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Fossil ammonite cephalopod extracted from Jurassic age limestone at Lyme Regis on England's south coast. Ammonites are extinct mollusks distantly related to the living chambered nautilus. Mary Anning (1799–1847), known as the mother of paleontology, collected scores of these fossils from this locality. (Copyright Sinclair Stammers/ Science Photo Library/Photo Researchers.)

CHAPTER 1

Introduction to Earth History

The face of places and their forms decay; And that is solid earth that once was sea; Seas, in their turn, retreating from the shore, Make solid land, what ocean was before.
Ovid, *Metamorphoses, XV*

OUTLINE

We live on the third planet from the Sun. Our planet was formed 4.6 billion years ago and since that time has circled the Sun like a small spacecraft observing a rather average star. Somewhere between 300,000 and 150,000 years ago, a species of primate named *Homo sapiens* evolved on planet Earth. Unlike earlier animals, these creatures with oversized brains and nimble fingers asked questions about themselves and their surroundings. Their questioning has continued to the present day. How was the Earth formed? Why do earthquakes occur? What lies beneath the lands we live on and beneath the floor of the ocean? Even ancient people sought answers for these questions. In frail wooden ships they probed the limits of the known world, fearing that they might tumble from its edge. Their descendants came to know the planet as an imperfect sphere, and they began an examination of every obscure recess of its surface. In harsher regions, exploration proceeded slowly. It has been only within the last 100 years that humans have penetrated the deep interior of Antarctica. Today, except for a few areas of great cold or dense forest, the continents are well charted. New frontiers for exploration now lie beneath the oceans and outward into space.

GEOLOGY

Physical and Historical Components of Geology

Geology is the study of planet Earth. It is concerned with the materials of which the planet is made, the physical and chemical processes that act on these materials, and the history of the Earth and its inhabitants.

Geologists concern themselves with an exceptional variety of scientific tasks and therefore must employ knowledge from diverse fields. Some examine the composition and texture of meteorites and Moon rocks. With magnifiers and computers, others scrutinize photographs of planets to understand the origin of the features that characterize their surfaces. Still others are busily unraveling the structure of mountain ranges, attempting to predict the occurrence of earthquakes and volcanic eruptions, or studying the behavior of glaciers, streams, or underground water. Large numbers of geologists search for fossil fuels and the metallic ores vital to our standard of living. They worry, as do you and I, about the fate of humans in a world of diminishing resources. To do their work, geologists draw on the knowledge of astronomy, physics, chemistry, mathematics, and biology. For example, the petroleum geologist must understand the physics of moving fluids, the chemistry of hydrocarbons, and the biology of the fossils used to trace subsurface rock layers. Because geo-logy incorporates information from so many other scientific disciplines, it can be termed an eclectic science. The term *eclectic* is useful in describing a body of selected information drawn from a variety of sources. All sciences are eclectic to some degree, but geology is decidedly so.

For convenience of study, the body of knowledge called geology can be divided into **physical geology** and **historical geology**. The origin, classification, and composition of earth materials, as well as the varied processes that occur on the surface and in the deep interior of the Earth, are the usual subjects of physical geology. Historical geology addresses the Earth's origin, evolution, changes in the distribution of lands and seas, growth and destruction of mountains, succession of animals and plants through time, and developmental history of the solar system. The historical geologist examines planetary materials and structures to discover how they came into existence. He or she works with the tangible *results* of past events and must work backward in time to discover the cause of those events.

The Scientific Method in Geology

Geologists employ the same procedures used by scientists in other disciplines. Those procedures are rather formally referred to as the *scientific method*. The scientific method is merely a scheme for finding answers to questions and solutions to problems. It is not a fixed series of steps that researchers strictly and consciously follow. A scientific investigation often begins with the formulation of *questions*, proceeds to the collection of *observations* or data, and is followed by the development of an *explanation* or hypothesis. Further observations, tests, and scrutiny by other scientists serve to validate or invalidate the hypothesis.

As an example of scientific methodology, consider the work of geologists Anita Harris, Jack Epstein, and Leonard Harris. While working in the Appalachian Mountains for the United States Geologic Survey, these scientists observed that a group of tiny fossils called conodont elements (Fig. 1-1) differed in color from pale yellow to black. Conodont elements are the microscopic hard parts of organisms that lived on Earth from about 520 to 200 million years ago. They are composed of apatite, the same mineral of which bone is made, and are abundant in many localities and in all kinds of sedimentary rocks.

The geologists asked the question: "Why do conodont elements of the same age but from different parts of a region have different coloration?" They then set about obtaining the data that might provide an answer. In the laboratory they selected pale yellow conodont elements from a sedimentary rock that had never been deeply buried. These fossils were then heated to temperatures from 300°C to 600°C in 50° steps over a period of 10 to 50 days. They observed that the conodont elements changed in color through five phases from pale yellow to black. On further heating, so as to approximate conditions that change sedimentary rocks into metamorphic rocks (rocks which are altered by heat and pressure), black fossils changed sequentially to gray, milky white, and finally crystal clear.

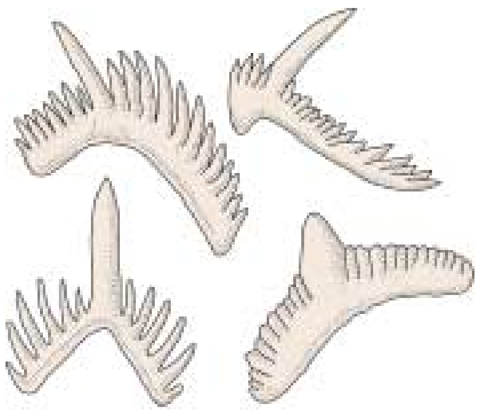


FIGURE 1-1 **Conodont elements** (magnified about 50 times).

Next, the colors produced experimentally were compared with conodont elements collected in the Appalachian Mountains from rocks that had been subjected to various depths and durations of burial. When plotted on a map, the data showed that the light-colored fossils occurred in rocks of the western Appalachians, where burial was least, and the dark-colored fossils were in rocks along the eastern side of the Appalachians, where burial was greatest. The original question could now be answered with a hypothesis stating that conodont element color alteration is caused by depth of burial and consequent increase in temperature. The study had practical value as well. Petroleum geologists learned that rocks containing black to clear conodont elements are less likely to yield commercial quantities of oil.

An Introduction to Plate Tectonics

A significant number of topics in both physical and historical geology are related to a grand unifying concept termed **plate tectonics**. "Tectonics" refers to large-scale deformation of rocks that compose the Earth's outer layers. The term "plate" is given to a large slab-like segment of the Earth's **lithosphere**. The lithosphere is the rigid outer 100 km or so of the Earth that includes the **crust** as well as the uppermost part of the **mantle** (Fig. 1-2).

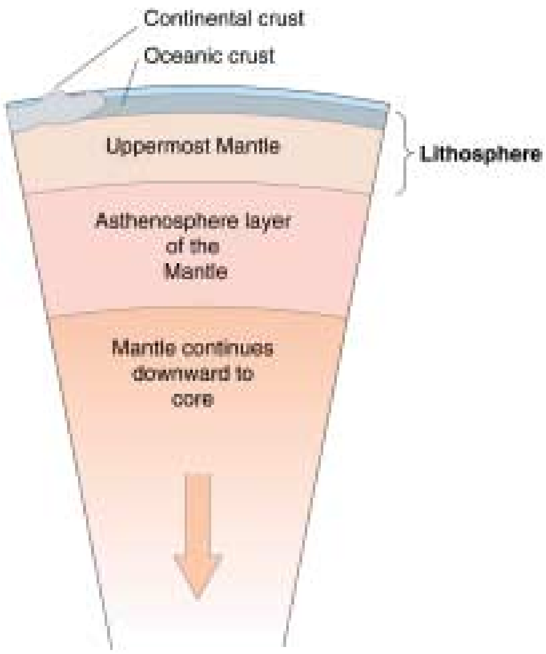


FIGURE 1-2 The lithosphere is the outer shell of the Earth that lies above the asthenosphere and comprises both the crust and an uppermost layer of the mantle.

On the Earth's surface there are seven large lithospheric plates and about 20 smaller plates. The plates rest on a partially molten layer of the mantle called the **asthenosphere**. The plates are in constant movement, probably because of heat-driven convectional plastic flow in the asthenosphere. Lithospheric plates must have margins or boundaries. Where two or more plates move apart from one another, the plate margins are termed **divergent boundaries**. **Convergent boundaries** occur where plates converge, and **transform boundaries** occur where they slide past one another. You will meet with all the above terms again in Chapter 5, where plate tectonics will be examined in more detail. Until then, this brief introduction will be useful.

THE FOUNDERS OF HISTORICAL GEOLOGY

Historical geology is a venerable science. Its beginnings can be traced to the time of classical Greece. Like other sciences, progress in historical geology has been based on the continuous accumulation of knowledge by past generations of workers. They have provided the foundations of geology upon which modern theories and precepts depend. A partial list of early contributors to our understanding of the origin and history of the Earth would include Nicolaus Steno, Abraham Gottlob Werner, James Hutton, William Smith, Georges Leopold Cuvier, Alexander Brongniart, Sir Charles Lyell, and Charles Darwin.

Nicolaus Steno (Niels Stensen)

Niels Stensen (1638–1687) was a Danish physician who was widely recognized for his studies in anatomy. Unable to secure a teaching position in Copenhagen's medical school, he settled in Florence, Italy. There he latinized his name to Nicolaus Steno and became physician to the Grand Duke of Tuscany. Since the duke was a generous employer, Steno had ample time to tramp across the countryside, visit quarries, and examine strata. His investigations of sedimentary rocks led him to formulate such basic principles of historical geology as superposition, original horizontality, and original lateral continuity.

The **principle of superposition** states that in any sequence of undisturbed strata, the oldest layer is at the bottom, and successively higher layers are successively

FIGURE 1-3 Steeply dipping strata grandly exposed in the Himalayan Mountains. It is often difficult to recognize the original tops of beds in strongly deformed sequences such as this. (*Courtesy of D. Bhattacharyya*.)

FIGURE 1-4 Superpositional sequence of undisturbed, horizontal, mainly Permian strata. Canyonlands National Park, Utah. The Colorado River is in the foreground. (*Photo by P. L. Kresan.*) ? *Along this bend in the river, where would one find the youngest stratum?**

younger. It is a rather obvious axiom. Yet Steno, on the basis of his observations of strata in northern Italy, was the first to explain the concept formally. The fact that it is self-evident does not diminish the principle's importance in deciphering Earth history. Furthermore, the superpositional relationship of strata is not always apparent in regions where layers have been steeply tilted or overturned (Fig. 1-3). In such instances, the geologist must examine the strata for clues useful in recognizing their uppermost layer. The way fossils lie in the rock and the evidence of mudcracks and ripple marks are particularly useful clues when one is trying to determine which way was up at the time of deposition.

The observation that strata are often tilted led Steno to his **principle of original horizontality**. He reasoned that most sedimentary particles settle from fluids under the influence of gravity. The sediment then must have been deposited in layers that were nearly horizontal and parallel to the surface on which they were accumulating (Fig. 1-4). Hence, steeply inclined strata indicate an episode of crustal disturbance after the time of deposition (Fig. 1-5).

The **principle of original lateral continuity** was the third of Steno's stratigraphic axioms. It pertains to the fact that, as originally deposited, strata extend in all directions until they terminate by thinning at the margin of the basin, end abruptly against some former barrier to deposition, or grade laterally into a different kind of sediment (Fig. 1-6). This observation is significant in that whenever one observes the exposed cross-section of strata in a cliff or valley wall, one should recognize that the strata, as originally deposited, should continue laterally for a distance that can be determined by field work and drilling. If lateral continuity is not observed and the lack of continuity is not related to one of the reasons given above, then the cause may be displacement of strata by faulting or erosional loss of strata. When geologists stand on a sandstone ledge at one side of a canyon, it is the principle of original lateral continuity that leads them to seek out the same

*Answers to the questions within the figure legends can be found in the *Student Study Guide* accompanying this text.

FIGURE 1-5 Steeply dipping shale and sandstone strata. Ouachita Mountains of Oklahoma.

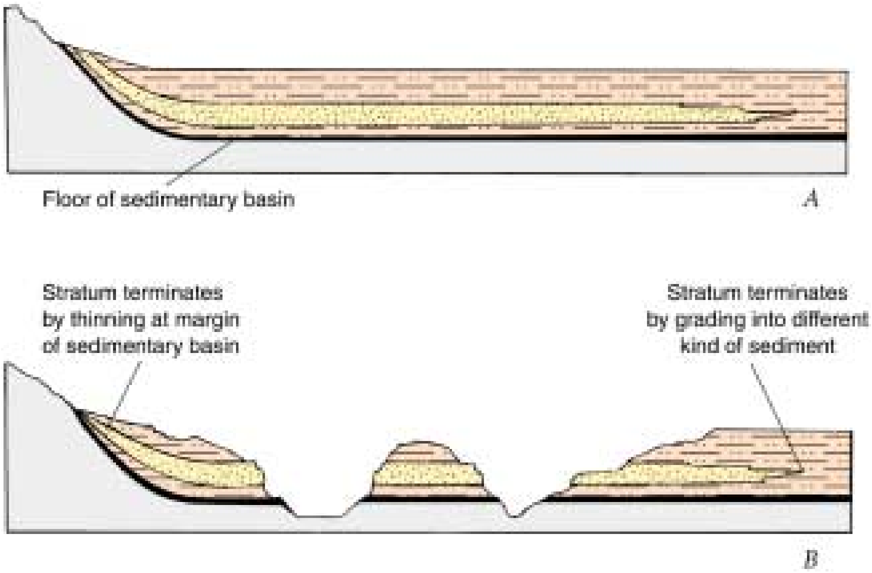


FIGURE 1-6 **Illustration of original lateral continuity.** Cross-section *A* shows a sandstone stratum deposited within a low-lying area or sedimentary basin that received sediment eroded from surrounding uplands. Cross-section *B* shows the same area after erosion has exposed the sandstone on hillsides. As indicated, the stratum continues horizontally until termination results from nondeposition at the margin of a basin or other obstruction or by gradation into different sediment. Strata may terminate abruptly as a result of erosion or faulting but were nevertheless *originally* laterally continuous. ? *What conditions in the environment of deposition may have caused the sandstone layer (stippled) to "pinch out" on the right side of section B?*

ledge of sandstone on the far canyon wall and then to realize that the two exposures were once continuous.

Today, we recognize that Steno's principles are basic to the geologic specialty known as **stratigraphy**, which is the study of layered rocks, including their texture, composition, arrangement, and correlation from place to place. Because stratigraphy enables geologists to place events as recorded in rocks in their correct sequence, it is the key to the history of the Earth.

Interpreters of the Geologic Succession

The stratigraphic principles formulated by Steno in the 17th century were rediscovered several decades later by other European scientists. Among the most prominent of these early geologists were John Strachey (1671–1743), Giovanni Arduino (1714–1795), Johann G. Lehmann (1719–1767), Georg Füchsel (1722–1776), and Peter Simon Pallas (1741–1811). John Strachey is best remembered for his use of the principles of superposition and original lateral continuity in deciphering the stratigraphic succession of coal-bearing formations in Somerset and Northumberland, England. He clearly illustrated the sequence of formations encountered at the surface and in mines and described the manner in which horizontal strata rested upon the eroded edges of inclined older formations. Years later this type of stratigraphic relationship would be termed *unconformable*.

Whereas John Strachey was particularly interested in a local stratigraphic succession, other naturalists developed a broader, more global view of the geologic succession. In Italy, Giovanni Arduino classified mountains according to the most abundant type of rock that composed them. He defined Primary mountains as those constructed of crystalline rocks of the kinds later to be named igneous and metamorphic. Arduino recognized that rocks of the Primary group were likely to be the oldest in a mountain system and were usually exposed along the central axis of ranges. Secondary mountains were constructed of layered, well-consolidated, fossiliferous rocks. Such rocks were later to be named sedimentary. Arduino's Tertiary designation was reserved for unconsolidated gravel, sand, and clay beds as well as lava flows.

Classifications similar to that of Arduino also appeared in the works of the German scientists Lehmann and Füchsel. These men were not rocking-chair theorists. Both were excellent field geologists. Füchsel worked chiefly in the mountains of Thuringia, whereas his contemporary Lehmann examined the rocks of the Harz and Erz Gebirge (Gebirge is the German word for mountains). They prepared excellent summaries of the stratigraphic succession in these mountains and further developed a remarkably perceptive understanding of some of the events involved in the making of mountain ranges.

This insight into the history of mountains was improved as a result of the work of a tireless field geologist named Peter Simon Pallas. Under the patronage of Catherine II of Russia, Pallas traveled across the whole of Asia and made careful studies of the Ural and Altai Mountains. He recognized the threefold division of mountains formulated by his predecessors. In addition, Pallas was able to construct a general geologic history of the Urals, and he provided a lucid description of how the rock assemblages change as one travels from the center to the flanks of mountain systems.

Abraham Gottlob Werner

One of the most influential geologists working in Europe near the close of the 18th century was Professor Abraham Gottlob Werner (1749–1817). Werner's eloquent and enthusiastic lectures at the Freiberg Mining Academy in Saxony transformed that school into an international center for geologic studies. Werner was a competent mineralogist, and many geologists of his day used his scheme for the identification of minerals and ores. He is not, however, remembered as much for his contributions to mineralogy as he is for his interpretation of the geologic history of the Earth. The cornerstone of that interpretation was his insistence that all rocks of the Earth's crust were deposited or precipitated from a great ocean that once enveloped the entire planet. Today we know that some rocks (the group called sedimentary) are indeed often of marine origin. Others, however, are decidedly not formed in water. Because they believed that all rocks had formed in the ocean, Werner and his many followers became known as *neptunists* (after Neptune, the Roman god of the sea).

Werner envisioned his universal ocean in the earliest stage of Earth history as a hot, steamy body saturated with all the dissolved minerals needed to form the rocks of his oldest division. He called these *Primitive Rocks*, or *Urgebirge*. Most of these rocks formed the cores of mountain ranges and would later come to be known as igneous and metamorphic.

In the second stage of the Wernerian interpretation of Earth history, the basin floor of the primitive ocean subsided and the waters filling the basin cooled. The ocean came to resemble the ocean of today. Werner told his students that this change was marked by the deposition of fossil-bearing, well-consolidated, stratified, and often structurally disturbed rocks that lie above the Urgebirge. These he designated Transition Rocks and suggested that they were deposited when the Earth had passed from an uninhabitable to an inhabitable condition. The fossils proved the planet had become suitable for life. Today, we recognize these rocks as part of Europe's predominantly sedimentary Paleozoic sequence of strata.

Above the Transition Rocks, Werner noted the occurrence of flat-lying sandstones, shales, coal beds, very fossiliferous limestones, and occasional layers of a black rock later determined to be basalt. These basalt layers were actually old lava flows. For all of these rocks lying above the Transition Rocks, Werner employed Johann Lehmann's term *Flötzgebirge*. A final term, Alluvium, was used for the unconsolidated sand, gravel, and clay that rested on the Flötzgebirge.

Although initially received with great interest and enthusiasm, Werner's ideas were soon to draw criticism. His theory failed to explain what had become of the immense volume of water that once covered the Earth to a depth so great that all continents were submerged. An even greater problem was his insistence that basaltic lava layers such as those in the Flötzgebirge were deposited in precisely the same manner as the enclosing limestones and shales. With visible, indisputable field evidence, geologists such as J. F. D'Aubisson de Voisins (1769–1832) in France clearly demonstrated the volcanic origin of these basaltic layers. Geologists with this opposing view came to be known as plutonists (after Pluto, the Roman god of the Underworld). According to the plutonists, fire rather than water was the key to the origin of igneous rocks. James Hutton of Scotland was a prominent plutonist who clearly stated that rocks such as basalt and granite "formed in the bowels of the Earth of melted matter poured into rents and openings of the strata."

James Hutton

James Hutton (1726–1797), an Edinburgh physician and geologist, is remembered not only as a staunch opponent of neptunism but also for his penetrating comprehension of how geologic processes alter the Earth's surface. For Hutton (Fig. 1-7), the Earth was a dynamic, ever-changing place in which new rocks, lands, and mountains arise continuously as a balance against their destruction by erosion and weathering. He took a cyclic view of our planet, as opposed to Werner's more static concept of an Earth that had changed very little from its beginning down to the present time. In addition, Hutton believed that "the past history of our globe must be explained by what can be seen to be happening now." This simple yet powerful idea was later to be named uniformitarianism by William Whewell. Charles Lyell (1797–1875) became the principal advocate and interpreter of uniformitarianism. We will speak of this great man again in the pages ahead.

Perhaps because it is so general a concept, uniformitarianism has been reinterpreted and altered in a variety of ways by scientists and theologians from Hutton's generation down to our own. Some of today's ideas

FIGURE 1-7 Portrait of James Hutton, the Scottish physician, farmer, and geologist. Hutton recognized that a study of present processes, such as weathering, erosion, the deposition of sediment, and volcanism, provided the means of understanding ancient rocks. The idea was later established as the principle of uniformitarianism. (*National Portrait Gallery of Scotland, Edinburgh, Scotland.*)

about what uniformitarianism implies would seem strange to Hutton himself. If the term uniformitarianism is to be used in geology (or any science), one must clearly understand what is uniform. The answer is that the physical and chemical laws that govern nature are uniform. Hence, the history of the Earth may be deciphered in terms of present observations on the assumption that natural laws are invariant with time. These so-called natural laws are merely the accumulation of all our observational and experimental knowledge. They permit us to predict the conditions under which water becomes ice, the behavior of a volcanic gas when it is expelled at the Earth's surface, or the effect of gravity on a grain of sand settling to the ocean floor. Uniform natural laws govern geologic processes such as weathering, erosion, transport of sediment by streams, movement of glaciers, and movement of water into wells.

Hutton's use of what later was termed uniformitarianism was simple and logical. By observing geologic processes in operation around him, he was able to infer the origin of particular features he discovered in rocks. When he witnessed ripple marks being produced by wave action along a coast, he was able to state that an ancient rock bearing similar markings was once a sandy deposit of some equally ancient shore. And if that rock now lay far inland from a coast, he recognized the existence of a sea that covered areas where Scottish sheep now grazed.

Hutton's method of interpreting rock exposures by observing present-day processes was given the catchy phrase "the present is the key to the past" by Sir Archibald Geike (1835–1924), a Scot with a brilliant career of discovery and experimentation in geology. The methodology implied in the phrase works very well for solving many geologic problems, but it must be remembered that the geologic past was sometimes quite unlike the present. For example, before the Earth had evolved an atmosphere like that existing today, different chemical reactions would have been prevalent during weathering of rocks. Life originated in the time of that primordial atmosphere under conditions that have no present-day counterpart. As a process in altering the Earth's surface, meteorite bombardment was once far more important than it has been for the past 3 billion years or so. Many times in the geologic past, continents have stood higher above the oceans, and this higher elevation resulted in higher rates of erosion and harsher climatic conditions, compared with intervening periods when the lands were low and partially covered with inland seas. Similarly, at one time or another in the geologic past, volcanism was more frequent than at present.

Nevertheless, ancient volcanoes disgorged gases and deposited lava and ash just as present-day volcanoes do. Modern glaciers are more limited in area than those of the recent geologic past, yet they form erosional and depositional features that resemble those of their more ancient counterparts. All of this suggests that present events do indeed give us clues to the past, but we must be constantly aware that in the past, the rates of change and intensity of processes often varied from those to which we are accustomed today and that some events of long ago simply do not have a modern analogue.

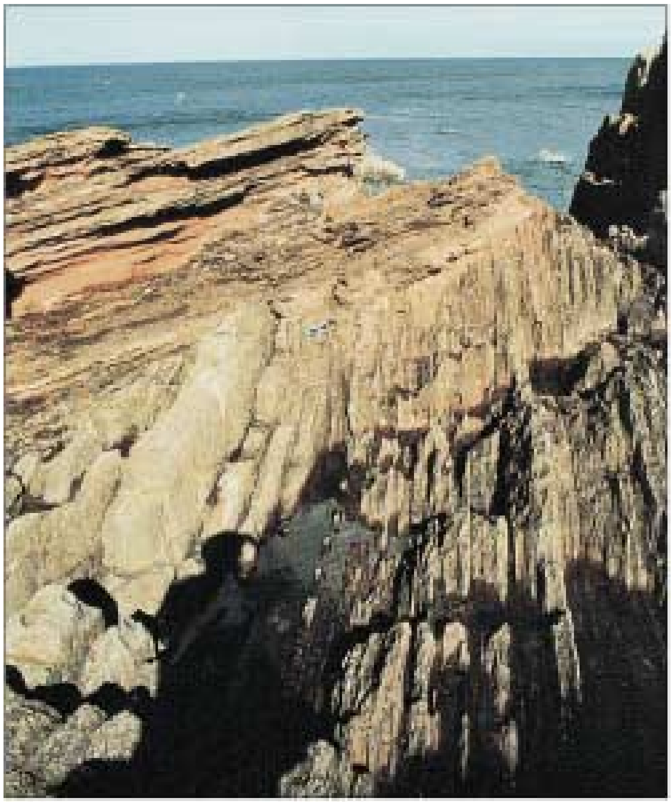
In order to emphasize the importance of natural laws over processes in the concept of uniformity, many geologists prefer to use the term *actualism* as a replacement for *uniformitarianism*. **Actualism** is the principle that natural laws governing both past and present processes on Earth have been the same. Hutton's friend John Playfair never suggested the term *actualism* but provided an eloquent statement of it when, in 1802, he wrote the following lines:

> Amid all the revolutions of the globe the economy of Nature has been uniform, and her laws are the only thing that have resisted the general movement. The rivers and rocks, the seas and the continents have changed in all their parts; but the laws that describe those changes, and the rules to which they are subject, have remained invariably the same.

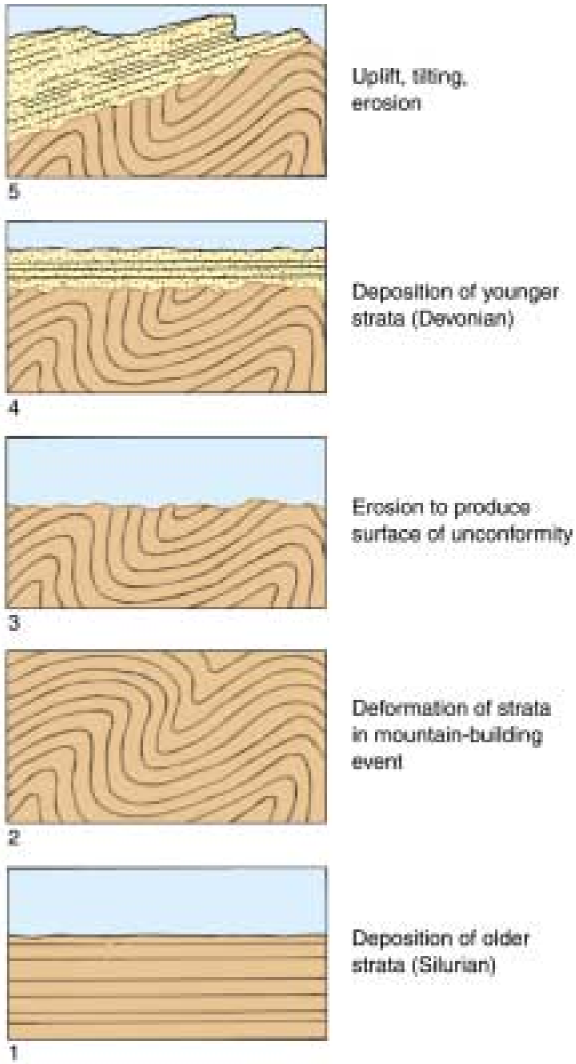
The 18th-century concept of uniformitarianism was not the only contribution James Hutton made to geology. In his *Theory of the Earth*, published in 1785, he brought together many of the formerly separate thoughts of the naturalists who preceded him. He showed that rocks recorded events that had occurred over immense periods of time and that the Earth had experienced many episodes of upheaval, separated by quieter times of denudation and sedimentation. In his own words, there had been a "succession of former worlds." Hutton saw a world of cycles in which water sculpted the surface of the Earth and carried the erosional detritus from the land into the sea. The sediment of the sea was compacted into stratified rocks, and then by the action of enormous forces the layers were cast up to form new lands. In this endless process, Hutton found "no vestige of a beginning, no prospect of an end." No longer could geologists compress all of Earth history into the short span suggested by the Old Testament.

At Siccar Point on the North Sea coast of Scotland, Hutton came across exposures of rock where steeply inclined older strata had been beveled by erosion and covered by flat-lying younger layers (Figs. 1-8*A* and *B*). It was clear to Hutton that the older sequence was not only tilted but also partly removed by erosion before the younger rocks were deposited. The erosional surface meant that there was a time gap or hiatus in the rock record. In 1805, Robert Jameson named this relationship an **unconformity**. More specifically, Hutton's famous rock exposure was an *angular unconformity* because the lower beds were tilted at an angle to the upper beds. This and other unconformities provided Hutton with evidence for periods of denudation in his "succession of worlds." Although he did not use the word *unconformity*, he was the first to understand and explain the significance of this feature.

During most of his career, Hutton's published reports attracted only modest attention, and a good part of that attention came from opponents who preferred to follow the views of Abraham Gottlob Werner. To remedy this situation, British scientists who appreciated the value of Hutton's ideas convinced his friend John Playfair, a professor of mathematics and natural philosophy, to publish a summary of and commentary



A



B

FIGURE 1-8 Angular unconformity at Siccar Point, eastern Scotland. (*A*) It was here that James Hutton first realized the historical significance of an unconformity. The drawings (*B*) indicate the sequence of events documented in this famous exposure. ? *Which of Steno's laws are illustrated in this rock exposure? (Photograph courtesy of E. H. Hay, De Anza College.)*

on *Theory of the Earth*. The work by Playfair was published in 1802 under the title *Illustrations of the Huttonian Theory of the Earth*. Whereas Hutton's writing was often complex and difficult to follow, Playfair's text was easy to read, unburdened by lengthy quotations from foreign sources, and highly persuasive. Indeed, subsequent geologists of the 19th century based much of their understanding of Hutton's ideas not on their reading of Hutton's original publications, but on the lucid, intelligent, and convincing phrases of John Playfair.

Hutton died 5 years before the publication of *Illustrations*. Throughout his life he had been absorbed in the investigation of the Earth. He was seen frequently in the field, scrutinizing every rock exposure he happened upon, and he soon became so familiar with certain strata that he was able to recognize them at different localities. What he was unable to do well, however, was determine whether dissimilar-looking strata were roughly equivalent in age. He had not discovered how to correlate beds that did not have a similar composition and texture (lithology). This problem was soon to be resolved by William Smith (1769–1839).

William Smith

William Smith was an English surveyor and engineer who devoted 24 years to the task of tracing out the strata of England and representing them on a map. Small wonder that he acquired the nickname "Strata Smith." He was employed to locate routes of canals, to design drainage for marshes, and to restore springs. In the course of this work, he independently came to understand the principles of stratigraphy, for they were of immediate use to him. By knowing that different types of stratified rocks occur in a definite sequence and that they can be identified by their lithology, the soils they form, and the fossils they contain, he was able to predict the kinds and thicknesses of rock that would have to be excavated in future engineering projects. His use of fossils was particularly significant. Prior to Smith's time, collectors rarely noted the precise beds from which fossils were taken. Smith, on the other hand, carefully recorded the occurrence of fossils and quickly became aware that certain rock units could be identified by the particular assemblages of fossils they contained. He used this knowledge first to trace strata over relatively short distances and then to extend over great distances his "correlations" to strata of the same age but of different lithology. Ultimately, this knowledge led to the formulation of the **principle of biologic succession**. This principle stipulates that the life forms of each age in the Earth's long history were unique for particular periods, that the fossil remains of life permit geologists to recognize contemporaneous deposits around the world, and that fossils could be used to assemble the scattered fragments of the record into a chronologic sequence.

Smith did not know why each unit of rock had a particular fauna. This was 60 years before the publication of Charles Darwin's *On the Origin of Species*. Today, we recognize that different kinds of animals and plants succeed one another in time because life has evolved continuously. Because of this continuous change, or evolution, only rocks formed during the same age contain similar assemblages of fossils.

News of Smith's success as a surveyor spread widely, and he was called to all parts of England for consultation. On his many trips, he kept careful records of the types of rocks he saw and the fossils they contained. Armed with his notes and observations, in 1815 he prepared a geologic map of England and Wales that is substantially accurate even today. In the 1830s, Smith was declared the "father of English geology."

Georges Cuvier and Alexandre Brongniart

The use of fossils for the correlation and recognition of formations was not exclusively William Smith's discovery. At the same time that Smith was making his observations in England, two scientists across the English Channel in France were diligently advancing the study of fossils. They were Baron Georges Léopold Cuvier (1769–1832) and his close associate Alexander Brongniart (1770–1847). Cuvier was an expert in comparative anatomy, and with this knowledge he became the most respected vertebrate paleontologist of his day. Brongniart was a naturalist who worked not only on fossil vertebrates but on plants and minerals as well. Together these men established the foundations of vertebrate paleontology. They validated Smith's findings that fossils display a definite succession of types within a sequence of strata and that this succession remains more or less constant wherever found. They also noticed that certain large groupings of strata were often separated by unconformities. As one would pass from one group of strata across the unconformity into the overlying group, a dramatic change in the kinds of animals preserved as fossils was apparent. From this observation, the two French scientists concluded that the history of life was marked by frightful catastrophes involving sudden violent flooding of the continents and abrupt crustal upheavals of stupendous magnitude. The last of these catastrophic episodes was considered to be the Noachian Deluge. Cuvier and Brongniart believed that each catastrophe resulted in the total extinction of life and was then followed by the appearance of new animals and plants. Cuvier did not speculate on how each of the many new species originated. Many geologists of the time, including the eminent Charles Lyell, held that geologic history was a uniform and gradual progression and could not accept Cuvier's concept of catastrophism. Thus began a catastrophism-versus-uniformitarianism controversy that rivaled the earlier neptunist-plutonist debates in scope and passion. Uniformitarianists

FIGURE 1-9 **Sir Charles Lyell.** (*Courtesy of Geological Society of London.*)

argued that many seemingly abrupt changes in fossil faunas were caused by missing strata or other imperfections in the geologic record. Other apparent breaks in the fossil record were actually not sudden, and the ancestors of each animal group could be found as fossils in underlying beds. Cuvier's idea that there were successive origins of life after each catastrophe is not supported by the fossil record, although rampant volcanism, asteroid impact, or the onslaught of harsh climatic conditions have caused mass extinctions at various times in the geologic past.

Charles Lyell

In the early 19th century, the English geologist Sir Charles Lyell (Fig. 1-9) authored the classic work *Principles of Geology*. This work both amplified the ideas of Hutton and presented the most important geologic concepts of the day. The first volume of this work was printed in 1830. It grew to five volumes and became immensely important in the Great Britain of Queen Victoria. In these volumes one can recognize Lyell's skill in explaining and synthesizing the geologic findings of contemporary geologists. As his friend Andrew C. Ramsey remarked, "We collect the data, and Lyell teaches us the meaning of them." Lyell's *Principles* became the indispensable handbook of every English geologist. In it are amplified many of the principles expressed earlier by Hutton regarding the recognition of the relative ages of rock bodies. For example, Lyell discusses the general principle that a geologic feature that cuts across or penetrates another body of rock must be younger than the rock mass penetrated (Fig. 1-10). In other words, the feature that is cut is older than the feature that crosses it. This generalization, called the **principle of cross-cutting relationships**, applies not only to rock bodies but also to geologic structures such as faults and unconformities. Thus, in Figure 1-11, fault *B* is younger than stratigraphic sequence *D*; the intrusion of igneous rock *C* is younger than the fault because it cuts across it; and by superposition, rock sequence *E* is youngest of all.

Another generalization to be found in Lyell's *Principles* relates to **inclusions**. Lyell logically discerned that fragments within larger rock masses are older than the rock masses in which they are enclosed. Thus, whenever two rock masses are in contact, the one containing pieces of the other will be the younger of the two.

In Figure 1-12*A*, the pebbles of granite (a coarse-grained igneous rock) within the sandstone tell us that

FIGURE 1-10 **An example of the principle of cross-cutting relationships.** The dark rock (basalt) was once molten. While in the molten state, it penetrated the surrounding light-colored rock that was already present and therefore older.

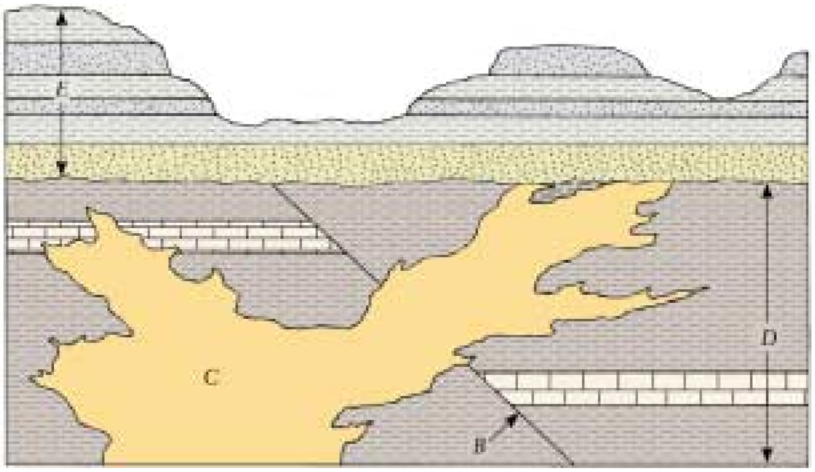


FIGURE 1-11 **An example of how the sequence of geologic events can be determined from cross-cutting relationships and superposition.** From first to last, the sequence indicated in the cross-section is first deposition of *D*, then faulting to produce fault *B*, then intrusion of igneous rock mass *C*, and finally erosion followed by deposition of *E*. Strata labeled *D* are oldest, and strata labeled *E* are youngest. ? *How do you know that the intrusion of C occurred after the formation of the fault?*

the granite is older and that the eroded granite fragments were incorporated into the sandstone. In Figure 1-12*B*, the granite was intruded as a melt into the sandstone. Because there are sandstone inclusions in the granite, the granite must be the younger of the two units.

Charles Darwin

As noted earlier, William Smith and some of his contemporaries were able to recognize that strata were often characterized by particular fossils and that there was a general progression toward more modern-looking assemblages of shells in higher, and thus younger, strata. It was Charles Darwin (1809–1882) who provided a general theory that would account for the changes seen in the fossil record.

As a young man (Fig. 1-13), Darwin had acquired an impressive knowledge of both biology and geology. That knowledge was the basis for his securing an unpaid position as a naturalist aboard the *H.M.S. Beagle*, bound for a 5-year mapping expedition around the world. On his return from the voyage in 1836, Darwin had assembled volumes of notes in support of his theory of evolution of organisms by natural selection. His theory was based on a logical system of observations and conclusions. He observed that all living things tend to increase their numbers at prodigious rates. Yet in spite of their reproductive potential to do so, no one group of organisms has been able to overwhelm the Earth's surface. In fact, the actual size of any given population remains fairly constant over long periods of time. Because of this, Darwin concluded that not all the individuals produced in any generation can survive. In addition, Darwin recognized that individuals of the same kind differ from one another in various morphologic and physiologic features. From this and the previous observation, he concluded that those individuals with variations most favorable in the existing environment would have the best chance of surviving and transmitting their favorable traits to the next generation. Darwin had no knowledge of genetics and

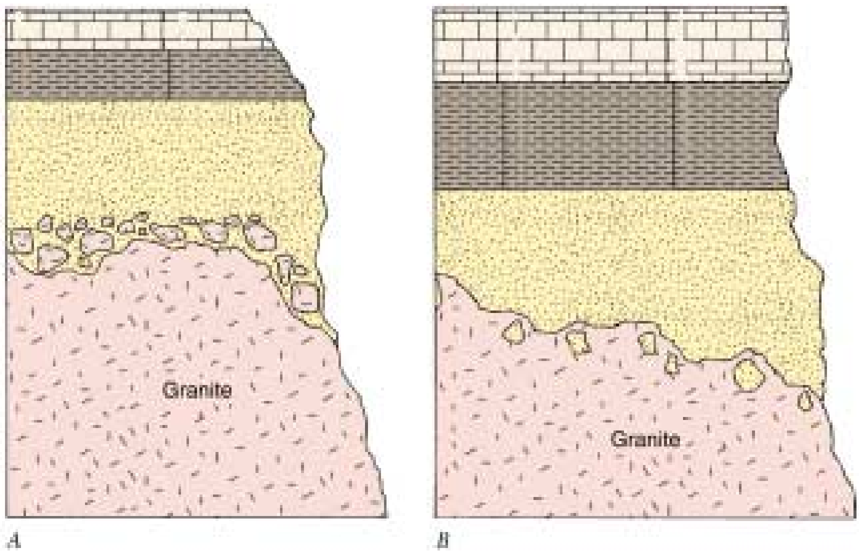


FIGURE 1-12 **(*A*)Granite inclusions in sandstone indicate that granite is the older unit. (*B*) Inclusions of sandstone in granite indicate that sandstone is the older unit.** ? *If the granite in (A) was found to be 150 million years old, and the shale above the sandstone 100 million years old, what can be stated about the age of the sandstone?*

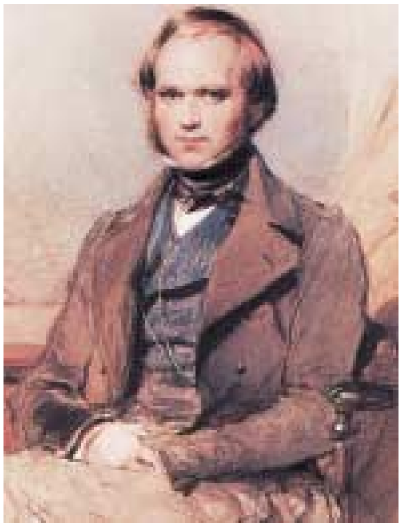


FIGURE 1-13 **Charles Darwin as a young man.** This portrait was made shortly after Darwin returned to England from his voyage around the world on the *H.M.S. Beagle*. Observations made during this voyage helped him formulate the concept of evolution by natural selection. (*Bridgeman/Art Resource, NY.*)

therefore did not know the cause of the variation that was so important to his theory. Gregor Mendel's 1865 report of experiments in heredity had escaped his attention. In the decades following Darwin's death, geneticists clearly established that the variability essential to Darwin's theory of natural selection is derived from new gene combinations that occur during reproduction and from genetic mutation.

Possibly because he was reluctant to face the controversy that his theory would provoke, Darwin did not publish his findings on his return to England. He did, however, confide in Lyell and the great botanist Joseph Hooker. These friends urged him to publish quickly before someone else anticipated his discoveries. Yet Darwin continued to procrastinate. Then, in 1858, a comparatively unknown young naturalist named Alfred Russel Wallace sent Darwin a manuscript for review that contained the basic concepts of natural selection. Wallace had conceived of natural selection while on a biologic expedition to Indonesia. The idea came to him while he was suffering with malaria shortly after he read an essay on overpopulation by Thomas Malthus.

Understandably disturbed by Wallace's letter, Darwin sought the help of his friends Lyell and Hooker. Recognizing the importance of giving Darwin the credit he deserved for his discovery and the long years of assembling supporting evidence, the two scientists arranged for a presentation of Darwin's work and Wallace's paper before the Linnaean Society. Thus, the theory of natural selection was credited simultaneously to both scientists. Darwin now worked at top speed to complete his famous *On the Origin of Species*. The book was published in 1859. In that volume, Darwin hoped to accomplish two things. The first was to convince the world that evolution had occurred. Organisms had evolved or changed throughout geologic time. The second was to propose a mechanism for evolution. That mechanism was natural selection. Darwin's success in achieving his objectives can be measured by the fact that, within a decade, organic evolution had become the guiding principle in all paleontologic and biologic research. His book changed the way people viewed the world, and for this reason it has been described as one of the greatest books of all time.

Darwin died at his home in Down, England, in 1882. By that time, geologists everywhere were using their knowledge of evolution, biologic succession, superposition, cross-cutting relationships, and inclusions to decipher Earth history.

Geologists in the New World

It was inevitable that the success of European geologists during the 19th century would motivate scientists across the Atlantic to begin their own explorations. The rocks of the New World soon resounded with the blows of pioneer geologists armed with geology picks and firearms (the latter to counter the menace of wild animals and hostile Indians). Prominent among these early explorers of American geology was **William Maclure** (1763–1840). Maclure was a Scotsman who visited the United States in 1797 and decided to stay. He traveled by horseback across the Allegheny Mountains 50 times while examining their petrology and stratigraphy. In 1809, Maclure published the first geologic map of the United States in his *Observations of the Geology of the United States, Explanation of a Geologic Map*.

Before becoming a geologist, **Amos Eaton** (1776–1842) worked 3 years as a lawyer, worked 9 as a land agent, and then was sent to prison for 5 years for a crime he had not committed. After receiving a pardon from prison, he studied geology under the distinguished Yale professor Benjamin Silliman. In 1818 he published his *Index to the Geology of the Northern States*. Eaton founded the Rensselaer Institute (then called the Rensselaer School). He was an exceptional teacher, insisting that his students do "hands on" geology involving laboratory and field work. Such methods were unusual in an age when courses of study consisted only of listening to professors read from carefully prepared manuscripts.

Louis Agassiz (1807–1873) was another emigrant from Europe. He was born in Switzerland and came to the United States in 1846. After his formal education in Zurich, Heidelberg, and Munich, he began a comprehensive study of fishes that was to be the basis of his work entitled *Fossil Fishes*. For a decade before coming to America, he studied glaciers in the Alps and promoted the then-unheard-of (but valid) theory that immense ice sheets once covered much of North America and Eurasia. In his 1840 work entitled *Studies of Glaciers*, he wrote:

> The surface of Europe, adorned before by tropical vegetation and inhabited by troops of large elephants, enormous hippopotami, and gigantic carnivora, was suddenly buried under a vast mantle of ice, covering alike plains, lakes, seas, and plateaus.

Agassiz found ample evidence in America for his ice age theory. Along the shores of Lake Superior he showed his students bedrock bearing the aligned scratches (glacial striations) made by rocks locked in the base of the advancing ice, as well as huge boulders transported by the ice from distant northern terrains. Agassiz had become an extremely well known American scientist by 1859. He continued to publish in his first discipline, paleontology, and was the founder of the Harvard Museum of Comparative Zoology.

James Hall (1807–1873) frequently corresponded with Agassiz. Hall had been educated at the Rensselaer Institute, where he subsequently became a professor of chemistry. He was a brilliant geologist and paleontologist who became the director of New York's first geologic survey. Geologic mapping in New York revealed fossiliferous sequences over 40,000 feet thick. On the basis of fossils, Hall knew these rocks were deposited in shallow water. Thus, he correctly reasoned that the sea floor had subsided concurrently with deposition, but that subsequently mountains were raised from what were once marine basins. Hall gained fame the world over, not only for his knowledge of stratigraphy but for eight volumes of *The Paleontology of New York*.

James D. Dana (1813–1895) was a contemporary of Hall who became a professor at Yale University. His *Manual of Geology*, *Textbook of Geology*, and *System of Mineralogy* were among the most important texts of his time. Dana referred to Hall's elongated basins as *geosynclinals* (later shortened to *geosynclines*) but disagreed that the subsidence of these basins was caused by the ever-increasing load of sediment. Instead, he proposed that thick sequences of sediment accumulated where crustal movements had already made the basins.

Inevitably, the focus of geologic work in the United States would shift westward, often in the course of surveys of the Western Territories mandated by Congress. Prominent in these expeditions was **Ferdinand V. Hayden** (1829–1887). Known to Indians as "he who picks up rocks running," Hayden (Fig. 1-14) conducted surveys of the Badlands of South Dakota and the Black Hills and examined the geology along the Missouri, Yellowstone, Gallatin, and Madison Rivers. He was influential in convincing Congress to pass a bill authorizing the establishment of Yellowstone National Park, the oldest national park in the United States. Hayden became director of the United States Geological and Geographical Survey of the Territories. From 1879 to 1886 he was a leading geologist with the United States Geologic Survey.

John Powell (1834–1902) was the commander of an artillery battery during the Civil War. At the Battle of Shiloh, a rifle ball struck his right arm. Surgery on the wound was poorly done. A second operation was required, which reduced Powell's forearm to a mere

FIGURE 1-14 **The Hayden field party in the summer of 1870, near Red Buttes, Wyoming.** Geologist Ferdinand Hayden is the bearded man seated at the center of the table. (*Courtesy of the United States Geological Survey.*)

stump. The loss, however, never impeded his efficiency and endurance as a field geologist. He rose quickly to become the director of several geological and geographic surveys of the West as well as director of the United States Geologic Survey. His greatest feat was a journey by boat through the Grand Canyon of the Colorado River in the summer of 1869.

John Powell was the second director of the United States Geological Survey, succeeding **Clarence King** (1841–1901). King had studied under James Dana at Yale, where he became particularly interested in mineral resources. He was appointed by Congress to plan and direct the expedition for the geological survey of the 40th Parallel. King's *Systematic Geology* describes much of the topography and stratigraphy encountered during the survey.

Although the primary mission of the expeditions conducted by Hayden, Powell, King, and others was mapping and surveying, the crews were also to report on bedrock geology, biology, archaeology, and paleontology. With regard to paleontology, it quickly became apparent that treasure troves of dinosaur bones and bones of giant mammals were to be found in some of the Western formations. Two paleontologists who were particularly proficient in exploiting these bony treasures were **Othniel C. Marsh** (1831–1899) and **Edwin D. Cope** (1850–1897). Marsh had received his paleontologic training in Europe. He became the first professor of paleontology at Yale University and later founded the Peabody Museum of Natural History (named for his affluent uncle, George Peabody). Cope was a wealthy Quaker who became a protégé of Joseph Leidy, a highly regarded professor of anatomy at the University of Pennsylvania. Both Marsh and Cope were men of great endurance and not adverse to field work, but to hasten the task of preparing and describing the abundance of fossils being discovered in the West, they employed professional collectors. These stalwart bone hunters traveled great distances through pathless wilderness searching for fossils, while at the same time keeping a watchful eye for menacing Indians. They excavated fossils from quarries they had dug with pick and shovel, prepared them for transport, and shipped them back to Marsh in New Haven and Cope in Philadelphia. Unfortunately, there was no cooperation between Marsh and Cope. Both men were egotistical, inclined to jealousy, and competitive. A bitter feud developed between them as each tried to surpass the other in naming and describing newly discovered vertebrates. Unnecessary mistakes were made because of their haste to be the first to publish a description of a newly discovered fossil beast. Nevertheless, the "great dinosaur rush" led by Marsh and Cope had its benefits. It provided thousands of specimens for study and museum exhibits, motivated research worldwide, enhanced our understanding of life during the Mesozoic and Cenozoic, provided evidence for evolution, and established paleontology as a dynamic science imbued with a spirit of discovery.

TIME AND GEOLOGY

Many people are intrigued by the great age of rocks and fossils. Geology instructors are aware of this interest, for they are often asked the age of rock and mineral specimens brought to them by students and amateur collectors. When told that the samples are tens or even hundreds of millions of years old, the collectors are often pleased but also perplexed. "How can this person know the age of this specimen by just looking at it?" they wonder. If they insist on knowing the answer to that question, they may next receive a short discourse on the subject of geologic time. It is explained that the rock exposures from which the specimens were obtained had long ago been organized into a standard chronologic sequence based largely on superposition, evolution as indicated by fossils, and actual rock ages in years, obtained from the study of radioactive elements in the rock. The geologist's initial estimate of age is based on experience. He or she may have spent a few hours kneeling at those same collecting localities and had a background of information to draw on. Thus, at least sometimes, a geologist can recognize particular rocks as being of a certain age. The science that permits accomplishment of this feat is called geochronology. It is a science that began over 4 centuries ago when Nicholaus Steno described how the position of strata in a sequence could be used to show the relative geologic age of the layers. As described earlier, this simple but important idea was expanded and refined much later by William Smith and some of his contemporaries. These practical geologists showed how it was also possible to correlate strata. Outcrop by outcrop, the rock sequences with their contained fossils were pieced together, one above the other, until a standard geologic time scale based on relative ages had been constructed.

There are two different frames of reference when dealing with geologic time. The work of William Smith and his contemporaries was based on the concept of **relative geologic dating**. It involved placing geologic events and the rocks representing those events in the order in which they occurred, without reference to actual time or dates measured in years. Relative geologic time tells us which event preceded or followed another event or which rock mass was older or younger, relative to others. In contrast, **actual geologic dating** expresses, in years, the actual age of rocks or geologic events, as usually determined by the decay of radioactive elements.

The Standard Geologic Time Scale

The early geologists had no way of knowing how many time units would be represented in the completed geologic time scale. Nor could they know which fossils would be useful in correlation or which new strata might be discovered at a future time in some distant corner of the globe. Consequently, the time scale grew piecemeal, in an unsystematic manner. Units were named as they were discovered and studied. Sometimes the name for a unit was borrowed from local geography, from a mountain range in which rocks of a particular age were well exposed, or from an ancient tribe of Welshmen; sometimes the name was suggested by the kind of rocks that predominated.

DIVISIONS IN THE GEOLOGIC TIME SCALE Geologists have proposed the term *eon* for the largest divisions of the geologic time scale. In chronologic succession, the eons of geologic time are the **Hadean, Archean, Proterozoic**, and **Phanerozoic** (see geologic time scale, Fig. 1-15). The beginning of the Archean corresponds approximately to the ages of the oldest known rocks on Earth. Although not universally used, the term *Hadean* refers to that period of time for which we have no rock record, which began with the origin of the planet 4.6 billion years ago. The Proterozoic Eon refers to the time interval from 2500 to 544 million years ago.

The rocks of the Archean and Proterozoic are informally referred to as Precambrian. The antiquity of Precambrian rocks was recognized in the mid-1700s by Johann G. Lehman, a professor of mineralogy in Berlin, who referred to them as the "Primary Series." One frequently finds this term in the writing of French and Italian geologists who were contemporaries of Lehman. In 1833, the term appeared again when Lyell used it in his formation of a surprisingly modern geologic time scale. Lyell and his predecessors recognized these "primary" rocks by their crystalline character and took their uppermost boundary to be an unconformity that separated them from the overlying-and therefore younger-fossiliferous strata.

The remainder of geologic time is included in the **Phanerozoic Eon**. As a result of careful study of the superposition of rock bodies accompanied by correlations based on the abundant fossil record of the Phanerozoic, geologists have divided it into three major subdivisions, termed eras. The oldest is the **Paleozoic Era**, which we now know lasted about 300 million years. Following the Paleozoic is the **Mesozoic Era**, which continued for about 179 million years. The **Cenozoic Era**, in which we are now living, began about 65 million years ago.

As shown in the geologic time scale, eras are divided into shorter time units called **periods**, and periods can in turn be divided into **epochs**. Eras, periods, epochs, and divisions of epochs, called **ages**, all represent intangible increments of time. They are **geochronologic units**. The actual rocks formed or deposited during a specific time interval are called **chronostratigraphic units**. Table 1-1 indicates the chronostratigraphic units that correspond to geochronologic units. A **system** refers to all of the actual rock units of a given period, whereas a **series** is the chronostratigraphic equivalent of an epoch, and a **stage** represents the tangible rock record of an age. As an example of the way these terms are used, one might correctly speak of climatic changes during the Cambrian Period as indicated by fossils found in the rocks of the Cambrian System.

RECOGNITION OF GEOCHRONOLOGIC UNITS Geochronologic units bear the same names as the chronostratigraphic units to which they correspond. Thus, we may speak of the Jurassic System (a rock unit) or the Jurassic Period (a time unit) according to whether we are referring to the rocks themselves or to the time during which they accumulated. Geochronologic terms have come into use as a matter of convenience. Their definition is necessarily dependent on the existence of tangible chronostratigraphic units. The steps leading to the recognition of chronostratigraphic units began with the use of superposition in establishing relative age relationships. Local sections of strata were used by early geologists to recognize beds of successively different age and, thereby, to record successive evolutionary changes in fauna and flora. (The order and nature of these evolutionary changes could be determined because stratigraphically higher layers are successively younger.) Once the faunal and floral succession was deciphered, fossils provided an additional tool for establishing the order and nature of recorded geologic events. They could also be used for correlation, so that strata at one locality could be related to the strata of other localities. No single place on Earth contains a complete sequence of strata from all geologic ages. Hence, correlation to standard sections of many widely distributed local sections was necessary in constructing the geologic time scale (Fig. 1-16). Clearly, the time scale was not conceived as a coherent whole but rather evolved piece by piece as a result of the individual studies of many geologists. Indeed, for some units at the series and stage level, the process continues even today. The fact that the time scale developed in piecemeal fashion is apparent when one reviews its growth and development.

THE GEOLOGIC SYSTEMS

The Cambrian System The rocks of the **Cambrian System** take their name from *Cambria*, the Latin name for Wales. Exposures of strata in Wales (Fig. 1-17) provide a standard section with which rocks elsewhere in Europe and on other continents can be correlated. The standard section in Wales is named Cambrian by definition. All other sections deposited during the same time as the rocks in Wales are recognized as Cambrian by comparison to the standard section.

Adam Sedgwick, a highly regarded professor of geology at Cambridge (Fig. 1-18), named the Cambrian

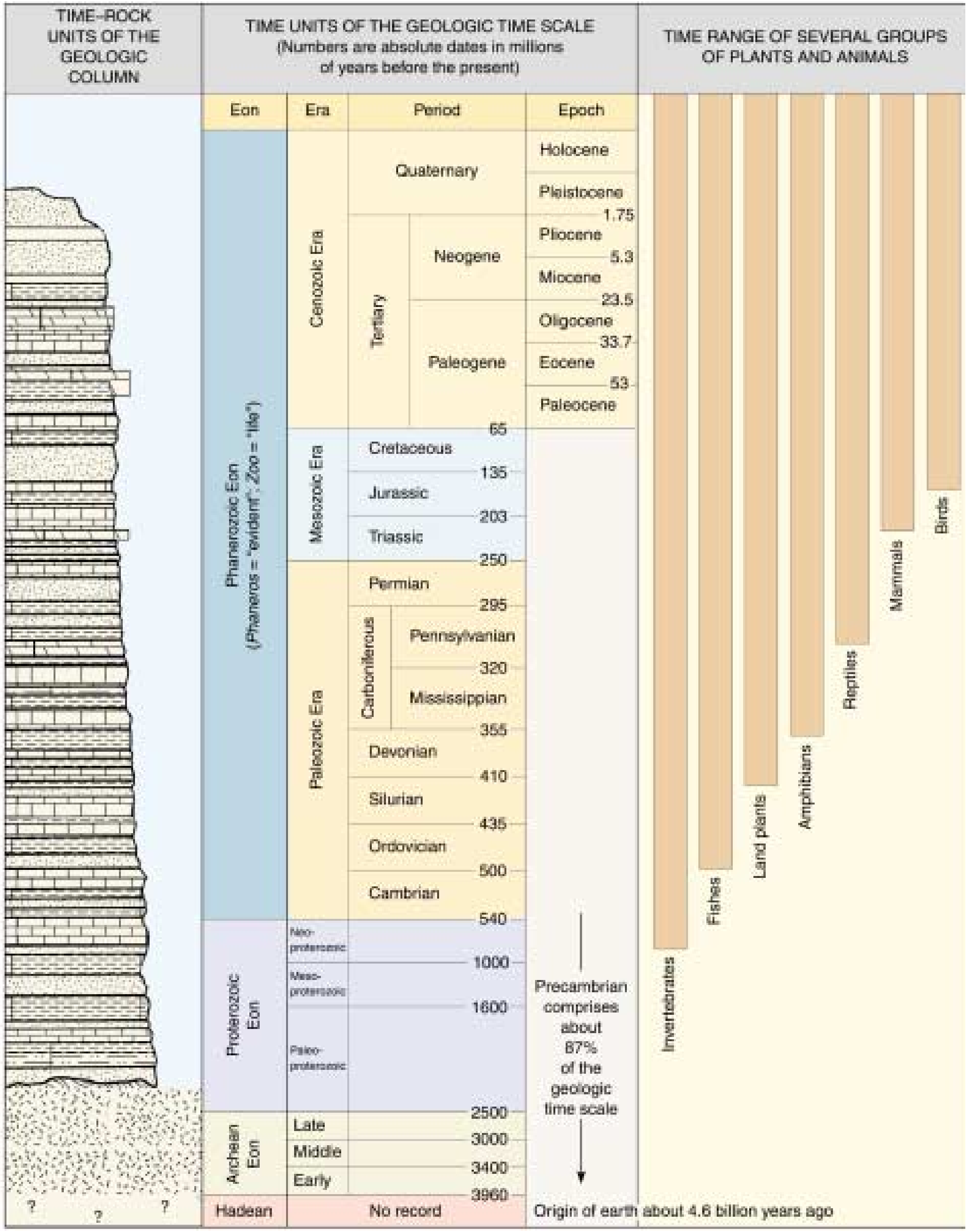


FIGURE 1-15 **Geologic Time Scale.** The age for the base of each division is in accordance with recommendations of the International Commission on Stratigraphy for the year 2000.

TABLE 1-1 Hierarchy of Geochronologic and Chronostratigraphic Terms

Geochronologic Divisions	Equivalent Chronostratigraphic Divisions
Era	Erathem (rarely used)
Period	System
Epoch	Series
Age	Stage
Chron	Zone (Chronozone)

in the 1830s for outcrops of poorly fossiliferous dark siltstones and sandstones. The area in northern Wales that Sedgwick studied was noted for its complexity, yet he was able to unravel its geologic history on the basis of spatial relationships and lithology.

The Ordovician and Silurian Systems At about the same time that Sedgwick was laboring with outcrops that were to become the standard section for the Cambrian System, his former student, Sir Roderick Impey Murchison, had begun studies of fossiliferous strata in the hills of southern Wales. Murchison named these rocks the **Silurian System**, taking the name from early inhabitants of western England and Wales known as the *Silures*. In 1835, Murchison and Sedgwick presented a paper, *On the Silurian and Cambrian Systems, Exhibiting the Order in Which the Older Sedimentary Strata Succeed Each Other in England and Wales*. With this publication, the two geologists initiated the development of the early Paleozoic time scale. In the years that followed, a controversy arose between the two men that was to sever their friendship. Because Sedgwick had not described fossils distinctive of the Cambrian, the unit could not be recognized in other countries. Murchison argued, therefore, that the Cambrian was not a valid system. During the 1850s, he maintained that all fossiliferous strata above the "Primary Series" (the old name for Precambrian) and below the Old Red Sandstone (of Devonian age) belonged within the Silurian System. Sedgwick, of course, disagreed, but his opinion that the Cambrian was a valid system did not receive wide support until

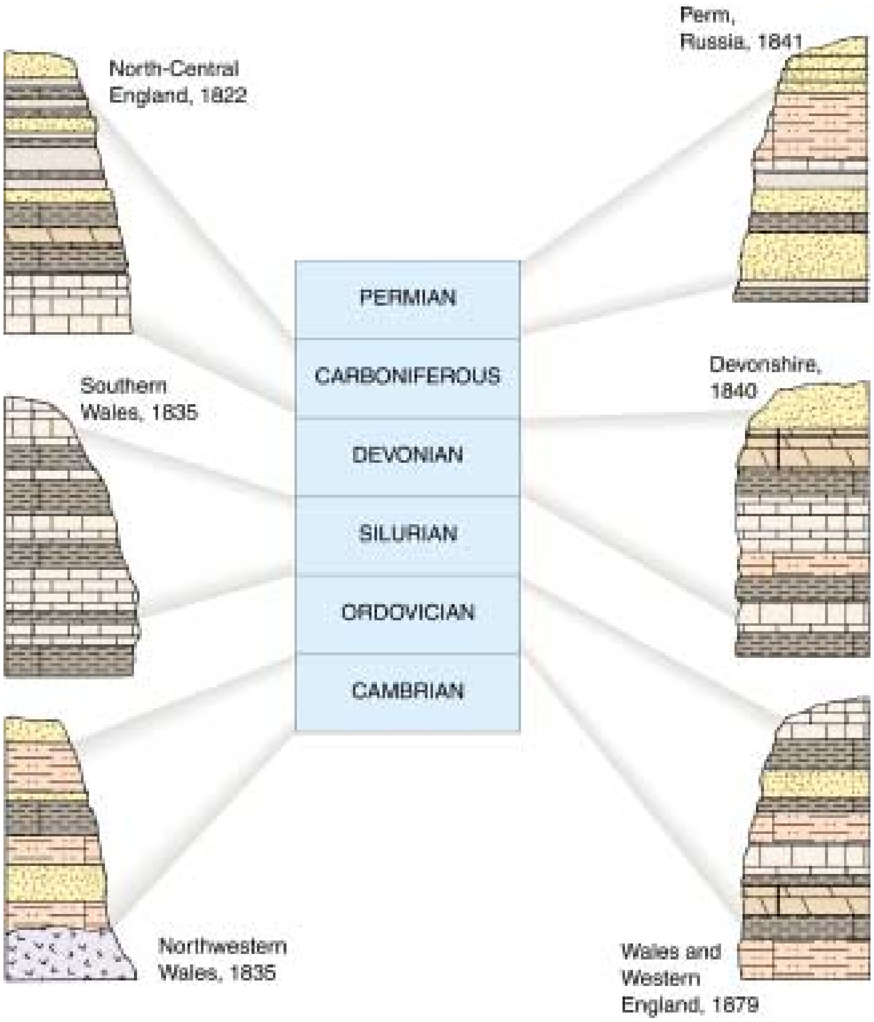


FIGURE 1-16 The standard geologic time scale for the Paleozoic and other eras developed without benefit of a grand plan. Instead, it developed by the compilation of "type sections" for each of the systems. ? *What criteria at Devonshire demonstrated that these strata were younger than those in Wales?*

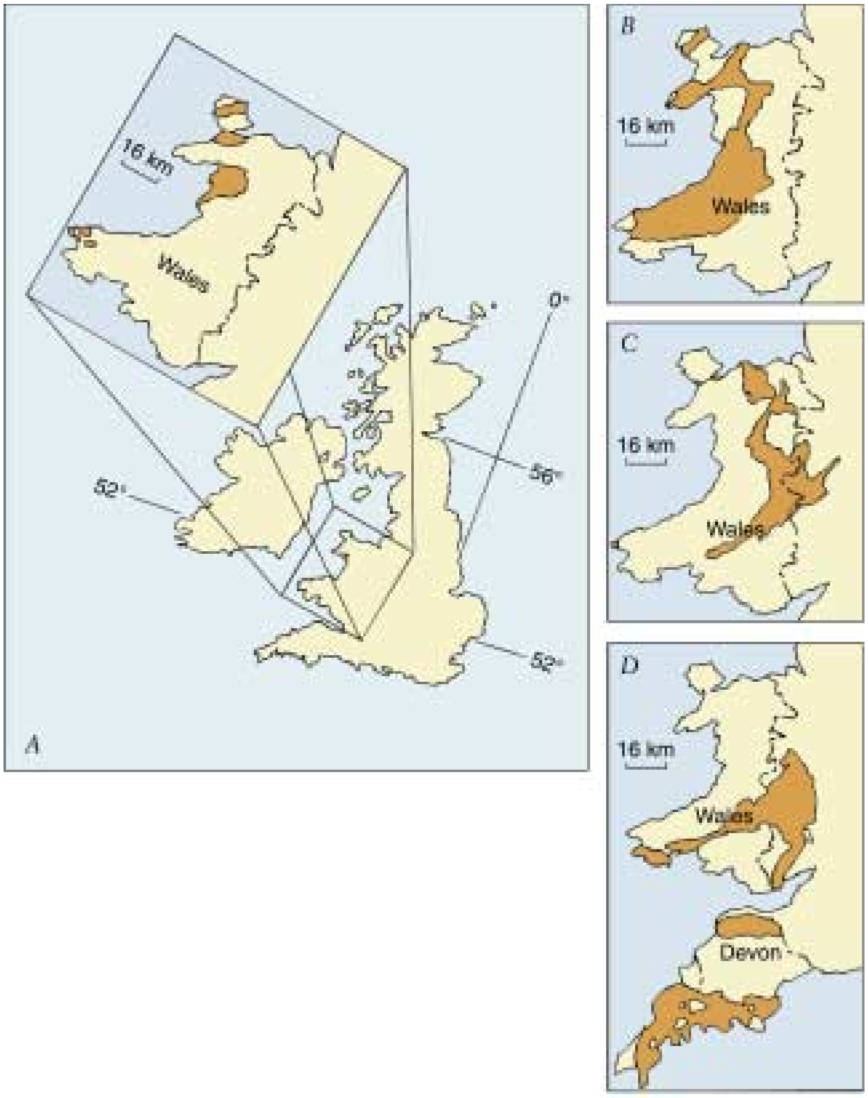


FIGURE 1-17 Outcrop areas for strata of the Cambrian (*A*), Ordovician (*B*), Silurian (*C*), and Devonian (*D*) systems in Great Britain.

fossils were described from the upper part of the sequence. The fossils proved to be similar to faunas in Europe and North America. Hence, the Cambrian did meet the test of recognition outside England. Using these fossils as a basis for reinterpretation, the English geologist Charles Lapworth proposed combining the upper part of Sedgwick's Cambrian and the lower part of Murchison's Silurian into a new system. In 1879, he named the system *Ordovician* after the *Ordovices*, an early Celtic tribe. The first three systems of the Paleozoic were thus established (Fig. 1-19).

The Devonian System The Devonian System was proposed for outcrops near Devonshire, England (Fig. 1-16), by Sedgwick and Murchison in 1839 (prior to the year of their bitter debate). They based their proposal on the fact that the rocks in question lay beneath the previously recognized Carboniferous System and contained a fauna that was different from that of the underlying Silurian and overlying Carboniferous. In their interpretation of the distinctive nature of the fauna, they were aided by the studies of William Lonsdale, a retired army officer who had become a self-taught specialist on fossil corals. Further evidence that the new unit was a valid one came when Murchison and Sedgwick were able to recognize it in the Rhineland region of Europe. The Devonian rocks of Devonshire were also found to be chronologically equivalent to the widely known *Old Red Sandstone* of Scotland and Wales.

The Carboniferous System The term **Carboniferous System** was coined in 1822 by the English geologists William Conybeare and William Phillips to designate strata that included beds of coal in north-central England. Subsequently, it became convenient in Europe and Britain to divide the system into a Lower Carboniferous and Upper Carboniferous—the latter containing most of the workable coal seams. Two systems in North America, the **Mississippian** and **Pennsylvanian**, are broadly comparable to these subdivisions.

FIGURE 1-18 **Adam Sedgwick, one of the foremost geologists of the 19th century.** A professor of geology at Cambridge University, Sedgwick is best remembered for deciphering the highly deformed system of rocks in northwestern Wales that he defined as the Cambrian System. He also founded the geologic museum at Cambridge that bears his name. (*Courtesy of the Cambridge Museum, Cambridge, England.*)

They are not precisely equivalent because detailed intercontinental correlations reveal that the boundary between the Mississippian and Pennsylvanian in North America is somewhat younger than the boundary between the Lower Carboniferous and Late Carboniferous in Europe. The American geologist Alexander Winchell formally proposed the name Mississippian in 1870 for the dominantly calcareous Lower Carboniferous strata that are extensively exposed in the upper Mississippi River drainage region. In 1891, Henry S. Williams provided the name Pennsylvanian for the coal-bearing Upper Carboniferous System.

The Permian System The **Permian System** takes its name from Permia, an ancient kingdom between the Urals and the Volga. In 1840 and 1841, Murchison, in company with the French paleontologist Edouard de Verneuil and several Russian geologists, traveled extensively across western Russia. To his delight, Murchison found he was able to recognize Silurian, Devonian, and Carboniferous rocks by the fossils they contained. As a result, he became even more convinced that groups of fossil organisms succeed one another in a definite and determinable order. Murchison established the new Permian System for rocks that overlay the Carboniferous System and contained fossils similar to those in German strata (the Zechstein beds), which had the same stratigraphic position as the Magnesian Limestone in England. Field studies had previously shown that the Magnesian Limestone rested on Carboniferous strata. Thus Murchison was able to include the Magnesian Limestone within the Permian by correlation. The fossils of the new system differed from those of the Carboniferous below and the Triassic above. In a letter to the Society of Naturalists of Moscow dated October 8, 1841, Murchison stated, "The Carboniferous System is surmounted, to the east of the Volga, by a vast series of marls, schists, limestones, sandstones, and conglomerates to which I propose to give the name 'Permian System.'" Murchison's establishment of the Permian System provides a fine example of the logic employed by early geologists in putting together the pieces of the standard time scale.

The Triassic System The influence of British geologists in providing names for the system of the Paleozoic is by now obvious. However, their presence is not as evident in the development of Mesozoic nomenclature. The **Triassic System**, for example, was applied in 1834 by a German geologist named Frederich von Alberti. The term refers to a threefold division of rocks of this age in

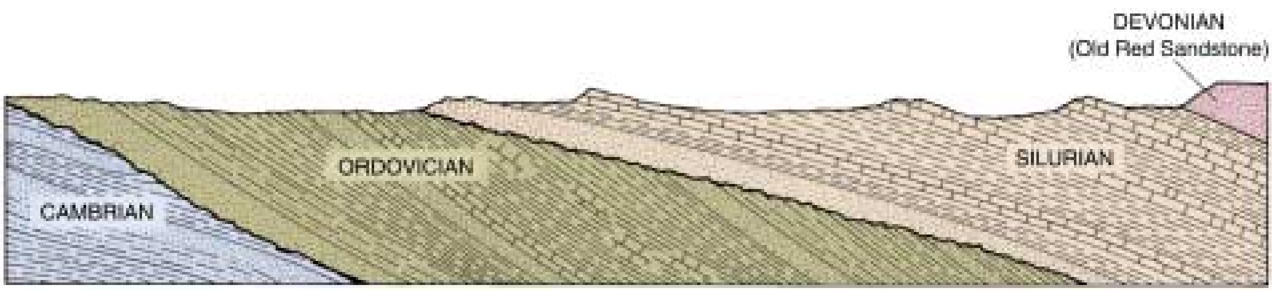


FIGURE 1-19 **Generalized geologic cross-section for the Silurian-type region.** Unconformities separate the Ordovician from the Cambrian and Silurian systems. Silurian strata are inclined toward the east, with more resistant rocks forming escarpments that face toward the west.

Germany. However, because the German strata in the type area are poorly fossiliferous, the standard of reference has been shifted to richly fossiliferous marine strata in the Alps.

The Jurassic System Another German scientist, Alexander von Humboldt, proposed the term **Jurassic** for strata of the Jura Mountains between France and Switzerland. However, in 1795, when he used the term, the concept of systems had not been developed. As a result, the Jurassic was redefined as a valid geologic system in 1839 by Leopold von Buch.

The Cretaceous System During the same year that Conybeare and Phillips were defining the Carboniferous, a Belgian geologist named Omalius d'Halloy proposed the term **Cretaceous** (from the Latin Creta, meaning "chalk") for rock outcrops in France, Belgium, and Holland. Although chalk beds are prevalent in some Cretaceous exposures, the system is actually recognized on the basis of fossils. Indeed, some thick sections of Cretaceous rocks contain no chalks whatsoever.

The Tertiary System The name **Tertiary** leads us back to the time when geology was just beginning as a science. Giovanni Arduino suggested a classification with four major divisions: Primary, Secondary, Tertiary, and Quaternary. The Tertiary was derived from his 1759 description of unconsolidated *montes tertiarii* sediments at the foot of the Italian Alps. Later, the Tertiary was more precisely defined, and standard sections for series of the Tertiary were established in France. The **Eocene, Miocene**, and **"Older" Pliocene**, for example, were proposed by Lyell in 1832 on the basis of the proportions of species of living marine invertebrates in the fossil fauna. He later used the name **Pleistocene** for a unit he had formerly called the Newer Pliocene. By Lyell's definition, 3 percent of the fossil fauna of the Eocene still live, whereas the Miocene contained 17 percent, and the Pliocene contained 50 to 67 percent. The term **Oligocene** was proposed by August von Beyrich in 1854, and the term **Paleocene** was proposed 20 years later by Wilhelm Schimper. Other system names are also used in place of the Tertiary. Many geologists now use the terms **Paleogene System** (for the Paleocene, Eocene, and Oligocene) and **Neogene System** (for the Miocene and Pliocene).

The Quaternary System In 1829, the French geologist Jules Desnoyers proposed the term **Quaternary** for certain sediments and volcanics exposed in northern France. Although these deposits contained few fossils, Desnoyers was convinced on the basis of field studies that they were younger than Tertiary rocks. In the decade following Desnoyer's establishment of the Quaternary, the unit was further divided into an older **Pleistocene Series**, composed primarily of deposits formed during the glacial ages, and the younger **Holocene Series**.

This brief review describing how geologists drew up a table of geologic time clearly shows a lack of any grand and coherent design. These geologic pioneers were influenced by conspicuous changes in assemblages of fossils from one sequence of strata to another. In many places in Europe they found that such changes frequently occurred above and below an unconformity. The success of their methods is apparent from the fact that, by and large, the systems have persisted and found wide use even to the present day.

Quantitative Geologic Time

EARLY ATTEMPTS AT QUANTITATIVE GEOCHRONOLOGY

Since the dawn of civilization, people have been curious about the age of the Earth. In addition, we have not been satisfied in being able to state the *relative* geologic age of a rock or fossil. Human curiosity demands that we know *actual* age in years. One early, but unscientific, attempt at quantitative dating was conducted in 1658 by James Ussher, Archbishop of Armagh and Primate of All England. After an analysis of solar and lunar cycles in the Julian Calendar that were calibrated against dates and events recorded in the Old Testament, Ussher stated that the Earth was created on October 23 in the year 4004 B.C. A refinement was added by Sir John Lightfoot, Vice Chancellor of Cambridge, who placed the precise hour at nine o'clock in the morning. The archbishop's date was inserted in many versions of the Bible and became widely accepted. However, geologists working during the 19th century showed that the archbishop's date could not be supported by objective scientific observation. They understood that if one were to discover the actual age of the Earth or of particular rock bodies, they would have to concentrate on natural processes that continue at a constant rate and that also leave some sort of tangible record in the rocks. Evolution is one such process, and Lyell recognized this. By comparing the amount of evolution exhibited by marine mollusks in the various series of the Tertiary System with the amount that had occurred since the beginning of the Pleistocene Ice Age, Lyell estimated that 80 million years had elapsed since the beginning of the Cenozoic. He came astonishingly close to the mark. However, for older sequences, estimates based on rates of evolution were difficult, not only because of missing parts in the fossil record but also because rates of evolution for many taxa were not well understood.

In another attempt, geologists reasoned that if rates of deposition could be determined for sedimentary rocks, they might be able to estimate the time required for deposition of a given thickness of strata. Similar reasoning suggested that one could estimate total elapsed geologic time by dividing the average thickness of sediment transported annually to the oceans into the total thickness of sedimentary rock that had ever been deposited in the past. Unfortunately, such estimates did not adequately account for past differences in rates of sedimentation or losses to the total stratigraphic section during episodes of erosion. Also, some very ancient sediments were no longer recognizable, having been converted to igneous and metamorphic rocks in the course of mountain building. Estimates of the Earth's total age based on sedimentation rates ranged from as little as a million to over a billion years.

Yet another scheme for approximating the Earth's age was proposed in 1715 by Sir Edmund Halley (1656–1742), whose name we associate with the famous comet. Halley surmised that the ocean formed soon after the origin of the planet and therefore would be only slightly younger than the age of the solid Earth. He reasoned that the original ocean was not salty and that subsequently salt derived from the weathering of rocks was brought to the sea by streams. Thus, if one knew the total amount of salt dissolved in the ocean and the amount added each year, it might be possible to calculate the ocean's age. In 1899, the Irish geologist John Joly attempted the calculation. From information provided by gauges placed at the mouths of streams, Joly was able to estimate the annual increment of salt to the oceans. Then, knowing the salinity of ocean water and the approximate volume of water, he calculated the amount of salt already held in solution in the oceans. An estimate of the age of the ocean was obtained by dividing the total salt in the ocean by the rate of salt added each year. Beginning with essentially nonsaline oceans, it would have taken about 90 million years for the oceans to reach their present salinity, according to Joly. The figure, however, was off the mark by a factor of 50, largely because there was no way to account accurately for recycled salt and salt incorporated into clay minerals deposited on the sea floors. Vast quantities of salt once in the sea had become extensive evaporite deposits on land; some of the salt being carried back to the sea had been dissolved, not from primary rocks but from eroding marine strata on the continents. Even though in error, Joly's calculations clearly supported those geologists who insisted on an age for the Earth far in excess of a few million years. The belief in the Earth's immense antiquity was also supported by Darwin, Huxley, and other evolutionary biologists, who saw the need for time in the hundreds of millions of years to accomplish the organic evolution apparent in the fossil record.

The opinion of the geologists and biologists that the Earth was immensely old was soon to be challenged by the physicists. Spearheading this attack was Lord William Thomson Kelvin, considered by many to be the outstanding physicist of the 19th century. Kelvin calculated the age of the Earth on the assumption that it had cooled from a molten state and that the rate of cooling followed ordinary laws of heat conduction and radiation. Kelvin estimated the number of years it would have taken the Earth to cool from a hot mass to its present condition. His assertions regarding the age of the Earth varied over 2 decades of debate, but in his later years he confidently believed that 24 to 40 million years was a reasonable age for the Earth. The biologists and geologists found Kelvin's estimates difficult to accept. But how could they do battle against his elegant mathematics when they were themselves armed only with inaccurate dating schemes and geologic intuition? For those geologists unwilling to capitulate, however, new discoveries showed their beliefs to be correct and Kelvin's to be unavoidably wrong.

A more correct answer to the question "How old is the Earth?" was provided only after the discovery of radioactivity, a phenomenon unknown to Kelvin during his active years. With the detection of natural radioactivity by Henri Becquerel in 1896, followed by the isolation of radium by Marie and Pierre Curie 2 years later, the world became aware that the Earth had its own built-in source of heat. It was not inexorably cooling at a steady and predictable rate, as Kelvin had suggested.

RADIOISOTOPIC METHODS FOR DATING ROCKS The solid Earth is composed of minerals and rocks. **Minerals** are solid, naturally occurring inorganic materials having a definite composition or range of compositions and usually possessing a uniform internal crystal structure. That uniform structure is derived from an orderly internal arrangement of the atoms that combine to make minerals. **Rocks** are solid, cohesive aggregates of the grains of one or more minerals occurring naturally in large quantities. To understand better the way atoms in rocks and minerals can reveal the numerical age of geologic events, a brief review of the nature of atoms is useful.

Atoms are the smallest particles of matter that can exist as an element. An individual atom consists of an extremely minute but heavy nucleus surrounded by rapidly moving negatively charged **electrons**. The electrons are relatively farther apart than are the planets surrounding our Sun; consequently, the atom consists primarily of empty space. However, electrons move so rapidly around the nucleus that they effectively fill the space within their orbits, giving volume to the atom and repelling other atoms that may approach.

In the nucleus of the atom are closely compacted particles called **protons**, which carry a unit charge of positive electricity equal to the unit charge of negative electricity carried by the electron. Associated with the protons in the nucleus are electrically neutral particles having the same mass as protons. These are called **neutrons**. Modern atomic physics has made us aware of still other particles in the nucleus. For our understanding of the atom, however, knowledge of protons and neutrons is sufficient. The number of protons in the nucleus of an atom establishes its number of positive charges and is called its **atomic number**. Each chemical element is composed of atoms having a particular atomic number. Thus, every element has a different number of protons in its nucleus. There are 90 naturally occurring elements that range in atomic number from 1 (for one proton) in hydrogen to 92 (for 92 protons) in uranium (Table 1-2 and Appendix D). The **mass** of an atom is approximately equal to the sum of the masses of its protons and neutrons. (The mass of electrons is so small that it need not be considered.) Carbon-12 is used as the standard for comparison of mass. By setting the atomic mass of carbon at 12, the atomic mass of hydrogen, which is the lightest of elements, is just a bit greater than 1 (1.008, to be precise). The nearest whole number to the total number of protons and neutrons in an element constitutes its **mass number**. Some atoms of the same substance have different mass numbers. Such variants are called **isotopes**. Isotopes are two or more varieties of the same element that have the same atomic number and chemical properties but differ in mass numbers because they have a varying number of neutrons in the nucleus. By convention, the mass number is noted as a superscript preceding the chemical symbol of an element, and the atomic number is placed beneath it as a subscript. Thus, $^{20}_{40}Ca$ is translated as the element calcium having an atomic number of 20 and mass number of 40 (Table 1-2).

Radioactivity The **radioactivity** discovered by Becquerel was observed in elements such as uranium and thorium, which are unstable and break down or decay to form other elements or other isotopes of the same element. Any individual uranium atom, for example, will eventually decay to lead if given a sufficient length of time. To understand what is meant by "decay," let us consider what happens to a radioactive element such as uranium-238 ($^{238}_{92}U$). Uranium-238 has a mass number of 238. The "238" represents the sum of the weights of the atom's protons and neutrons (each proton and neutron having a mass of 1). Uranium has an atomic number (number of protons) of 92. Such atoms with specific atomic number and weight are sometimes termed **nuclides**. Sooner or later (and entirely spontaneously), the uranium-238 atom will fire off a particle from the nucleus called an **alpha particle**. Alpha particles are positively charged ions of helium. They have an atomic weight of 4 and an atomic number of 2. Thus, when the alpha particle is emitted, the new atom will now have an atomic weight of 234 and an atomic number of 90. The new

TABLE 1-2 Number of Protons and Neutrons and Atomic Mass of Some Geologically Important Elements

Element and Symbol	Atomic Number (Number of Protons in Nucleus)	Number of Neutrons in Nucleus	Mass Number
Hydrogen (H)	1	0	1
Helium (He)	2	2	4
Carbon-12 (C)*	6	6	12
Carbon-14 (C)	6	8	14
Oxygen (O)	8	8	16
Sodium (Na)	11	12	23
Magnesium (Mg)	12	13	25
Aluminum (Al)	13	14	27
Silicon (Si)	14	14	28
Chlorine-35 (Cl)*	17	18	35
Chlorine-37 (Cl)	17	20	37
Potassium (K)	19	20	39
Calcium (Ca)	20	20	40
Iron (Fe)	26	30	56
Barium (Ba)	56	82	138
Lead-208 (Pb)*	82	126	208
Lead-206 (Pb)	82	124	206
Radium (Ra)	88	138	226
Uranium-238 (U)	92	146	238

*When two isotopes of an element are given, the most abundant is starred.

atom, which is formed from another by radioactive decay, is called a **daughter element**. From the decay of the parent nuclide, uranium-238, the daughter nuclide, thorium-234, is obtained (Fig. 1-20). A shorthand equation for this change is written:

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

This change is not, however, the end of the process, for the nucleus of thorium-234 ($^{234}_{90}Th$) is not stable. It eventually emits a beta particle (an electron discharged from the nucleus when a neutron splits into a proton and an electron). There is now an extra proton in the nucleus but no loss of atomic weight because electrons are essentially weightless. Thus, from $^{234}_{92}Th$ the daughter element $^{234}_{91}Pa$ (protactinium) is formed. In this case, the atomic number has been increased by 1. In other instances, a beta particle may be captured by the nucleus, where it combines with a proton to form a neutron. The loss of the proton would decrease the atomic number by 1.

Another kind of emission in the radioactive decay process is called gamma radiation. It consists of a form of invisible electromagnetic waves having even shorter wavelengths than X-rays.

The rate of decay of radioactive isotopes is uniform and is not affected by changes in pressure, temperature, or the chemical environment. Therefore, once a quantity of radioactive nuclides has been incorporated into a growing mineral crystal, that quantity will begin to decay at a steady rate, with a definite percentage of the radiogenic atoms undergoing decay in each increment of time. Each radioactive isotope has a particular mode of decay and a unique decay rate. As time passes, the quantity of the original or parent nuclide diminishes, and the number of the newly formed, or daughter, atoms increases, thereby indicating how much time has elapsed since the clock began its timekeeping. The beginning, or "time zero," for any mineral containing radioactive nuclides would be the moment when the radioactive parent atoms became part of a mineral from which daughter elements could not escape. The retention of daughter elements is essential, for they must be counted to determine the original quantity of the parent nuclide.

The determination of the ratio of parent to daughter nuclides is usually accomplished with the use of a mass spectrometer, an analytic instrument capable of measuring the atomic masses of elements and isotopes of elements. In the mass spectrometer, samples of elements are vaporized in an evacuated chamber, where they are bombarded by a stream of electrons. This bombardment knocks electrons off the atoms, leaving them positively charged. A stream of these positively charged ions is deflected as it passes between plates that bear opposite charges of electricity. The degree of deflection depends on the charge-to-mass ratio. In general, the heavier the ion, the less it will be deflected (Fig. 1-21).

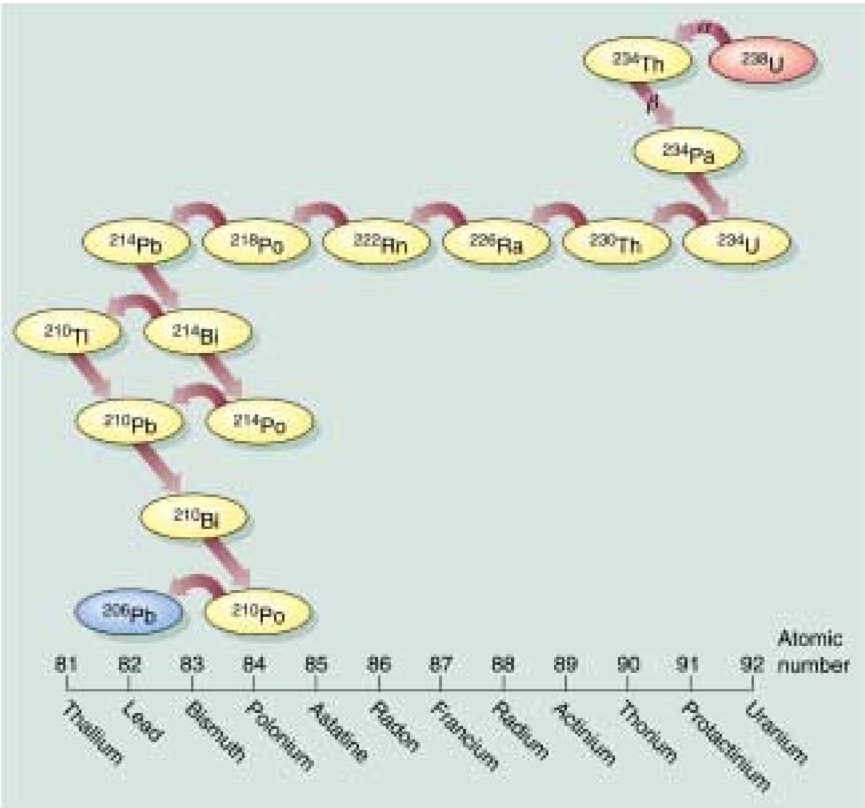


FIGURE 1-20 Radioactive decay series of uranium-238 (^{238}U) to lead-206 (^{206}Pb).

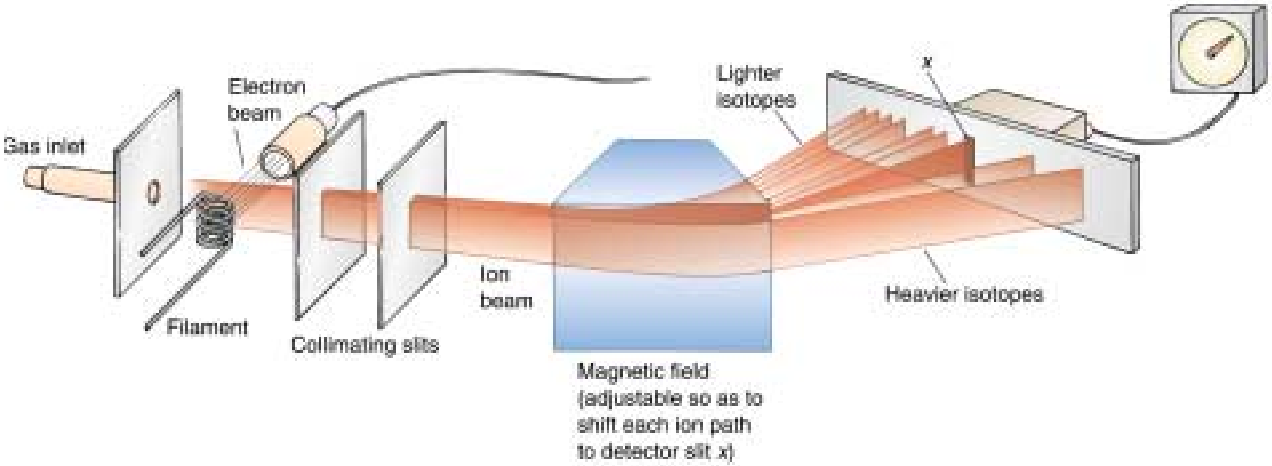


FIGURE 1-21 **Schematic drawing of a mass spectrometer.** In this type of spectrometer, the intensity of each ion beam is measured electrically (rather than recorded photographically) to permit determination of the isotopic abundances required for radiometric dating.

Of the three major families of rocks, the igneous clan is by far the best for isotopic dating. Fresh samples of igneous rocks are less likely to have experienced loss of daughter products, which must be accounted for in the age determination. Igneous rocks can provide a valid date for the time that a silicate melt containing radioactive elements solidified.

In contrast to igneous rocks, the minerals of sediments can be weathered and leached of radioactive components, and age determinations are far more prone to error. In addition, the age of a detrital grain in a sedimentary rock does not give an age of the sedimentary rock but only of the parent rock that was eroded much earlier.

Dates obtained from metamorphic rocks may also require special care in interpretation. The age of a particular mineral may record the time the rock first formed or any one of a number of subsequent metamorphic recrystallizations.

Once an age has been determined for a particular rock unit, it is often possible to use that data to approximate the age of adjacent rocks. For example, in Figure 1-22, a geology student on a field trip is showing the location of a thin, brown-colored layer of altered volcanic ash called **bentonite**. Zircon crystals within the altered ash yield uranium-to-lead ratios indicating the ash is 453.7 million years old. Thus, strata below the ash are older than 453.7 million years, and those above are younger.

In Figure 1-23, a shale bed lying below a lava flow that is 110 million years old and above another flow that is 180 million years old must be between 110 and 180 million years old. Similarly, as shown in Figure 1-24, the age of a shale deposited on the erosional surface of a 490-million-year-old granite mass and covered by a 450-million-year-old lava flow must be between 450 and 490 million years old. The fossils in that shale might then be used to assign the shale to a particular geologic system or series. Then, by correlation, the quantitative age determination obtained at the initial locality (Fig. 1-24, section *A*) could be assigned to formations at other locations (Fig. 1-24, section *B*).

FIGURE 1-22 **Thin layer of altered volcanic ash (dark brown) between layers of Ordovician marine limestones.** ? *By means of a high-resolution uranium-lead method, the ash was found to be 453.7 million years old. What can now be stated about the age of the stratum beneath the ash?*

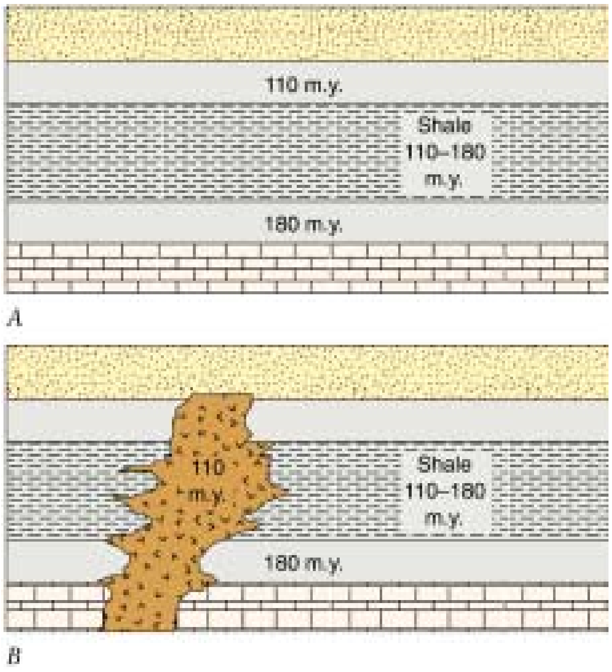


FIGURE 1-23 **Igneous rocks that have provided absolute radiogenic ages can often be used to date sedimentary layers.** (*A*) The shale is bracketed by two lava flows. (*B*) The shale lies above the older flow and is intruded by a younger igneous body. (Note: m.y. = million years.)

Half-Life One cannot predict with certainty the moment of disintegration for any individual radioactive atom in a mineral. We do know that it would take an infinitely long time for all of the atoms in a quantity of radioactive elements to be entirely transformed to stable daughter products. Experimenters have also shown that there are more disintegrations per increment of time in the early stages than in later stages (Fig. 1-25), and one can statistically forecast what percentage of a large population of atoms will decay in a certain amount of time.

Because of these features of radioactivity, it is convenient to consider the time needed for half of the original quantity of atoms to decay. This span of time is termed the **half-life**. Thus, at the end of the time constituting one half-life, half of the original quantity of radioactive element still has not undergone decay. After another half-life, half of what was left remains, or 1/4 of the original quantity. After a third half-life, only 1/8 would remain, and so on.

Every radioactive nuclide has its own unique half-life. Uranium-235, for example, has a half-life of 704 million years. Thus, if a sample contains 50 percent of the original amount of uranium-235 and 50 percent of its daughter product, lead-207, then that sample is 704 million years old. If the analyses indicate 25 percent of uranium-235 and 75 percent of lead-207,

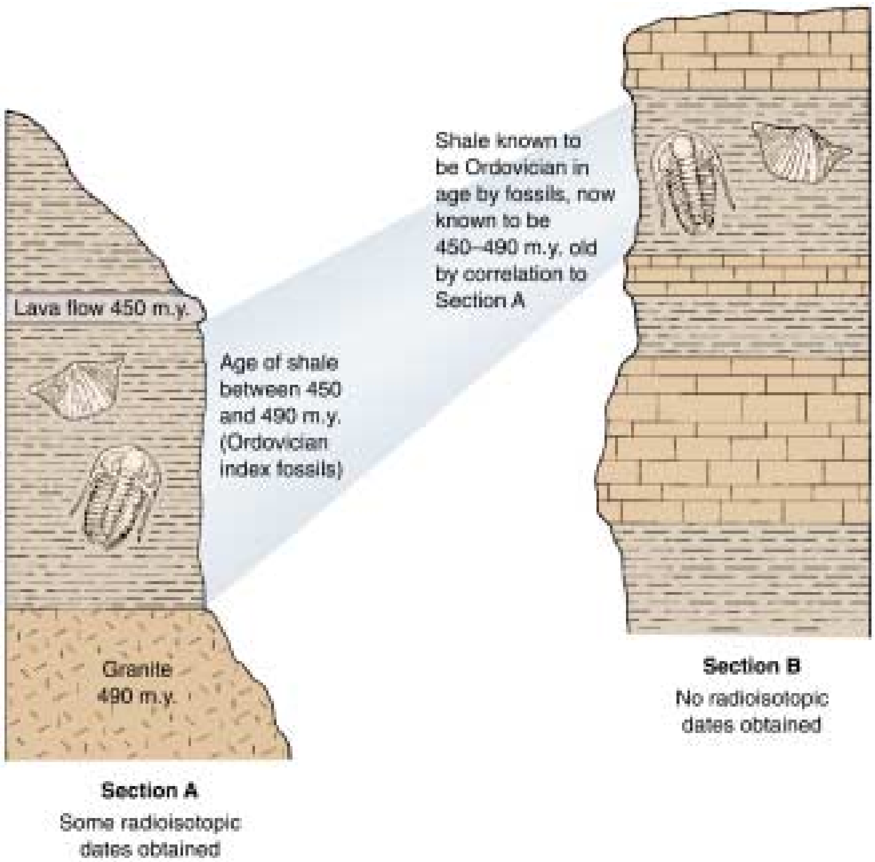


FIGURE 1-24 **The actual age of rocks that cannot be dated isotopically can sometimes be ascertained by correlation.**

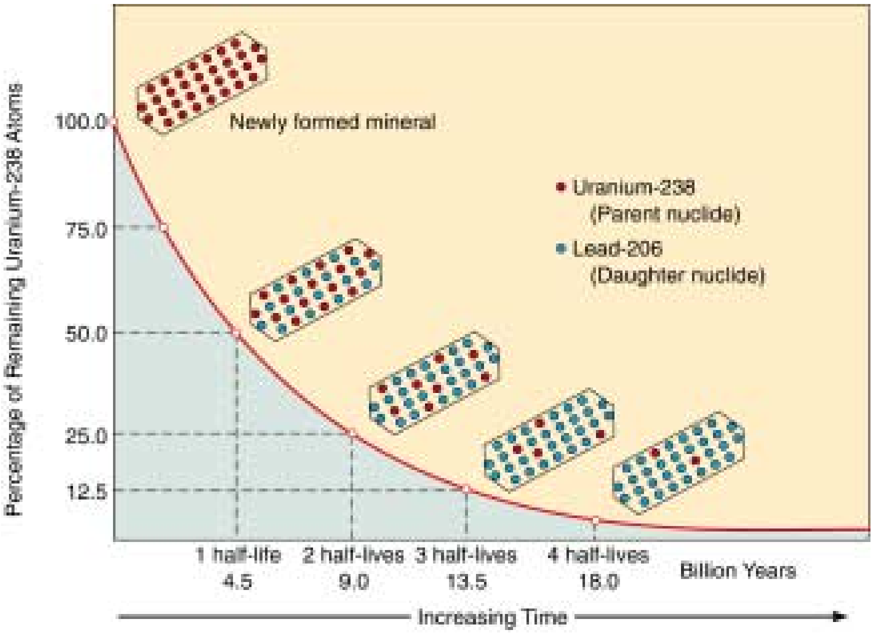


FIGURE 1-25 Rate of radioactive decay of uranium-238 to lead-206 During each half-life, half of the remaining amount of the radioactive element decays to its daughter element. In this simplified diagram, only the parent and daughter nuclides are shown, and the assumption is made that there was no contamination by daughter nuclides at the time the mineral formed. ? *If you were to draw a graph showing how many grains of sand passed through an hourglass each minute, how would the graph differ from the one depicted here?*

two half-lives would have elapsed, and the sample would be 1408 million years old.

THE PRINCIPAL GEOLOGIC TIMEKEEPERS At one time, there were many more radioactive nuclides present on Earth than there are now. Many of these had short half-lives and have long since decayed to undetectable quantities. Fortunately for those interested in dating the Earth's most ancient rocks, there remain a few long-lived radioactive nuclides. The most useful of these are uranium-238, uranium-235, rubidium-87, and potassium-40 (Table 1-3). There are also a few short-lived radioactive elements that are used for dating more recent events. Carbon-14 is an example of such a short-lived isotope. There are also short-lived nuclides that represent segments of a uranium or thorium decay series.

Uranium-Lead Methods Dating methods involving lead require the presence of radioactive nuclides of uranium or thorium that were incorporated into a rock when the rock originated. To determine the age of a sample of mineral or rock, one must know the original number of parent nuclides as well as the number remaining at the present time. The original number of parent atoms should be equal to the sum of the present

TABLE 1-3 Some of the More Useful Nuclides for Radioisotopic Dating

Parent Nuclide*	Half-Life†	Daughter Nuclide	Source Materials
Carbon-14	5730 years	Nitrogen-14	Organic matter
Uranium-238	4.5 billion years	Lead-296	Zircon, uraninite, pitchblende
Uranium-235	704 million years	Lead-207	
Thorium-232	14 billion years	Lead-208	
Rubidium-87	48.8 billion years	Strontium-87	Potassium mica, potassium feldspar, biotite, glauconite, whole metamorphic or igneous rock
Potassium-40	1251 million years (1.251 billion years)	Argon-40 (and calcium-40)‡	Muscovite, biotite, hornblende, whole volcanic rock, glauconite, and potassium feldspar†‡

**Nuclide* is a convenient term for any particular atom (recognized by its particular combination of neutrons and protons).
†Half-life data from Steiger, R. H., and Jäger, E. 1977. Subcomission on geochronology: Convention on the use of decay constants in geo- and cosmochronology, *Earth and Planetary Science Letters* 36:359–362.
‡Although potassium-40 decays to argon-40 and calcium-40, only argon is used in the dating method because most minerals contain considerable calcium-40, even before decay has begun.

number of parent atoms and daughter atoms. The assumptions are made that the system has remained closed, so neither parent nor daughter atoms have ever been added or removed from the sample except by decay, and that no daughter atoms were present in the system when it formed. The presence, for example, of original lead in the mineral would cause the radiometric age to exceed the true age. Fortunately, geochemists are able to recognize original lead and make the needed corrections.

As we have seen, different isotopes decay at different rates. Geochronologists take advantage of this fact by simultaneously analyzing two or three isotope pairs as a means to cross-check ages and detect errors. For example, if the $^{235}U/^{207}Pb$ radiometric ages and the $^{238}U/^{206}Pb$ ages from the same sample agree, then one can confidently assume that the age determination is valid.

Isotopic ages that depend on uranium-lead ratios may also be checked against ages derived from lead-207 to lead-206. Because the half-life of uranium-235 is much less than the half-life of uranium-238, the ratio of lead-207 (produced by the decay of uranium-235) to lead-206 will change regularly with age and can be used as a radioactive timekeeper (Fig. 1-26). This is called a lead-lead age, as opposed to a uranium-lead age.

Another uranium isotope, uranium-234, is often incorporated into the calcium carbonate skeletons of reef-building corals. Uranium-234 has a very short half-life and decays rapidly to thorium-230. The $^{234}U/^{230}Th$ dating method provides very reliable ages for reef corals that range in age from only a few thousand years to about 300,000 years. The ages, however,

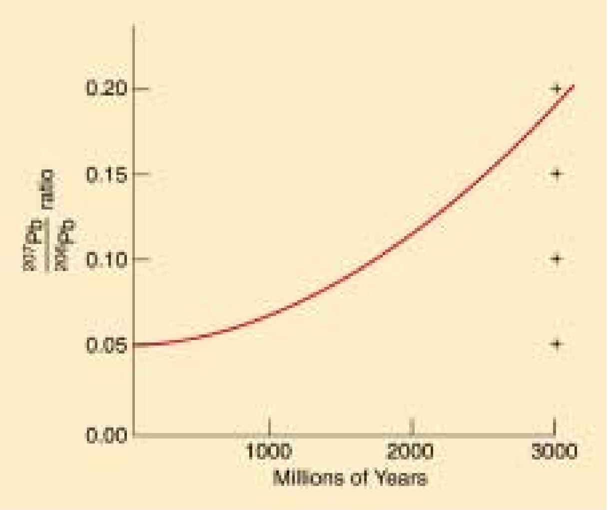


FIGURE 1-26 Graph showing how the ratio of lead-207 to lead-206 can be used as a measure of age.
? *What would be the age of a rock having a $^{207}Pb/^{206}Pb$ ratio of 0.15?*

are accurate only if unaltered skeletal material is used in the analysis.

The Potassium-Argon Method Potassium and argon are another radioactive pair widely used for dating rocks. By means of electron capture (causing a proton to be transformed into a neutron), about 11 percent of the potassium-40 in a mineral decays to argon-40, which may then be retained within the parent mineral. The remaining potassium-40 decays to calcium-40 (by emission of a beta particle). The decay of potassium-40 to calcium-40 (by emission of a beta particle) is not used because the calcium-40 formed during radioactive disintegration cannot be distinguished from calcium-40 that may have originally existed in the rock. The advantage of using argon is that it is inert; that is, it does not combine chemically with other elements. Argon-40 found in a mineral is very likely to have originated there following the decay of adjacent potassium-40 atoms in the mineral. Also, potassium-40 is a constituent of many common minerals. However, like all isotopic dating methods, potassium-argon is not without its limitations. A sample will yield a valid age only if none of the argon has leaked out of the mineral being analyzed. Leakage may indeed occur if the rock has experienced temperatures above about 125°C. In specific localities, the ages of rocks dated by this method reflect the last episode of heating rather than the time of origin of the rock itself.

The half-life of potassium-40 is 1251 million years (1.251 billion years). As illustrated in Figure 1-27, if the ratio of potassium-40 to daughter products is found to be 1 to 1, then the age of the sample is 1251 million years (1.251 billion years). If the ratio is 1 to 3, then yet another half-life has elapsed, and the rock would have an isotopic age of two half-lives, or 2502 million years (2.502 billion years).

The Rubidium-Strontium Method The dating method based on the disintegration by beta decay of rubidium-87 to strontium-87 can sometimes be used as a check on potassium-argon dates because rubidium and potassium are often found in the same minerals. The rubidium-strontium scheme has a further advantage in that the strontium daughter nuclide is not diffused by relatively mild heating events, as is the case with argon.

In the rubidium-strontium method, a number of samples are collected from the rock body to be dated. With the aid of the mass spectrometer, the amounts of radioactive rubidium-87, its daughter product strontium-87, and strontium-86 are calculated for each sample. Strontium-86 is an isotope not derived from radioactive decay. A graph is then prepared in which the $^{87}Rb/^{86}Sr$ ratio in each sample is plotted against the $^{87}Sr/^{86}Sr$ ratio (Fig. 1-28). From the points on the graph, a straight line that is termed an isochron

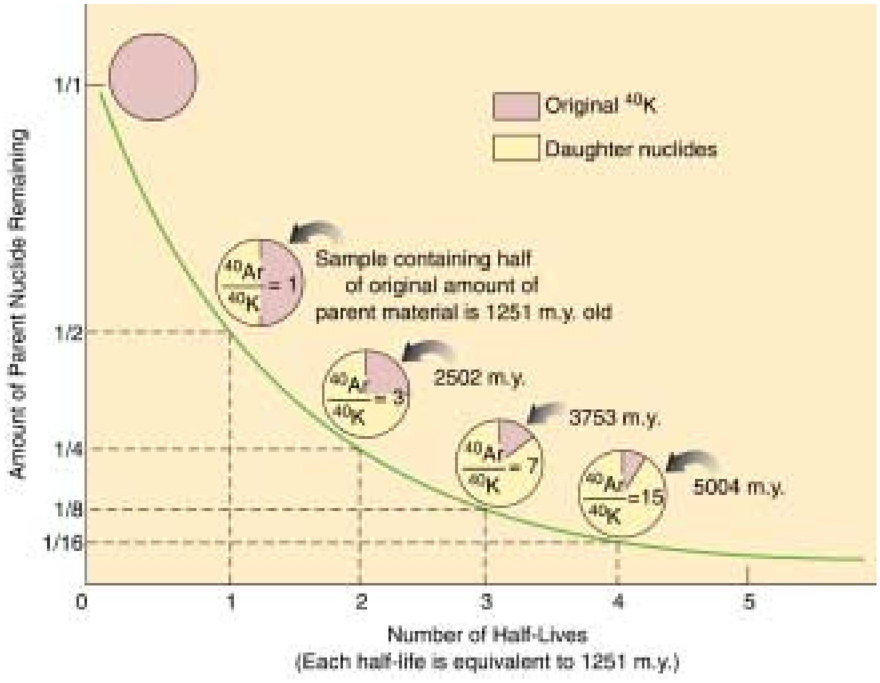


FIGURE 1-27 **Decay curve for potassium-40.**

is constructed. The slope of the isochron results from the fact that, with the passage of time, there is continuous decay of rubidium-87, which causes the rubidium-87/strontium-86 ratio to decrease. Conversely, the strontium-87/strontium-86 ratio increases as strontium-87 is produced by the decay of rubidium-87. The older the rocks being investigated, the more the original isotope ratios will have been changed and the greater will be the inclination of the isochron. The slope of the isochron permits a computation of the age of the rock.

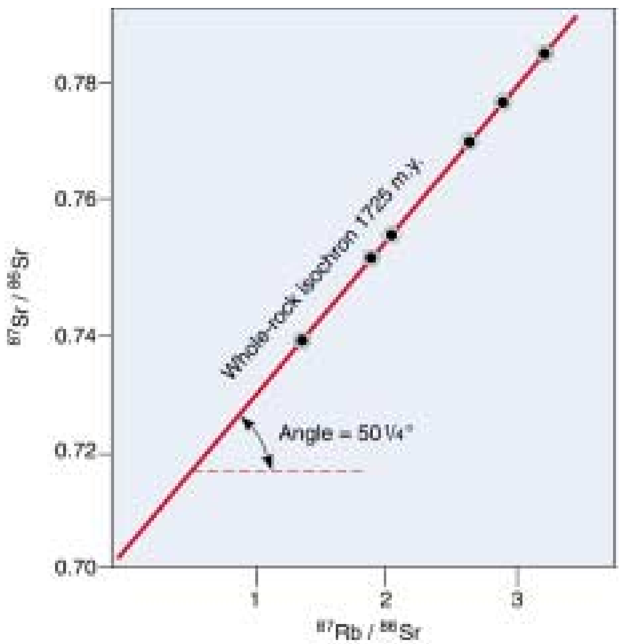


FIGURE 1-28 **Whole-rock rubidium-strontium isochron for a set of samples of a Precambrian granite body exposed near Sudbury, Ontario.** (*Modified from Krogh, T. E. et al. 1968. Carnegie Institute Washington Year Book 66:530.*)

The rubidium-strontium and potassium-argon methods need not always depend on the collection of discrete mineral grains containing the required isotopes. Sometimes the rock under investigation is so finely crystalline and the critical minerals so tiny and dispersed that it is difficult or impossible to obtain a suitable collection of minerals. In such instances, large samples of the entire rock may be used for age determination. This method is called **whole-rock analysis**. It is useful not only for fine-grained rocks but also for rocks in which the yield of useful isotopes from mineral separates is too low for analysis. Whole-rock analysis has also been useful in determining the age of rocks that have been so severely metamorphosed that the potassium-argon or rubidium-strontium radiometric clocks of individual minerals have been reset. In such cases, the age obtained from the minerals would be that of the episode of metamorphism, not the total age of the rock itself. The required isotopes and their decay products, however, may have merely moved to nearby locations within the same rock body, and therefore analyses of large chunks of the whole rock may provide valid radiometric age determinations.

The Carbon-14 Method Techniques for age determination based on content of radiocarbon were first devised by W. F. Libby and his associates at the University of

Chicago in 1947. The method is an indispensable aid to archaeologic research and is useful in deciphering very recent events in geologic history. Because of the short half-life of carbon-14—a mere 5730 years—organic substances older than about 50,000 years contain very little carbon-14. New techniques, however, allow geologists to extend the method's usefulness back to almost 100,000 years.

Unlike uranium-238, carbon-14 is created continuously in the Earth's upper atmosphere. The story of its origin begins with cosmic rays, which are extremely high-energy particles (mostly protons) that bombard the Earth continuously. Such particles strike atoms in the upper atmosphere and split their nuclei into small particles, among which are neutrons. Carbon-14 is formed when a neutron strikes an atom of nitrogen-14. As a result of the collision, the nitrogen atom emits a proton, captures a neutron, and becomes carbon-14 (Fig. 1-29). Radioactive carbon is being created by this process at the rate of about two atoms per second for every square centimeter of the Earth's surface. The newly created carbon-14 combines quickly with oxygen to form CO_2, which is then distributed by wind and water currents around the globe. It soon finds its way into photosynthetic plants because they utilize carbon dioxide from the atmosphere to build tissues. Plants containing carbon-14 are ingested by animals, and the isotope becomes a part of their tissue as well.

Eventually, carbon-14 decays back to nitrogen-14 by the emission of a beta particle. A plant removing CO_2 from the atmosphere should receive a share of carbon-14 proportional to that in the atmosphere. A state of equilibrium is reached in which the gain in newly produced carbon-14 is balanced by the decay loss. The rate of production of carbon-14 has varied somewhat over the past several thousand years (Fig. 1-30). As a result, corrections in age calculations must be made. Such corrections are derived from analyses of standards such as wood samples, whose exact age is known from tree ring counts.

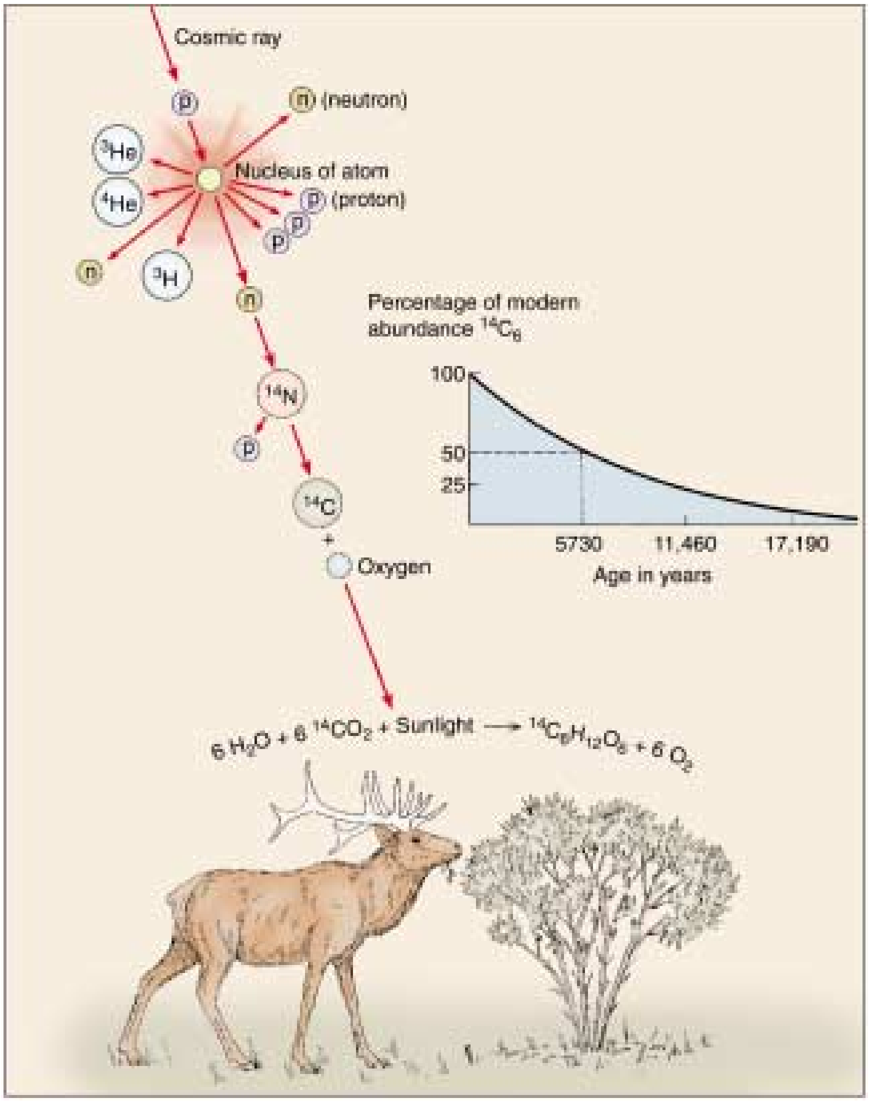


FIGURE 1-29 Carbon-14 is formed from nitrogen in the atmosphere. It combines with oxygen to form radioactive carbon dioxide and is then incorporated into all living things.

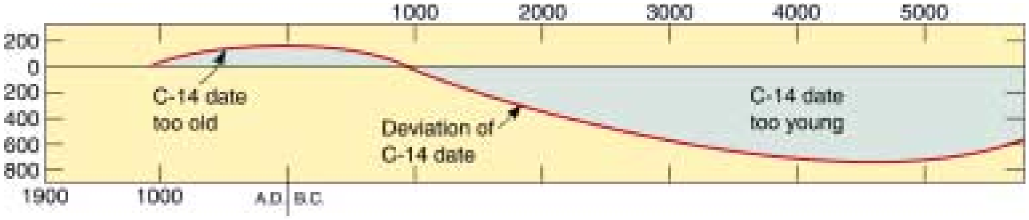


FIGURE 1-30 **Deviation of carbon-14 ages to true ages from the present back to about 5000 B.C.** Data are obtained from analysis of bristle cone pines from the western United States. Calculations of carbon-14 deviations are based on half-life of 5730 years. (*Adapted from Ralph, E. K., Michael, H. N., and Han, M. C. 1973. Radiocarbon dates and reality. MASCA Newsletter 9:1.*)

The age of some ancient bits of organic material is not determined from the ratio of parent to daughter nuclides, as is done with previously discussed dating schemes. Rather, the age is estimated from the ratio of carbon-14 to all other carbon in the sample. After an animal or plant dies, there can be no further replacement of carbon from atmospheric CO_2, and the amount of carbon-14 already present in the once-living organism begins to diminish in accordance with the rate of carbon-14 decay. Thus, if the carbon-14 fraction of the total carbon in a piece of pine tree buried in volcanic ash were found to be about 25 percent of the quantity in living pines, then the age of the wood (and the volcanic activity) would be two half-lives of 5730 years each, or 11,460 years.

The carbon-14 technique had considerable value to geologists studying the most recent events of the Pleistocene Ice Age. Prior to the development of the method, the age of sediments deposited by the last advance of continental glaciers was surmised to be about 25,000 years. Radiocarbon dates of a layer of peat beneath the glacial sediments provided an age of only 11,400 years. The method has also been found useful in studies of groundwater migration and in dating the geologically recent uppermost layer of sediment on the sea floors. Carbon-14 analysis of tissue from the baby mammoth depicted in Figure 4-7 indicates that the animal died 27,000 years ago. The age of giant ground sloth dung recovered from a cave near Las Vegas indicated the presence of these ancient beasts in Nevada 10,500 years ago. Charcoal from the famous Lascaux cave in France revealed that the artists who drew pictures of mammoths, woolly rhinoceroses, bison, and reindeer on the walls of the cave lived about 15,000 years ago. In archaeology, dates obtained by the carbon-14 method overturned many cherished concepts by demonstrating that the beginnings of agriculture and urbanization occurred much earlier than had formerly been thought.

Nuclear Fission Track Timekeepers Nuclear particle fission tracks were discovered in the early 1960s, when scientists using the electron microscope were able to examine the areas around presumed locations of radioactive particles that were embedded in mica. Closer examination showed that the tracks were really small tunnels—like bullet holes—that were produced when high-energy particles of the nucleus of uranium were fired off in the course of spontaneous fission (spontaneous fragmentation of an atom into two or more lighter atoms and nuclear particles). The particles speed through the orderly rows of atoms in the crystal, tearing away electrons from atoms located along the path of trajectory and rendering them positively charged. Their mutual repulsion produces the track (Fig. 1-31). The tracks are only a few atoms in width and are impossible to see without an electron microscope. Therefore, the sample is immersed for a short

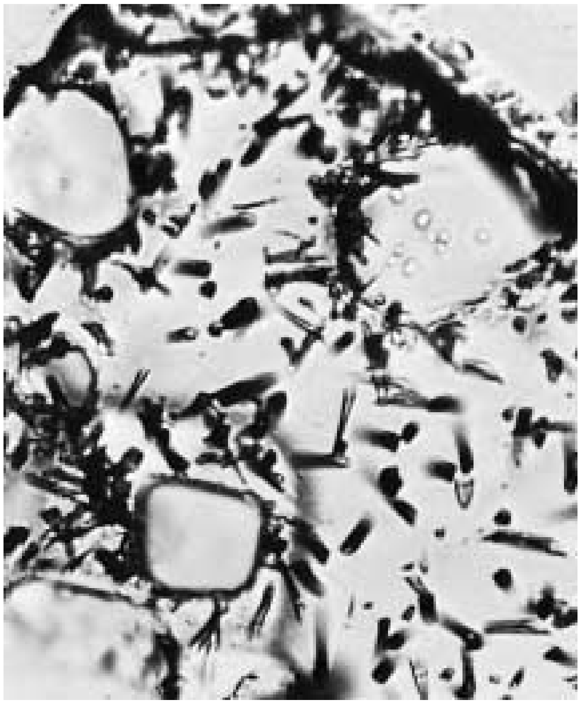


FIGURE 1-31 **Fission tracks.** These tracks were produced by plutonium-244 in a melilite crystal that was extracted from a meteorite. The small crystals are spinel inclusions. Melilite is a calcium-magnesium aluminosilicate. (*Photograph courtesy of F. Podosek, Department of Earth and Planetary Sciences, Washington University, St. Louis, MO.*)

period of time in a suitable solution (acid or alkali), which rushes up into the tubes, enlarging the track tunnel so that it can be seen with an ordinary microscope.

The natural rate of track production by uranium atoms is very slow and uniform. For this reason, the tracks can be used to determine the number of years that have elapsed since the uranium-bearing mineral solidified. One first determines the number of uranium atoms that have already disintegrated. This number is obtained with the aid of a microscope by counting the etched tracks. Next, one must find the original number of uranium atoms. This quantity can be determined by bombarding the sample with neutrons in a reactor and thereby causing the remaining uranium to undergo fission. A second count of tracks reveals the original quantity of uranium. Finally, one must know the spontaneous fission decay rate for uranium-238. This information is determined by counting the tracks in a piece of uranium-bearing synthetic glass of known date of manufacture.

Fission track dating is of particular interest to geochronologists because it can be used to date specimens only a few centuries old as well as to date rocks billions of years in age. The method helps to date the period between 50,000 and 1 million years ago; a period for which neither carbon-14 nor potassium-argon methods are suitable. As with all radiometric techniques, however, there can be problems. If rocks have been subjected to high temperatures, tracks may heal and fade away.

THE AGE OF THE EARTH

Anyone interested in the total age of the Earth must decide what event constitutes its "birth." Most geologists assume that "year 1" commenced as soon as the Earth had collected most of its present mass and had developed a solid crust. Unfortunately, rocks that date from those earliest years have not been found on the Earth. They have long since been altered and converted to other rocks by various geologic processes. The oldest materials known are grains of the mineral zircon taken from a sandstone in western Australia. The zircon grains are 4.1 to 4.2 billion years old. The zircons were probably eroded from nearby granitic rocks and deposited, along with quartz and other detrital grains, by rivers. Other very old rocks on Earth include 3.7-billion-year-old granites of southwestern Greenland, metamorphic rocks of about the same age from Minnesota, and 3.96-billion-year-old rocks from the Northwest territories of Canada (north of Yellowknife, Canada).

Meteorites, which many consider to be remnants of a shattered planet or asteroid that originally formed at about the same time as the Earth, have provided uranium-lead and rubidium-strontium ages of about 4.6 billion years. From such data, and from estimates of how long it would take radioactive decay to produce the quantities of various lead isotopes now found on the Earth, geochronologists feel that the 4.6-billion-year age for the Earth can be accepted with confidence. Evidence substantiating this conclusion comes from returned moon rocks. The ages of these rocks range from 3.3 to about 4.6 billion years. The older age determinations are derived from rocks collected on the lunar highland, which may represent the original lunar crust. Certainly, the moons and planets of our solar system originated as a result of the same cosmic processes and at about the same time.

SUMMARY

Simply stated, geology is the study of all naturally occurring processes, phenomena, and materials of the past and present Earth. Historical geology is that branch of the science concerned particularly with decoding the rock and fossil record of the Earth's long history. In the past few decades, advances in technology have added immensely to the store of geologic knowledge. Interpretation of the new data requires an exceptional understanding not only of geology but also of physics, chemistry, mathematics, and biology. However, the historical inferences that are drawn from the data are frequently derived from the fundamental geologic and paleontologic concepts introduced by Nicolaus Steno (superposition), James Hutton (uniformitarianism), Sir Charles Lyell (cross-cutting relationships, inclusion), William Smith (correlation), Charles Darwin (organic evolution), and others. These scientists formulated the principles by which geologists determine the relative age of rock outcrop, its history of deposition and deformation, and its spatial and chronologic relationship to strata in other regions of the Earth. American geologists such as William Maclure, Amos Eaton, James Hall, Ferdinand Hayden, and John Powell used the precepts of their European colleagues and predecessors in their studies of the geology of America, while Othniel Marsh and Edwin Cope revealed the rich fossil record of vertebrates in the American West.

In the early stages of its development, geology was totally dependent on relative dating of events. Hutton helped scientists visualize the enormous amount of time needed to accomplish the events indicated in sequences of strata, and the geologists who followed him pieced together the many local stratigraphic sections by using fossils and superposition. A scale of relative geologic time gradually emerged. Initial attempts to decide what the rock succession meant in terms of years were made by estimating the amount of salt in the ocean, the average rate of deposition of sediment, and the rate of cooling of the Earth. However, these early schemes did little more than suggest that the planet was at least tens of millions of years old and that the traditional concept of a 6000-year-old Earth did not agree with what could be observed geologically.

An adequate means of measuring geologic time was achieved only after the discovery of radioactivity at about the turn of the 20th century. Scientists found that the rate of decay by radioactivity of certain elements is constant and can be measured and that the proportion of parent and daughter elements can be used to reveal how long they had been pres- ent in a rock. Over the years, continuing efforts by investigators as well as improvements in instrumentation (particularly of the mass spectrometer) have provided many thousands of age determinations. Frequently, these numerical dates have shed light on difficult geologic problems, provided a way to determine rates of movement of crustal rocks, and permitted geologists to date mountain building or to determine the time of volcanic eruptions. In a few highly important regions, isotopic dates have been related to particular fossiliferous strata and have thereby helped to quantify the geologic time scale and to permit estimation of rates of organic evolution. Isotopic dating has also changed the way humans view their place in the totality of time.

The isotopic transformations most widely used in determining absolute ages are uranium-238 to lead-206, uranium-235 to lead-207, thorium-232 to lead-208, potassium-40 to argon-40, rubidium-87 to strontium-87, and carbon-14 to nitrogen-14. Methods involving uranium-lead ratios are of importance in dating the Earth's oldest rocks. The short-lived carbon-14 isotope that is created by cosmic ray bombardment of the atmosphere provides a means to date the most recent events in Earth history. For rocks of intermediate age, schemes involving potassium-argon ratios, those utilizing intermediate elements in decay series, or those employing fission tracks are most useful. A figure of 4.6 billion years for the Earth's total age is now supported by ages based on meteorites and on lead ratios from terrestrial samples.

Improvements in numerical geochronology are being made daily and will provide further calibration of the standard geologic time scale in the future. Some of the time boundaries in the scale, such as that between the Cretaceous and Tertiary systems, are already well validated. Others, such as the boundary between the Paleozoic and Mesozoic, require additional refinement. Additional efforts to incorporate isotopic ages into sections of sedimentary rocks are among the continuing tasks of historical geologists. The usual methods for determining the age of strata involve the dating of intrusions that penetrate these sediments or the dating of interbedded volcanic layers. Less frequently, strata can be dated by means of radioactive isotopes incorporated within sedimentary minerals that formed in place at the time of sedimentation. At present, the best numerical age estimates indicate that Paleozoic sedimentation began about 540 million years ago, the Mesozoic Era began about 250 million years ago, and the Cenozoic commenced about 65 million years ago.

QUESTIONS FOR REVIEW AND DISCUSSION

1. Describe the general steps used by geologists and other scientists in their attempt to solve particular problems or explain natural phenomena.

2. Discuss the principles that Steno, Lyell, and Smith formulated for the development of the geologic time scale.

3. What interpretation did Steno make on observing rock layers that were not horizontal? What could be said of a sequence of strata having oldest beds at the top and younger at the bottom?

4. Explain the difference between a geochronologic term (sometimes called a time term) and a chronostratigraphic term (sometimes called a time-rock term).

5. What features in a rock layer might a geologist seek in attempting to determine the top from the bottom of strata that had been forced into vertical alignment or overturned during mountain building?

6. What is meant by uniformitarianism?

7. Why is the concept of half-life necessary? (Why not use whole life?)

8. Pebbles of a black rock called basalt occur in a sedimentary rock composed of those pebbles. The sedimentary rock is called a conglomerate. The pebbles yield an isotopic age of 300 million years. Is the conglomerate younger or older than the pebbles?

9. How do isotopes of a given element differ from one another in regard to number of protons and neutrons in the nucleus?

10. How are dating methods involving decay of radioactive elements unlike methods for determining elapsed time that involve the funneling of sand through an hourglass?

11. What would be the effect on the isotopic age of a zircon crystal being dated by the potassium-argon method if a small amount of argon-40 escaped from the crystal?

12. State the age of a sample of prehistoric mummified human skin that contains 12.5 percent of the original amount of carbon-14.

13. How do fission tracks originate? What geologic events might destroy fission tracks in a mineral crystal?

READINGS

Adams, F. D. 1938. *The Birth and Development of the Geological Sciences*. Baltimore: Williams & Wilkins Co. (Reprinted by Dover Press, 1954.)

Albritton, C. C., Jr. 1980. *The Abyss of Time*. San Francisco: Freeman, Cooper & Co.

Berry, W. B. N. 1987. *Growth of a Prehistoric Time Scale*. San Francisco: W. H. Freeman & Co.

Dean, D. R. 1992. *James Hutton and the History of Geology*. Ithaca, NY: Cornell University Press.

Eicher, D. L. 1976. *Geologic Time*, 2nd ed. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Eiseley, L. C. 1959. Charles Lyell, *Sci. Am*. 201(8): 98–106. (Offprint No. 846. San Francisco: W. H. Freeman & Co.)

Gohau, G. 1990. *A History of Geology*. New Brunswick, NJ: Rutgers University Press.

Hallam, A. 1983. *Great Geologic Controversies*. Oxford, England: Oxford University Press.

Jaffe, M. 2000. *The Gilded Dinosaur: the Fossil War Between E. D. Cope and O. C. Marsh and the Rise of American Science*. New York: Crown Publishers.

Speakman, C. 1982. *Adam Sedgwick, Geologist and Dalesman*, 1785–1873. Cambridge, England: Trinity College.

Winchester, S. 2001. *The Map that Changed the World: William Smith and the Birth of Modern Geology*. New York: HarperCollins.

York, D., and Farquhar, R. M. 1972. *The Earth's Age and Geochronology*. Oxford, England: Oxford University Press.

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