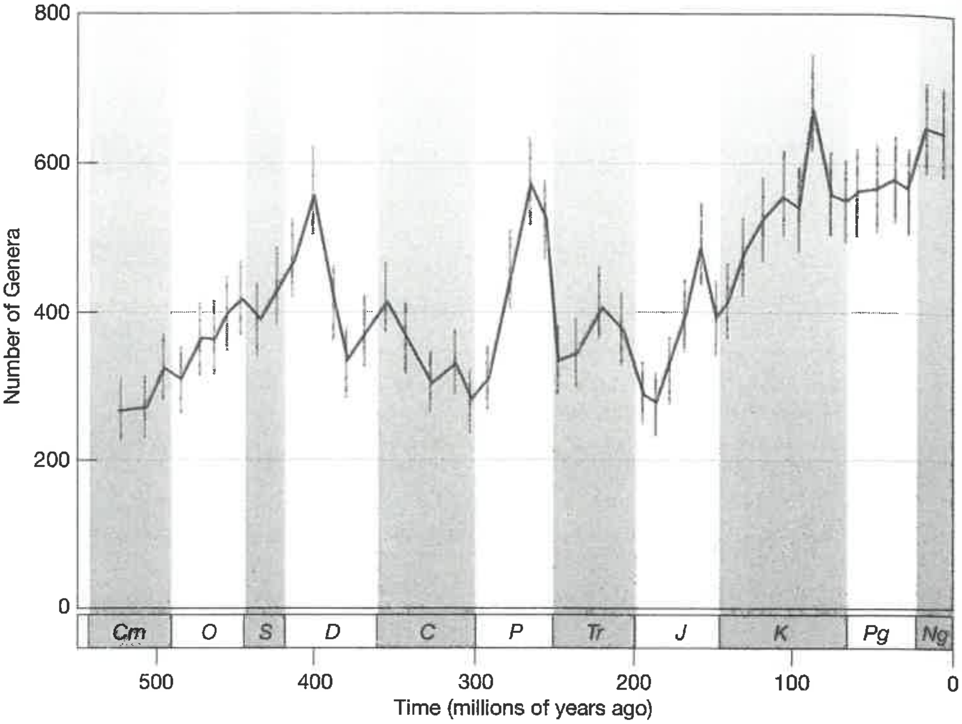


FIGURE 13-2 The fossil record of marine organism biodiversity at the genus level of classification. These data have been corrected for a number of sampling biases by the Paleobiology Database project and collected into bins that average about 11 million years in duration. (*Source:* Study published in J. Alroy et al., *Science* 321, 2008, pp. 97–100.)

into the Early Permian, rather than reaching any sort of plateau. Diversity then increases rapidly in the Permian, only to decline abruptly once more in the Late Permian. Notably missing from these data is any sign of the extinction at the end of the Cretaceous (K), which heralded the demise of the dinosaurs (Chapter 1). The unbinned data do indeed show the extinction, but because biodiversity recovered within a few million years of this event and the data are binned into approximate 11-million-year increments, the graph does not display this severe but brief diversity drop (see below).

The fossil data can also be compiled at even higher taxonomic levels to reveal more fundamental features of the evolution of biodiversity on the planet. Like the species-level curve in the Paleozoic (Figure 13-1a) and the genus-level diversity curve in the Mesozoic and Cenozoic (Figure 13-2), the order-level diversity curve (Figure 13-3a) reaches a plateau early in the Phanerozoic that is sustained for the rest of Earth history (although there is a marked Silurian high and Permian low). Early in the Cambrian period, as organisms evolved fossilizable hard parts, new species evolved rapidly as they developed new ways to utilize their environment. Common morphologies such as particularly shaped shells or skeletons arose that were related to form or function required by their particular ecological **niche** (the role a particular organism plays in the ecosystem: decomposer, surface grazer, etc.; see Chapter 9). For the paleontologist, these common features allow the species to be grouped into higher taxonomic levels. As these ecological niches were filled and the opportunities for new lifestyles diminished, the rate of appearance of novel body shapes for marine organisms (as reflected in the number of new orders) diminished. The rest of the Phanerozoic had slower rates of origination of new orders (Figure 13-3b), and this slowdown was very nearly balanced by the loss of orders (steady state was achieved).

Evolution, Extinction, and Origination

What drives these trends in biodiversity through time? The biological diversity of Earth today has been acquired through the process of biological evolution. **Evolution** can be defined as the change from one generation to the next of inherited characteristics of a population of organisms. Variability in the genetic makeup of a population of organisms arises through *genetic mutation*—damage to the DNA of organisms that occurs as a result of such processes as exposure to ultraviolet radiation (from the sun), natural radioactivity in the environment, and exposure to certain chemicals. Mutations can also result from mistakes made in DNA replication during reproduction. Usually, mutated genes are detrimental to the organism, reducing its prospects for reproduction or survival, but occasionally they are beneficial. Organisms with these desirable traits (termed **adaptations**) have a higher likelihood of reproduction and/or survival under given environmental conditions, allowing them to pass on the trait to their descendants. This process, **natural selection**, is the major driver for evolution. If a population of organisms becomes isolated from the rest of the members of its species and acquires favorable adaptations through natural selection, it may eventually become a new species, unable to breed with the original species; this process is called **origination.** **Extinction** is the loss of all individuals within a species. It can occur because the species has become unfit or

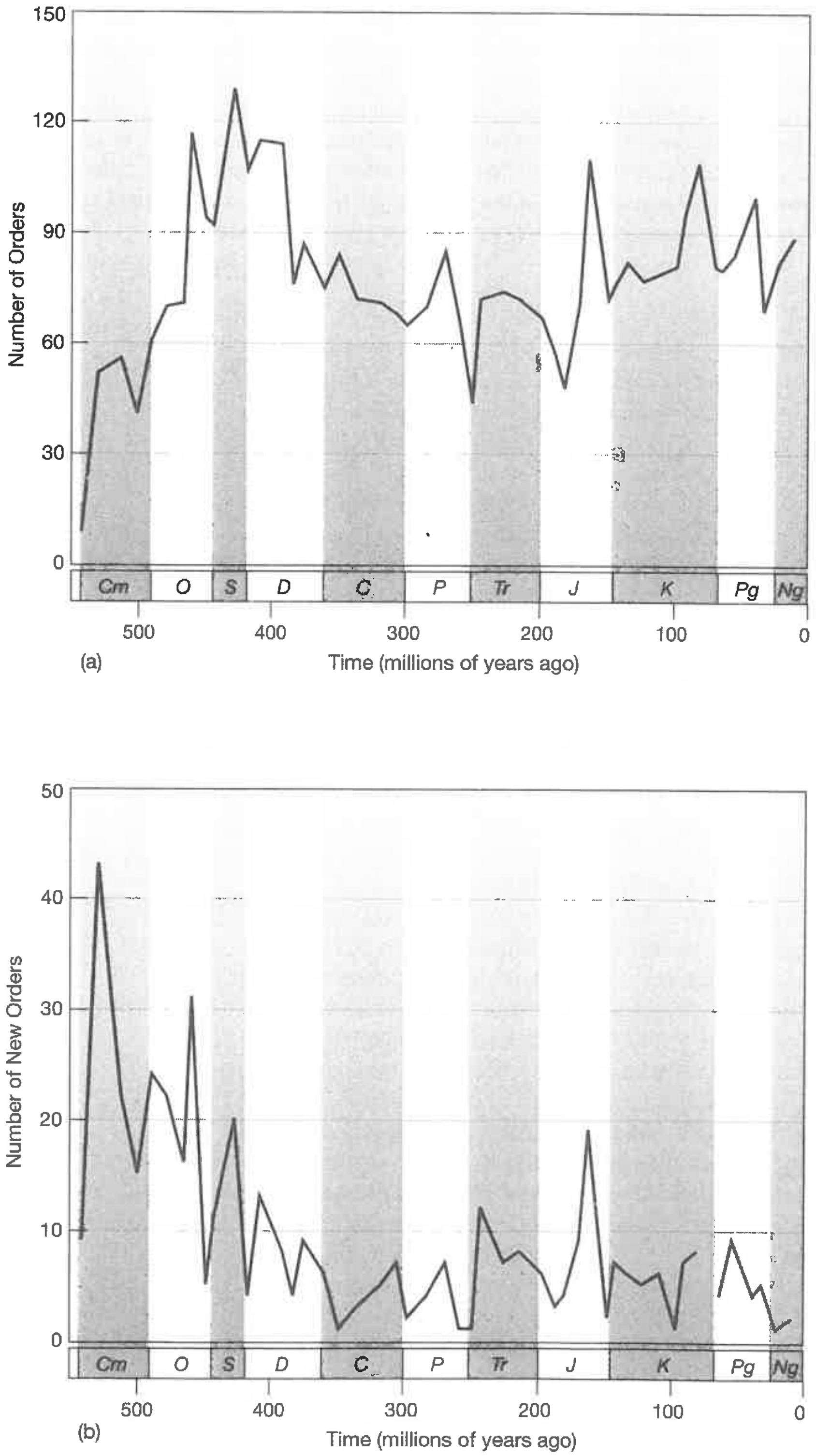


FIGURE 13-3 (a) The apparent diversity of fossilized marine organisms through geological time, grouped at the order taxonomic level. (b) The number of new orders of marine organisms that first appear in sedimentary rocks of a given age. The Cambrian and Ordovician were clearly a remarkable time of origination of a variety of new body shapes (which allow paleontologists to recognize the appearance of the various taxonomic groups). (*Source:* Courtesy John Alroy, Paleobiology Database, National Center for Ecological Analysis and Synthesis.)

uncompetitive in its (often changing) environment, or it could result from an external stress that affects a particular species or many species simultaneously.

Diversity is best thought of as a dynamic characteristic of the biota:

$$\begin{array}{c}\text{rate of change in number}\\ \text{of species on Earth}\end{array} = \begin{array}{c}\text{origination}\\ \text{rate}\end{array} - \begin{array}{c}\text{extinction}\\ \text{rate}\end{array}$$

Researchers estimate that 10 to 25 species originate every year, and 10 to 25 go extinct. These are considered to be the average rates of origination and extinction as a result of natural selection, which was first described by Charles Darwin. We can safely presume that, through evolution by natural selection, the total number of species has increased over the 3.5-billion-year history of life on Earth, indicating that origination has slightly exceeded extinction over these very long time scales. Whether this increase has been linear, exponential, or represented by some more complicated pattern is a fundamental question of paleontology. Certain intervals of Earth history exhibit much greater rates of origination and extinction. Like the most recent diversity data, these trends are expressed at the genus level (Figure 13-4).

Three **mass extinctions**, in which 50% or more of the genera (plural of genus) go extinct during one bin, are evident in the data: these occur at the ends of the Permian (P), Triassic (Tr), and Cretaceous (K) periods. Each of these is followed "immediately" (in the next data bin, or in less than 10 million years) by enhanced rates of origination. High apparent rates of extinction in the Cambrian (Cm),

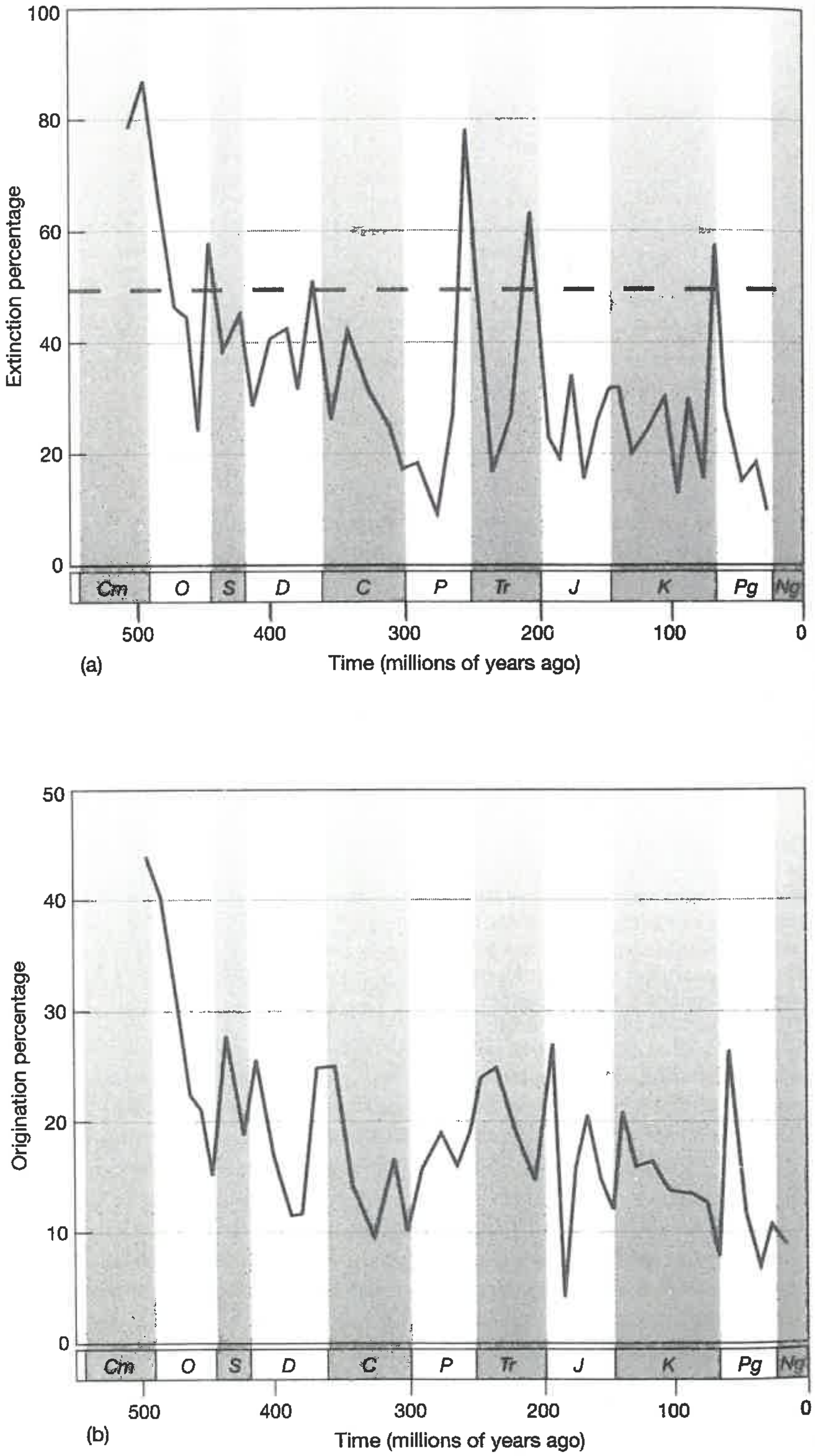


FIGURE 13-4 Rates of origination and extinction of genera during the Phanerozoic. Extinction is defined as the percentage of genera present in a bin that are absent in the next bin. Bin length averages 11 million years. Origination likewise is expressed as the percentage of genera appearing during an interval of time that weren't present in the previous bin. The five major Phanerozoic extinctions are those that exhibited greater than 50% genus loss. (*Source:* Courtesy John Alroy, Paleobiology Database, National Center for Ecological Analysis and Synthesis.)

Late Ordovician (O), the Late Devonian (D), the latter two commonly identified as mass extinctions in the literature, may be artifacts of uncorrected biases in the record. The biodiversity drop in the Late Devonian in the new dataset seems to be brought about as much by a failure of origination (Figure 13-4b) as by a peak of extinction (Figure 13-4a). Another biodiversity drop, at the end of the Ordovician, has been well studied as a mass extinction but here doesn't appear to be particularly anomalous. The three undisputed mass extinctions are at one extreme of a continuum of origination and extinction rates from the small to the extremely large. Thus, origination and extinction, like other natural phenomena (floods, earthquakes), are likely to be the result of a variety of causes occurring on many different time scales and over a range of magnitudes.

The time period from the Triassic to the Recent exhibits a plateau in genus-level diversity (Figure 13-2) despite very high rates of turnover of the biota on geologic time scales: origination and extinction rates typically range from 20 to 40% per bin interval (~11 million years), meaning that the genera that make up one bin are quite different from those of the next bins. Thus, the diversity curve could be considerably more variable than it actually is. The fact that it does not vary that greatly may reflect feedbacks that tend to stabilize diversity over time. According to the fossil data, extinction rates tend to be highest when diversity is high (tending to suppress unrestrained growth of biodiversity; a negative coupling), and origination rates tend to increase markedly following large extinction events. Presumably, mass extinction empties ecological niches that newly evolved species can fill. Although the response is geologically rapid, it takes up to tens of millions of years. The fossil record shows that if modern species diversity continues to decrease, it will be a long time before the system recovers.

Causes of Mass Extinction

The largest of all known mass extinctions occurred at the end of the Permian period, 252 million years ago. It occurs near the beginning of a series of huge volcanic eruptions in Siberia, suggesting that these events could be causally related. The eruptions created massive basalt flows that are known today as the **Siberian Traps**. The volcanic eruptions also appear to have permeated a gigantic coal bed that had been previously emplaced. Heating of this coal could have led to a rapid buildup in atmospheric carbon dioxide, extreme global warming, and loss of oxygen from the oceans, leading to an "anoxic" state that would be inhospitable to oxygen-dependent organisms. One hypothesis suggests that toxic hydrogen sulfide (H_2S) built up in the anoxic oceans and was released suddenly to the atmosphere, causing extinctions on land and in the surface ocean. However, all of these explanations are still considered speculative, and the end-Permian extinction remains a topic for research and debate.

In contrast, the Cretaceous–Tertiary (K–T) mass extinction (65 million years ago) has been the focus of a tremendous amount of research in the past few decades. It has also captured the attention of the general public, because it is the event at which the dinosaurs went extinct. And, it appears that the killer has been identified. For these reasons, we end this chapter with a detailed discussion of the K–T event.

THE CRETACEOUS–TERTIARY MASS EXTINCTION

It has been estimated that 75% of all species went extinct in a very short interval of geologic time at the end of the Cretaceous period. The species affected included both marine- and land-based organisms. The most well known, of course, were the dinosaurs.

Two important questions arise concerning the K–T mass extinction: What caused it? And, how did the Earth system respond to and recover from it? The first of these has been one of the most thoroughly studied questions in Earth science and has perhaps engendered more hypotheses than the origin of life itself. The second question is of particular importance to us because it returns us to our discussion of the resiliency of the Earth system to perturbations.

Possible Causes of the K–T Mass Extinction

As many as 20 hypotheses on the cause of the mass extinction at the end of the Cretaceous period have appeared in the scientific literature. Add to that a similar number of wild speculations appearing in the tabloids (including invasions by extraterrestrial life-forms), and you have the sort of scientific enigma that is certain to stimulate discussions in all forums for some time to come. Of these, only four survived the scrutiny of scientists working on the problem in the late 20th century: (1) sudden sea-level changes, (2) sharp temperature fluctuations, (3) volcanic eruptions, and (4) meteorite impacts.

A central tenet of the scientific method is that hypotheses cannot be proved, only disproved. A hypothesis that continues to be consistent with observations may be elevated to the status of theory. Eventually, however, even well-established theories may be disproved as new observations are made that are inconsistent with theory. The debate about the causes of mass extinctions, especially that at the K–T boundary, provides a good example of how theories rise and fall from general acceptance within the scientific community.

SEA-LEVEL CHANGE AND CLIMATE CHANGE Until quite recently, changes in sea level or climate were the generally accepted theories for explaining mass extinctions including the K–T. Major drops in sea level are known to have contributed to extinctions of marine life by exposing vast regions of the continental shelves to the atmosphere, leading to the loss of habitat for shallow-marine organisms (which tend to dominate the fossil record). Climate excursions, especially glaciations or periods of extreme warmth, have also severely stressed marine communities, especially those in the tropics, which are especially temperature-sensitive, causing substantial losses of biodiversity.

However, some of the largest known sea-level drops were not associated with mass extinctions. It is also unclear how sea-level changes could have exterminated land-dwelling organisms, such as the dinosaurs. As for climate change, the best studied of the glaciations, those of the Pleistocene epoch (see Chapter 14), were associated with only a modest level of extinction, despite rapid climate swings and sea-level fluctuations. Glacial sea-level fall seems to be the best explanation for the Late Ordovician mass extinction, though.

METEORITE IMPACT AND VOLCANIC ERUPTIONS. Astronomical explanations for mass extinctions have long existed but have suffered from lack of substantiation. One such hypothesis called for a nearby supernova, which would have destroyed Earth's ozone layer, leading to high levels of exposure to ultraviolet radiation. On similar, purely theoretical footing was the idea that a large meteorite impact caused the K–T extinction.

Anomalously high concentrations of **iridium**—an element that is rare at Earth's surface but is concentrated in Earth's interior and in extraterrestrial materials—were found in 1979 in unusual, fine-grained sediments deposited at the end of the Cretaceous (the K–T boundary clays of Gubbio, Italy). This iridium anomaly was the piece of evidence needed to establish meteorite impact as the currently accepted theory for the cause of the K–T extinction (see Chapter 1). However, a minority of scientists were still convinced that widespread volcanism was to blame. These scientists argued that volcanism would lead to many of the same environmental changes as a meteorite impact would have. We will examine this controversy as an example of how theories compete for acceptance by the scientific community.

Proponents of the meteorite-impact theory made a number of predictions, any of which, if invalidated, would disprove the theory. Luis Alvarez, one of the discoverers of the iridium enrichment layer, has enumerated predictions to test the theory and the ways in which previously made and new observations are consistent with the theory:

1. ***An iridium enrichment should be found in K–T boundary sediments worldwide.*** The K–T iridium anomaly has been documented in more than 75 localities around the globe in both marine- and land-based sediments. A 10-km-diameter meteorite is required to account for the amount of iridium deposited in all these regions.
2. ***This enrichment should always be found within the same interval of geologic time.*** All iridium layers found near the K–T occur in an interval defined by magnetic polarity reversals (see Chapter 7) known as *polarity chron C29R,* which has been precisely dated to span the interval from 65.6 to 64.9 million years ago. The K–T boundary is placed at 65.0 million years ago by these researchers.
3. ***Large meteorites strike Earth sufficiently frequently to explain the extinction record.*** The late Eugene Shoemaker of the U.S. Geological Survey (a codiscoverer of the Shoemaker–Levy comet that collided with Jupiter in 1994) demonstrated that a strong relationship exists between the frequency and size of impacts (Figure 13-5). The data he used span time and size scales ranging from observations of the rate of space shuttle pitting (one dust-sized impact every 30 μsec on average) to the frequency of large cratering events (every 10,000 years for 100-m-wide impactors). Recent satellite observations confirm the left side of the figure (objects smaller than 10 m in diameter), and near-Earth asteroid tracking studies confirm the diagram up to ~200-m-diameter objects. According to this relationship, a meteorite 10 km in diameter should strike Earth on average every 100 million years. This is a rare event, but many such events have occurred since the origin of life. Five or six such events should have occurred since the beginning of the Phanerozoic. Impacts of the sort that caused the widespread devastation of Tunguska, Siberia, in 1908 occur about once every thousand years. In this event the bolide exploded in the atmosphere, flattening trees over hundreds of square kilometers (the area of a large city).
4. ***On shorter time scales, such events should be rare.*** In polarity chron C29R, there are no other iridium enrichments. In a study of a 34 million-year interval surrounding the K–T event, it is the only known anomaly. In fact, no iridium anomalies of comparable size have been detected anywhere else in the geologic record. According to prediction 3, several iridium layers should be lurking in rocks that have not been analyzed, unless most meteorites do not have large iridium abundances. (A comet, for example, would leave much less iridium for the same magnitude impact event because it is roughly half water ice—the iridium would be contained only in the rocky part—and because a typical comet impact would occur at much higher velocity than an asteroid impact. Comets originate from the outer solar system or beyond and often have orbits that are highly inclined to Earth's orbit, sometimes even in the opposite direction. A typical comet that hit Earth would do so at ~60 km/s, compared to ~20 km/s for a typical Earth-crossing asteroid. The kinetic energy of the impact is proportional to the square of the velocity: $K.E. = 1/2\ mv^2$. Thus, for impacts of the same total kinetic energy, a comet would deliver only about 1/20th as much iridium as would an asteroid.)
5. ***Plants as well as animals should have suffered as a result of the meteorite impact.*** There is

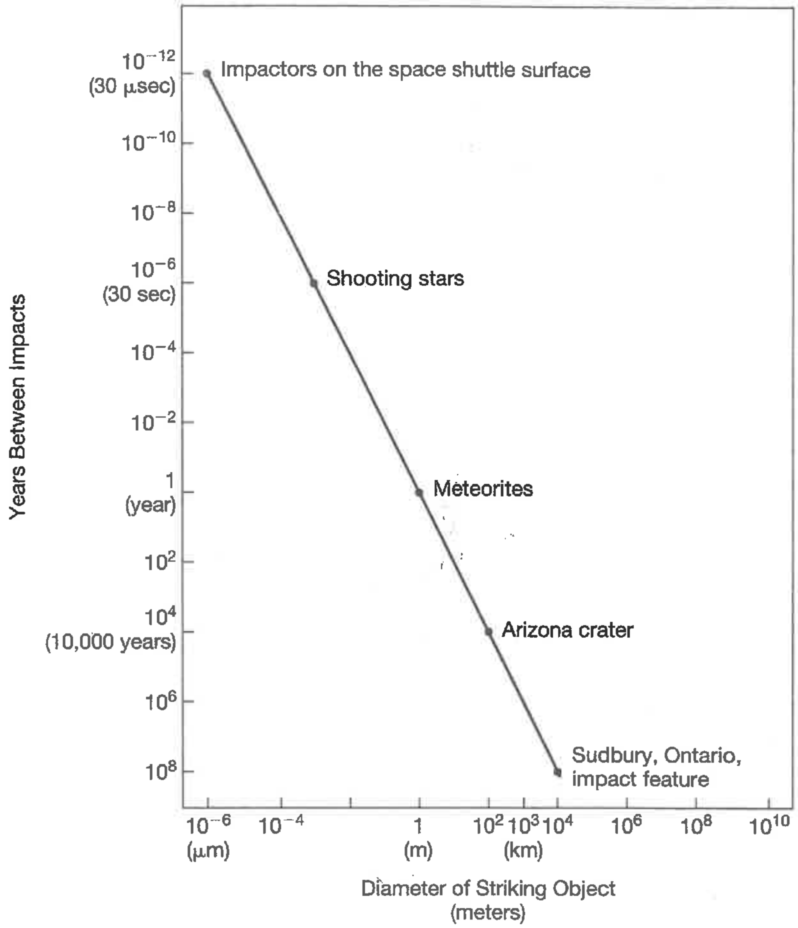


FIGURE 13-5 The Shoemaker curve: the frequency of collisions of extraterrestrial material with Earth, as a function of the size of the material. (*Source:* Luis W. Alvarez, *Physics Today*, July 1987, pp. 24–33.)

now clear evidence of significant turnover in the types of vegetation inhabiting the land surface, as recorded particularly well by spores and pollen (Figure 13-6).

6. ***The gross chemical composition of the boundary clays should be identical worldwide, given that they all originated from the same excavated material.*** The K–T boundary clays from Denmark and from the central Pacific are reported to be so similar in composition as to preclude diverse, local origins. The boundary clay is thought to contain debris from the impactor itself, along with a larger amount of

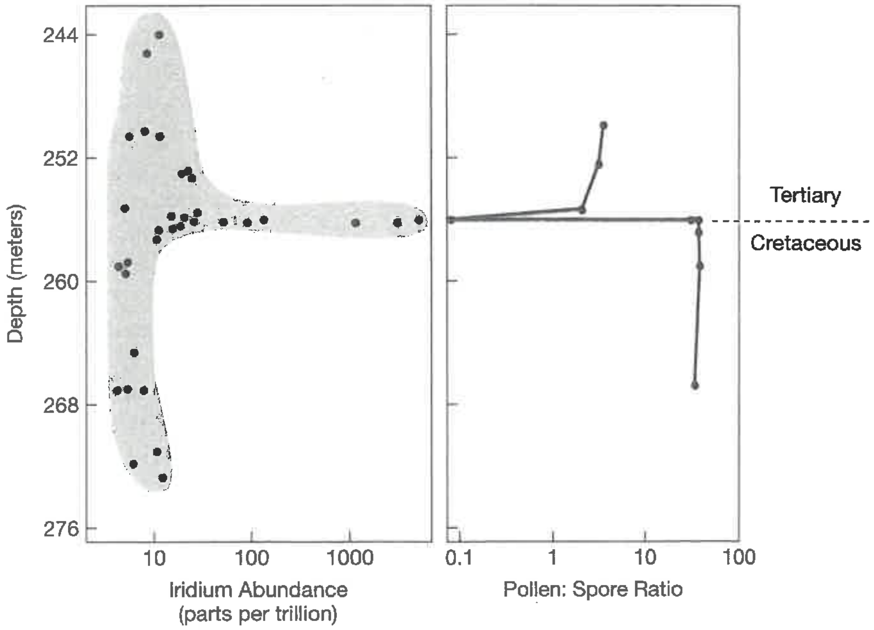
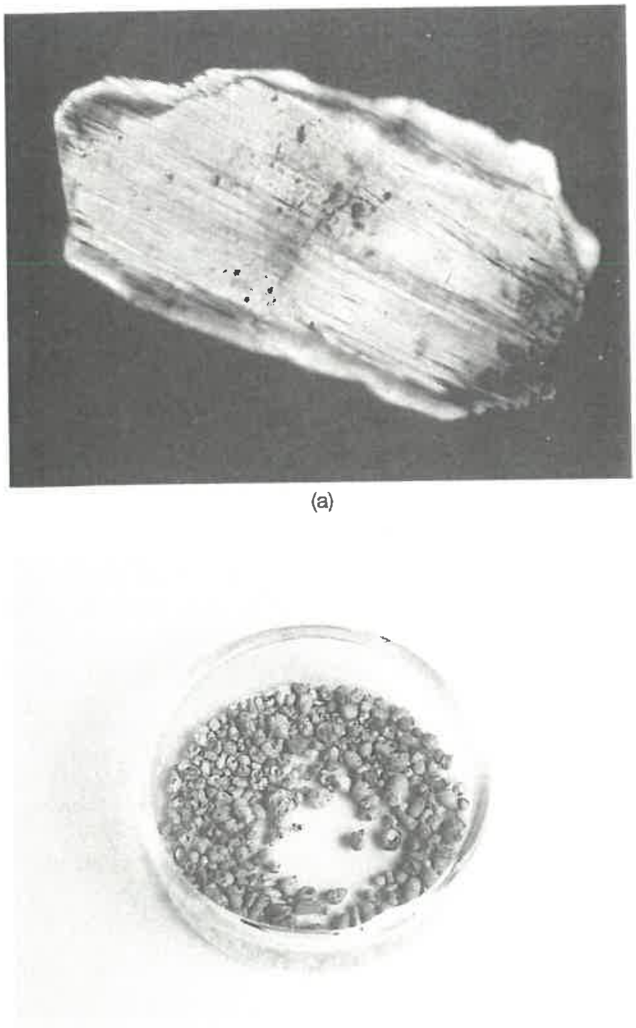


FIGURE 13-6 The Cretaceous–Tertiary iridium anomaly is coincident with a major change in the types of plants inhabiting the Ràton Basin of New Mexico, as indicated by the fossil pollen-to-fern spore ratio. A diverse community of plants collapsed to one dominated by a few species of fern. Samples were drawn from a drill core at the depths indicated on the graph. (*Source:* Luis W. Alvarez, *Physics Today*, July 1987, pp. 24–33.)

material from Earth's crust and upper mantle that was excavated by the impact.

7. ***The boundary clays should differ in composition from more typical clays deposited above and below the boundary clays at individual sites.*** Compositional differences between the iridium-rich boundary clays and the surrounding sediments have been confirmed at a number of sites.
8. ***Any chemical or isotopic signature in the boundary clay will have a significant extraterrestrial component.*** The iridium anomaly is the best studied of these anomalies, although other geochemical and isotopic signatures are arguably extraterrestrial.
9. ***The boundary clays should bear some evidence of the high temperatures generated during impact.*** Small *spherules* of silicate minerals (Figure 13-7) have been found in the boundary clays. These spherules are thought to have formed when molten rock droplets, ejected into the atmosphere during the impact, cooled and solidified into glassy spheres before being redeposited at Earth's surface.
10. ***The boundary clays should bear some evidence of the high pressures generated during impact.*** Small, fractured grains of *shocked quartz* are commonly found in boundary clays (see Figure 13-7). These grains form only when quartz is subjected to very high pressures—the sort we would expect from a meteorite impact. Under these conditions, the crystal structure of quartz is deformed in a characteristic fashion, so geologists can easily differentiate shocked quartz from quartz that is gradually subjected to the high pressures deep within Earth. Shocked quartz has also been found near known meteorite craters and in rocks surrounding the sites of underground nuclear explosions.
11. ***The K–T event should have generated wildfires that might have left a sedimentary record of charred material.*** Charcoal is indeed commonly found in K–T boundary clays. Calculations by Jay Melosh of the University of Arizona and colleagues provide a natural explanation for the apparent worldwide occurrence of wildfires during the K–T event. The impact excavated a huge amount of material in forming the crater, and this material was blasted in all directions away from the point of impact. Some of it was injected high into the atmosphere. The heating associated with reentry of ejected material through the atmosphere, estimated to be 50–100 times the solar flux, created unbearably hot conditions in cloud-free regions all over the world. Thus, a mechanism for rapid drying and ignition of vegetation on all continents would have existed. In cloudy areas, or beneath the sea or lakes, this energy would instead have gone into evaporating liquid water in cloud droplets.
12. ***The iridium-rich layer should be just above the last dinosaur fossil.*** At Gubbio, Italy, the iridium layer is less than a millimeter above the last occurrence of Cretaceous *foraminifera* (microscopic plankton; see Chapter 8). However, foraminifera are not dinosaurs. Dinosaur fossils are rare, and we are unlikely to find the last dinosaur fossil directly below the iridium layer (although, theoretically, if we keep looking we might find a charred dinosaur fossil buried in iridium-rich clay). Paleontologists have found articulated dinosaur fossils (fossils with joints intact) no closer than 2 m below the K–T boundary, as defined by the iridium layer. The low probability of preservation of fossils near boundaries can make an abrupt mass extinction appear to be gradual; this is called the *Signor-Lipps effect* and is well known to paleontologists. Conversely, disarticulated dinosaur fossils have been found in sedimentary rocks well above the K–T boundary. This has generated some confusion and controversy, but these fossils likely have been



(a)

(b)

FIGURE 13-7 [See color section] Shocked quartz and (b) microspherules from K–T boundary clays. (*Source:* (a) Dr. David Kring/SPL/Photo Researchers and (b) David Parker/ SPL/Photo Reasearchers.)

eroded from older rocks and redeposited in younger sediments. No complete dinosaur skeleton has ever been found above the boundary.

13. ***The pattern of extinction should show no evidence of preferential survival of species that were well adapted to the Cretaceous environment.*** As mentioned before, mass extinctions in general, and the K–T one in particular, have been notably nonspecific. However, it does appear that large land animals were particularly hard hit by the K–T mass extinction; virtually all species with average weights greater than 25 kg (55 lb) went extinct. In contrast, mammals, which at the time were lightweights, fared much better. Perhaps smaller animals fared better simply because their population sizes were larger: Statistically speaking, some would survive the event. Or perhaps they were better able to avoid the immediate effects of the meteorite impact. After the extinction, mammals evolved, filling many of the niches left vacant by the demise of the dinosaurs.

The confirmation of the Alvarez predictions supports the meteorite-impact theory for the K–T extinction, but it does not prove it. The volcanic theory of mass extinction shares many features of the meteorite-impact theory, and is a more plausible explanation for the end-Permian mass extinction. Large increases in volcanic activity could, in the short term, increase the amount of sulfuric acid aerosol in the stratosphere, cooling the climate. Indeed, several such volcanic cooling events have been identified in the climate record of the past few centuries (see Chapter 2). However, only explosive volcanoes like Mt. Pinatubo or El Chichón inject aerosols into the stratosphere. Large volcanic eruptions did occur during the Late Cretaceous; they formed great layers of basalt in India that are known as the Deccan Traps. If these flows resembled modern flood basalts, though, they were gentle outpourings of basalt that did not produce much aerosol. The settling ash from volcanic eruptions could create a worldwide clay layer similar to the K–T boundary clay and might also produce spherules and shocked quartz. In the long term, carbon dioxide released by volcanism would lead to global warming. These climatic fluctuations would present environmental stresses to which many groups of organisms could not adapt. However, according to Alvarez, the volcanic theory is inconsistent with three observations:

1. Sand-sized spherules, even if ejected by volcanoes, would not reach ballistic orbits (as do impact ejecta) or be distributed globally, as the K–T spherules are observed to be.
2. Shocked quartz of the sort found at the K–T boundary has never been found in deposits of volcanic origin but is common in deposits associated with known impact craters.
3. Volcanic ejecta tend to have very low iridium concentrations.

Who is right? The arguments are complicated, but the evidence strongly favors the impact hypothesis. Indeed, since the Alvarez team performed their study, additional evidence has emerged that provides further support for the impact hypothesis. One such new piece of evidence is the discovery of fullerenes or "buckeyballs" in K–T boundary sediments. *Fullerenes* are large cagelike molecules containing 60 or more carbon atoms arranged in a sphere. (They derive their name from architect Buckminster Fuller, who designed the first geodesic dome. Fullerenes resemble a tiny version of his visionary creation.) Fullerenes are formed in all sorts of environments where carbon is burned, including ordinary candle flames. However, the fullerenes found at the K–T boundary contain helium with isotopic ratios that are clearly extraterrestrial. (Recall that most of Earth's helium, ^{4}He, is produced from decay of uranium and thorium. By contrast, the K–T fullerenes contain mostly ^{3}He. This suggests that they were formed in the expanding envelopes of dying, carbon-rich stars.)

This argument, like most of the original arguments presented by the Alvarez team, is somewhat technical. It is convincing to most experts in the field, but is hard to explain to a nonscientist. As we will see, however, the evidence for the impact hypothesis has become quite down-to-Earth.

The Smoking Gun: The Chicxulub Crater

Another prediction from the meteorite-impact theory is that somewhere on Earth a very large crater should exist, representing the site of impact of the 10-km meteorite. Until very recently, scientists had explained their inability to locate such a crater by pointing out that it was probably excavated in oceanic crust, given that three-quarters of Earth's surface is ocean-covered, and thus might have already been subducted into the mantle by plate tectonics (see Chapter 7). Even if the impact had occurred in continental crust, they argued, the crater is likely to have been eroded. Nevertheless, the search continued. Several putative K–T craters were discovered but found to be of a different age or of insufficient size to explain the observed iridium anomaly.

Then, in the early 1990s, geologists discovered convincing evidence that a structure buried 1 km below the surface, located near the town of Chicxulub (sheek'-soo-loob), Mexico (Figure 13-8), was indeed of K–T age. Previous investigators had suspected, on the basis of remotely sensed geophysical anomalies, that this structure was an impact crater. The only expression at the surface of this subsurface feature was a ring of sinkholes, known in Mexico as cenotes. Then, exploratory wells previously drilled into the Chicxulub structure by Pemex, the Mexican oil company, provided samples containing shocked quartz and glass microspherules that closely resembled samples from known K–T intervals elsewhere. Further analysis of the drilled core materials revealed very strong enrichments of iridium. Isotopic age dating and paleomagnetic evidence

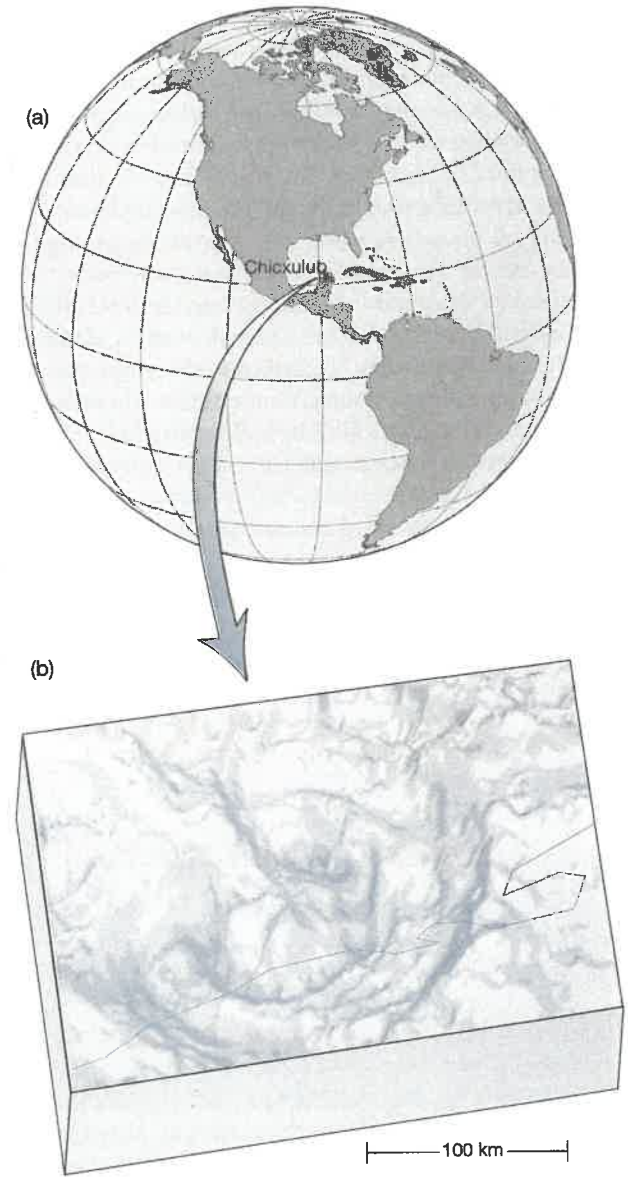


FIGURE 13-8 (a) The location of the Chicxulub impact crater. (b) The shape of the crater as inferred from gravity anomalies. (*Source:* Courtesy V. L. Sharpton, Lunar and Planetary Institute.)

constrained the age of the materials to polarity chron C29R, the interval containing all K–T iridium anomalies. Current estimates of at least a 200-km diameter for the crater indicate that it is the largest on Earth and one of the largest in the solar system.

Environmental Consequences of the K–T Meteorite Impact

What was Earth like during the Late Cretaceous period when the meteorite hit? How did the global environment change after the impact? If we could transport ourselves back 65 million years to the day of the impact, we would find ourselves in a world quite different from that of today. Equator-to-pole gradients in temperature were less, and the poles were essentially ice-free, most likely the result of high atmospheric CO_2 levels. Dinosaurs inhabited tropical to near-polar latitudes—not in the abundances of their peak some tens of millions of years before, but still in sufficient numbers to dominate higher levels of the food chain.

The impact would have been unexpected and sudden. The passage of the meteorite through the atmosphere would have converted nitrogen gas (N_2) to nitric oxide (NO), as does lightning on a smaller scale today (see Chapter 11). Produced in large quantities, the NO would have destroyed the stratospheric ozone layer by catalyzing reactions that consume ozone, allowing ultraviolet radiation to reach Earth's surface unimpeded for as long as several years. Organisms unfortunate enough to be on the Yucatan Peninsula would have instantly been annihilated as an explosion of unimaginable intensity sent shock waves across the landscape. A huge crater would have been carved out immediately. The excavated material would have been sent on ballistic trajectories, enveloping Earth in a blanket of dust and debris. As the impact ejecta passed back through the atmosphere, the material would have been heated to temperatures sufficient to ignite wildfires in the affected areas, and those organisms not protected beneath the water surface or underneath clouds would have been subjected to air temperatures likened to putting your head in the oven on "broil." Soot would have been introduced into the atmosphere, further reducing the amount of sunlight reaching Earth. Because the bedrock of the Chicxulub area (mostly limestone) contained a thick layer of the calcium sulfate mineral *anhydrite,* a huge quantity of sulfuric acid aerosol would have been injected into the stratosphere. The scattering of sunlight from this aerosol layer would have reduced the amount of incoming solar radiation even further. Presuming a coastal impact, huge *tsunamis* (tidal waves) would have been initiated, wreaking havoc on Caribbean coastal environments. Evidence of tsunamis has been found on the island of Haiti and elsewhere in the Caribbean area.

In the next weeks, an unrelenting series of environmental insults would have ensued that few organisms could survive. The amount of solar radiation reaching Earth's surface would have been drastically reduced because of the presence of dense debris clouds and aerosol layers. The resultant dramatic cooling at all latitudes and cessation of photosynthesis would have removed the source of food for most of the life on the planet, both on land and in the sea. Where precipitation fell, it would have been in the form of rain and snow of sulfuric and nitric acids, produced from the rainout of sulfate aerosols and oxidation of NO. The acid rain may have been the least of the dinosaurs' problems, though.

Over the next several months, these tremendously detrimental effects would have lessened. The dust, soot, and much of the sulfate aerosol would have rained out of the atmosphere, and the acidity of the precipitation would have been reduced. However, very little life would have remained. The organisms that had survived the direct effects of the impact would have been subjected to a scarcity of food and suitable habitat. Cool climates would have continued for more than a year because of the approximately 6-month residence time of sulfate aerosol in the stratosphere.

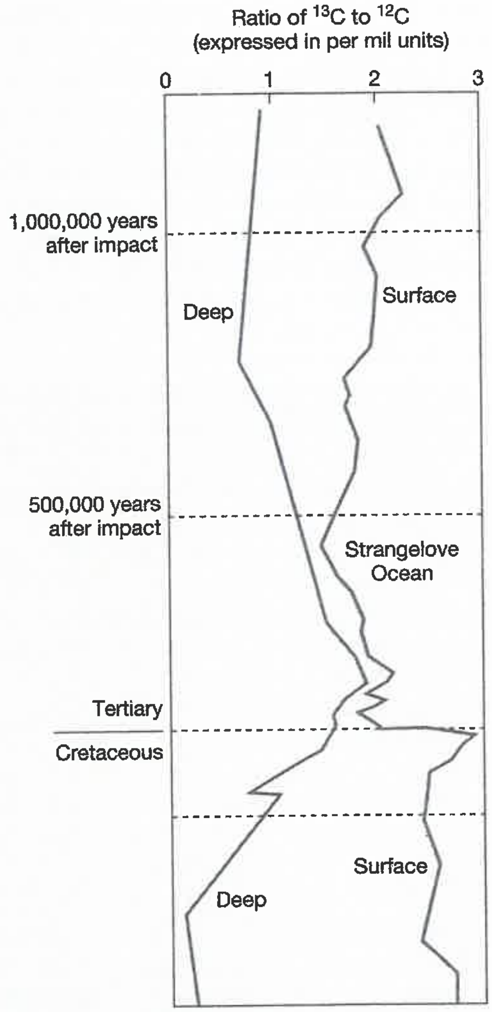
Environmental recovery would have continued over the next few years, as the ozone layer was restored and the climate warmed. However, the warming would have continued well beyond the initial state as the result of thousands of gigatons of carbon dioxide released from the vaporization of limestone at the impact site. Atmospheric pCO_2 may have increased to a few thousand ppm, and global average temperatures could have risen 10–15°C. These warm conditions could have persisted for thousands to tens of thousands of years. Given that many organisms are intolerant of rapid temperature excursions, this warming (following the initial cooling) might have assisted in the mass extinction and been at least one of the factors delaying the reestablishment of an active oceanic *biological pump* (see Chapter 9 and the Box "A Closer Look: The K–T Strangelove Ocean") for hundreds of thousands of years.

A CLOSER LOOK

The K–T Strangelove Ocean

Scientists studying the isotopic composition of carbon in skeletons of foraminifera deposited in sediments that span the K–T impact have found an intriguing perturbation of the marine ecosystem that persisted for hundreds of thousands of years after the K–T event. Normally, the operation of the oceanic biological pump (see Chapter 8) causes an enrichment in the carbon isotope ^{13}C in surface waters and an enrichment in ^{12}C in deep waters. The ^{12}C is preferentially incorporated into algal tissue during photosynthesis. It is then added to deep waters as the organic carbon in that tissue settles to the deep ocean and is decomposed by aerobic processes to dissolved CO_2. As a result, the $^{13}C:^{12}C$ ratio is enhanced in surface waters and diminished in deep waters. Foraminifera and other calcareous organisms (those producing $CaCO_3$ skeletons) record the ratio of ^{13}C to ^{12}C in their skeletons. Planktonic foraminifera, which live near the surface, record surface-water ratios, whereas benthic foraminifera, which live on the seafloor, record deep-sea ratios. In the modern ocean and in sediments recovered from layers deposited prior to the K–T event, the measured difference in the $^{13}C:^{12}C$ ratio between planktonic and benthic foraminifera is about 2 per mil (parts per thousand). However, as shown in Box Figure 13-2, the K–T event is marked by a collapse of this gradient. The implication is that the biological pump ceased to exist and that the ocean was essentially lifeless. Scientists have dubbed this the Strangelove Ocean, an allusion to the classic 1964 movie about nuclear war, *Dr. Strangelove*.

Perhaps even more intriguing than the collapse of the biological pump itself is its persistence. According to the isotopic record, the export of organic carbon from the surface ocean persisted at very low levels for hundreds of thousands of years, despite rapid rates of origination of new species and reestablishment of ecosystems in other settings. Although it is conceivable that slow rates of evolution retarded the reestablishment of the biological pump, other explanations seem to be required. One possibility is that toxic levels of trace metals such as copper, cadmium, and zinc resulted from the dissolution of the impact ejecta. Only after hundreds of thousands of years were these metals reduced to sufficiently low concentrations that metal-intolerant organisms could become reestablished.



BOX FIGURE 13-2 Changes in the ratio of carbon isotopic composition between the surface ocean and deep ocean as a result of the Cretaceous–Tertiary mass extinction. The ocean's isotopic value is recorded in the skeletons of planktonic foraminifera, which represent surface waters, and benthic foraminifera, which represent deep waters. (*Source:* J. C. Zachos, M. A. Arthur, and W. E. Dean, *Nature* 337, 1989, pp. 61–64.)

Other factors that influence the recovery interval include persistently high levels of toxic metals brought to the ocean with the impactor and the inherent time it takes to reestablish ecosystems and biodiversity.

EXTRATERRESTRIAL INFLUENCES AND EXTINCTION

There are two varieties of impacts: those caused by comets and those caused by asteroids. **Comets** are essentially large, dirty snowballs. They are composed of dust (metallic and rocky material) and solidified compounds that exist on Earth as gases: water, ammonia, methane, and carbon dioxide. Comets exist in stable orbits around the Sun, well beyond Pluto, in a region known as the **Oort cloud** (Figure 13-9), and closer in, outside of Neptune in the *Kuiper Belt*. The Oort cloud is a spherical reservoir of comets that extends more than one light year from the Sun. Comets in the Oort cloud can be perturbed by passing stars into orbits that pass through the solar system. Because they are arranged in a sphere, they can come in from any direction. These comets include many that have been observed over historic time, such as Halley's comet and comet Hale–Bopp. Kuiper Belt comets, by contrast, orbit the Sun in the same direction as do the planets. They are essentially pieces of material that never accreted to form a planet because they formed too far from the Sun and they did not collide frequently enough. Paradoxically, the Oort cloud comets are actually thought to have formed closer to the Sun, mostly in the Uranus/Neptune region, from which they were ejected early in solar system history by near-collisions with the giant planets.

Asteroids, by contrast, are composed of minerals and metallic elements characteristic of Earth and the other inner solar system planets (Mercury, Venus, and Mars). Most asteroids are in orbit around the Sun in a region known as the **asteroid belt,** between Mars and Jupiter (see Figure 13-9). The asteroid belt represents the remains of an inner planet that failed to form, probably because of the gravitational influence of nearby Jupiter. The largest asteroid, Ceres, is 1000 km in diameter, and two others, Vesta and Pallas, are both ~500 km in diameter. Were any of these three bodies to hit Earth, they would likely vaporize the entire ocean and might sterilize Earth completely. Fortunately, most asteroids are much smaller than this. Many thousands of kilometer-sized bodies exist, and collisions between these bodies create millions of small, dust-sized fragments.

As mentioned earlier, iridium is an indicator of an asteroid impact because it is associated with the mineral and metallic material in extraterrestrial materials. Earth has lots of iridium as well; however, nearly all of it is in the core because iridium is a **siderophile** element that

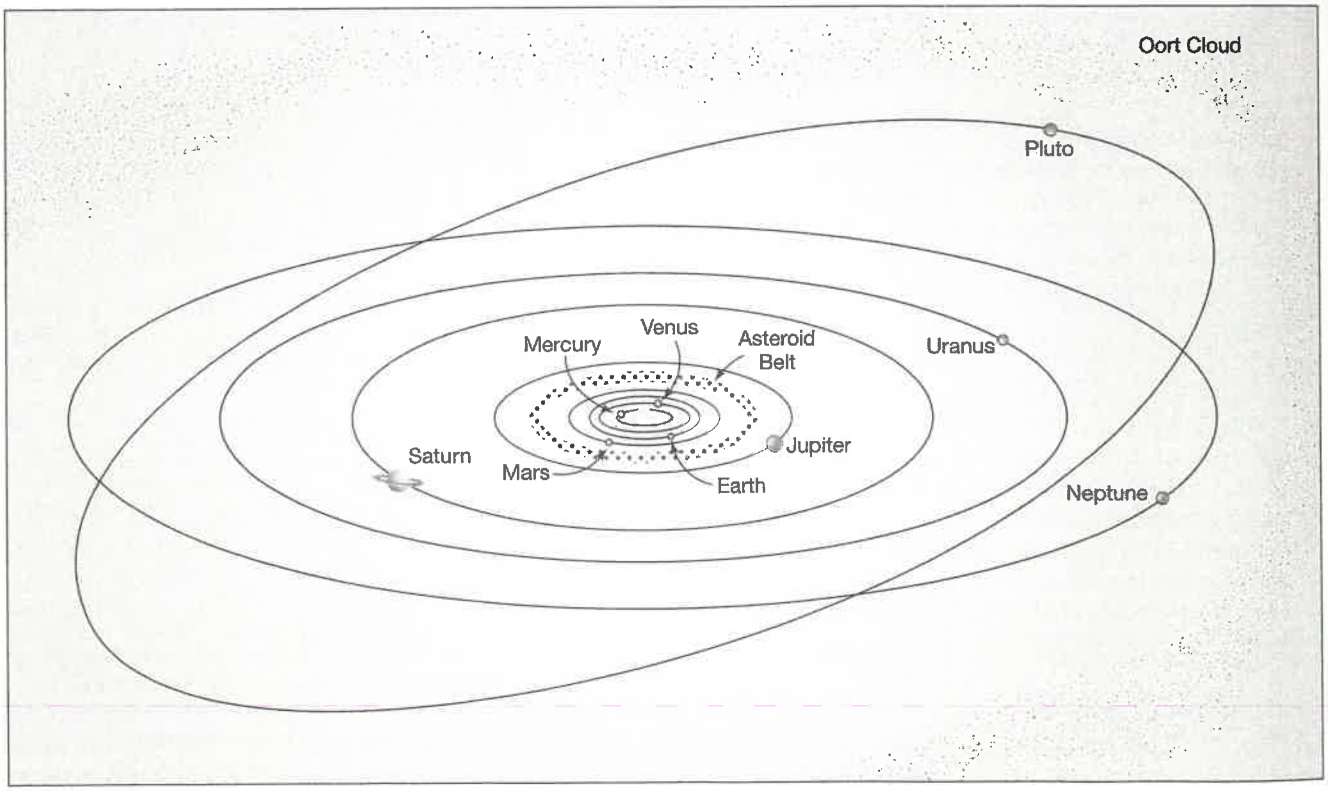


FIGURE 13-9 The solar system, showing the location of the Oort cloud (not drawn to scale) and the asteroid belt. (*Source:* From T. McKnight, *Physical Geography: A Landscape Appreciation*, 6/e, 1999. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

dissolves readily in molten iron. (The term *siderophile* means "iron-loving.") As we have seen, an asteroid impact should produce a significantly higher concentration of iridium than would a comet impact because of the differences in their composition and in their expected impact velocities. The large iridium spike in the K–T boundary clay thus indicates that the impactor was most likely an asteroid. Some of the other Phanerozoic mass extinctions for which no Ir layer exists—which, if you recall, is all the rest of them—could conceivably have been caused by comets.

Most asteroids in the asteroid belt and comets in the Oort Cloud or Kuiper Belt pose no immediate threat of impact. Their orbits can be disturbed, however, sending them on paths through the inner solar system. For example, collisions within the asteroid belt occasionally cause asteroids to be deflected into what's called a 3:1 *resonance* with Jupiter. At this distance the orbital period of the asteroid is precisely one-third that of Jupiter (3.95 Earth years, compared to 11.86 Earth years for Jupiter). This resonance occurs at an orbital distance of 2.50 astronomical units from the Sun, that is, 2.50 times the mean Earth–Sun distance. (In the next chapter, we show how to derive this distance using Kepler's third law.) Asteroids that find themselves within the 3:1 resonance do funny things. Because they always pass by Jupiter on the same side of the Sun, their orbits become elongated by the tug of Jupiter's gravity. Eventually, the orbits become **chaotic**. To a mathematician or celestial mechanician, this means that small changes in their positions at some initial time can lead to large changes in their positions at some later time. In practice, some of these asteroids get shunted into orbits that pass through the inner solar system and directly across the path of planet Earth. Some of these bodies, like the K–T impactor, end up hitting Earth and causing mass extinctions.

Comets get deflected from their normally stable orbits by other means. Oort cloud comets can be perturbed by passing stars or by shifting tidal forces caused by the rotation of the galaxy. Comets on the inner edge of the Kuiper Belt get "nibbled" away by Neptune's gravity, causing some of them to begin orbiting within the normal boundaries of the solar system. Such comets eventually pass near to one of the giant planets. This provides a gravitational "slingshot" effect that ejects most of them right out of the solar system. However, a few get kicked into Earth-crossing orbits, and a few of those wind up eventually hitting Earth. Sometimes, of course, the giant planets get hit as well, as happened in July 1994 when the comet Shoemaker–Levy collided with Jupiter.

Periodicity of Impacts and Extinctions?

A quantitative analysis of the fossil record by Robert Rohde and Richard Muller of the University of California, Berkeley, using the older, pre-2008 biodiversity curve, has revealed a 62-million-year **periodicity**—a time interval of regular recurrence—in the fossil diversity curve. A separate, and earlier, analysis by Jack Sepkoski (see above) and his colleague David Raup revealed a 26-million-year periodicity in the extinction rate curve. Any such long-term regularity in the fossil record that can be shown to be a robust feature (in other words, not simply some bias) suggests an extraterrestrial pacemaker for extinctions and/or originations, because no known Earthbound process has such regular periodicities at these long time scales. However, another theory is required to link these periods to higher likelihoods of asteroid or cometary impact if one wants to demonstrate that impacts have been the major driver of diversity trends over the Phanerozoic. The presence of another star or undetected large planet circling our star with elongated orbits and periodically disturbing the Oort cloud or asteroid belt is one such theory. Another is a regularity in the oscillation of our galaxy through the galactic plane and spiral arms of the Milky Way galaxy that would also create gravitational disturbances. Alternatively, mechanisms other than impacts might be responsible for these patterns. Moreover, the jury is still out on the issue of whether there are periodicities at all in these data, and if so, whether they require extraterrestrial explanations. Strong evidence for impact as the kill mechanism during mass extinctions exists only for the K–T event; for the others, extreme global warming brought on by massive volcanism or release of methane from the seafloor (for the end-Permian and Triassic–Jurassic extinctions), oceanic anoxia (for the end-Permian extinction and Late Devonian biodiversity loss) or glaciation and sea-level fall (for the Late Ordovician event) seem to be adequate explanations for the tremendous losses of biodiversity experienced.

Future Impacts

What are the odds that a large impactor will hit Earth in our lifetime? They are higher than you might think. The direct correlation between impactor size and diameter (see Figure 13-5) allows us to make this determination with some confidence. Let us assume that humans live about 100 years (admittedly, a bit optimistic). Because 100-m-diameter impactors (the size of the one that created Meteor Crater in Arizona) strike Earth about every 10,000 years, the likelihood of one striking Earth during your lifetime is about (100 years)/(10,000 years), or 1 in 100. The environmental consequences of such an impact are not tremendous, however, except close to the impact site. The impact frequency decreases by a factor of 100 for every factor of 10 increase in impactor diameter. Thus, the probability of a 1-km meteorite impact during your lifetime is about 1 in 10,000, and the probability of a K–T-sized impact during that time is 1 in 1 million. By comparison, your chances of being struck by lightning are about 1 in 3,000. Your chances of being killed by a lightning strike are quite high compared with your chances of being killed by the direct effects of a 1-km meteorite. But the likelihood that civilization will be destroyed by a meteorite impact is much larger than that of destruction by lightning strikes.

Chapter Summary

1. The diversity of life on Earth has varied in response to imbalances between the origination of new species and the extinction of existing species.
2. The fossil record of species-level diversity is biased by preservational artifacts associated with the likelihood of discovering fossils from a given interval of time.
3. The fossil record of genus-level diversity has been largely corrected for these biases and can thus be interpreted in terms of true trends in biodiversity through Earth history.
    a. Biodiversity of marine organisms increased dramatically during the Cambrian through Devonian.
    b. The largest extinction known occurred 252 million years ago when approximately 75% of all genera became extinct.
    c. Biodiversity recovered relatively rapidly after this event, and the general trend continues to the present. A significant disruption to this trend occurred 65 million years ago, at the end of the Cretaceous period, but it too was followed by a period of rapid origination of new species (and genera).
4. The Cretaceous–Tertiary mass extinction is the best studied of all major mass extinctions. Current scientific opinion favors the impact of a 10-km-diameter meteorite as the primary cause of this extinction.
    a. All available geological data are consistent with this hypothesis.
    b. A large crater dated as 65 million years old has been found in the subsurface at Chicxulub, Mexico.
    c. The meteorite impact would have destroyed the ozone layer, blocked out sunlight for days to weeks, ignited wildfires worldwide, baked organisms exposed to red-hot reentering ejecta, bathed the land surface in acid rain, and caused substantial global warming from elevated atmospheric CO_2.
    d. Although asteroid or cometary impact seems to be the best explanation for the K–T event, the other mass extinctions seem to have been the result of Earthbound causes: massive volcanism causing extreme global warming, or glaciation and sea-level fall.

Key Terms

adaptation
asteroid belt
asteroids
biodiversity
chaotic orbit
comets
evolution
extinction
iridium
mass extinction
meteorite
natural selection
niche
Oort cloud
origination
periodicity
Siberian Traps
siderophile
taxon
taxonomy

Review Questions

1. How do paleontologists deal with the incomplete nature of the fossil record to establish a geologic history of biodiversity changes?
2. What two processes cause the diversity of life on Earth to change through time?
3. How has fossil diversity changed over time? Why do these trends differ among taxonomic levels?
4. What explanations have been proposed for the mass extinction at the K–T boundary? Why is a meteorite impact the favored theory today?
5. What are the environmental consequences of the impact of a 10-km-diameter meteorite with Earth?
6. What are some other hypotheses for mass extinctions?

Critical-Thinking Problems

1. Changes in biodiversity over time are the result of imbalances between origination and extinction. Stability in diversity requires that either or both of these processes depend on the diversity at any particular time. In many ways, this situation is similar to the controls on the growth of populations. Here you will calculate the change in a population of organisms (N) as a result of births and deaths. A mathematical expression can be used to calculate next year's population (N_{t+1}) on the basis of this year's population (N_t), where t = years

$$N_{t+1} = N_t + rN_t\left(1 - \frac{N_t}{K}\right).$$

Let us dissect this equation. The potential growth rate—that is, the birth rate minus the death rate—is r, and the carrying capacity—the population size that can be supported (given constraints of food or other resource availability, competition, and so on)—is K. If the population is small relative to K, then the term in parentheses is essentially 1, and the potential growth rate is achieved. In other words, next year's population would simply be some multiple of this year's population (exponential growth). As N approaches K, the population will tend to slow its growth, finally reaching the carrying capacity. This behavior is called *logistic growth*. You will also witness something bizarre: behavior that has been labeled chaos.

PART 1 (Logistic growth): Fill in the following table, and then graph N_t versus t; assume that $r = 1.0$ and $K = 1{,}000$.

TABLE 13-1

Time (years)	N_t	$1 - \frac{N_t}{K}$	$rN_t \times \left(1 - \frac{N_t}{K}\right)$	N_{t+1} (use as N_t next time)
1	20.0	0.98	19.6	39.6
2	39.6	0.96	38.0	77.6
3	77.6	0.92	71.6	149.2
4				
5				
6				
7				
8				
9				
10				

Describe the growth curve, and explain why it has the logistic growth shape (on the basis of the numbers you calculate).

PART 2 (Chaos): Now repeat your calculations (do 15 years' worth) for the following values of r:

$$r = 2.0$$
$$r = 2.8$$

Graph your results, either on separate graphs or using different symbols or colors on the same graph (be sure the graph[s] is [are] legible). If the population goes negative, call it quits on that series of calculations; the population has gone extinct.

Describe how the behavior changes as the growth rate increases from 1.0 to 2.0 to 2.8. When $r = 2.8$, the system is described as being chaotic. A scientist who observed this population might conclude that purely random factors are controlling the size of this population. What is wrong with this conclusion?

2. Perform the calculation that Luis Alvarez used to establish the size of the K–T impactor. Use the following information:
   a. Assume that the clay layer with iridium was uniformly distributed around Earth by the impact.
   b. On average, the layer had a concentration of iridium of 10 parts per billion (ppb) by weight.
   c. On average, the layer was 4 cm thick.
   d. The density of the layer was 2.5 g/cm^3.
   e. Assume the meteor was spherical, with a density of 6.0 g/cm^3, and an iridium content of 0.5 parts per million (ppm) by weight.
   f. The radius of Earth is 6378 km.

   What is the diameter of the meteorite? The answer isn't exactly 10 km, as stated. By how much would you have to change the assumed thickness of the iridium layer to arrive at an asteroid diameter of exactly 10 km?
3. Determine the probability that an asteroid of the following diameters will hit Earth during your (optimistic) 100-year lifetime: 1 m, 100 m, 10 km.

Further Reading

General

Erwin, D. H. 2006. *Extinction: How life on Earth nearly ended 250 million years ago* (p. 296). Princeton, NJ: Princeton University Press.

Fastovsky, D. E., D. B. Weishampel, and J. Sibbick. 2005. *The evolution and extinction of dinosaurs* (p. 485). Cambridge: Cambridge University Press.

Hallam, A. 2004. *Catastrophes and lesser calamites* (p. 274). Oxford: Oxford University Press.

Ward, P. D. 2008. *Under a green sky: Global warming, the mass extinctions of the past, and what they can tell us about our future* (p. 242). New York: HarperCollins.

Advanced

Alroy, J. et al. 2008. Phanerozoic trends in the global diversity of marine organisms. Science 321:97–100.

Alvarez, L. W. 1987. Mass extinctions caused by large bolide impacts. *Physics Today*, July 1987, pp. 24–33.

Bambach, R. K. 2006. Phanerozoic biodiversity and mass extinctions. In *Annual Reviews of Earth and Planetary Sciences* 34, ed. R. Jeanloz, A. L. Albee, K. C. Burke, and K. H. Freeman, 127–55.