Chapter 1

Introduction to Fossils

Outline

- History, Science, and Historical Science
- Time, Life, and Stratigraphy
- What is a Fossil?
- How do Fossils Form?
- Conclusions: Fossils as Curious Stones
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History, Science, and Historical Science

Paleontologists are those people who are fortunate enough to be able to study fossils for a living. George Gaylord Simpson was one of the most famous American paleontologists. He studied vertebrate fossils—those animals with backbones; among other things he specialized on the evolution of horses. In his work on the evolution of fossils through time, what we call the fossil record, Simpson was very much a historian—a historian of life on Earth.

Studying the History of Life

We often think of history as implying something distinctly human. For example, at a university the football or basketball program may have had a long history with many illustrious athletes associated with it, but because of the nature of universities (student’s actually graduate in spite of some professor’s best efforts), the teams change very year. The city in which the university is located also has a history,
and information on the changes that have taken place through time is available through archives of the local newspaper or perhaps made evident in plaques marking the sites of noteworthy past events. Civilizations have histories, too. Those that flourished in the ancient world are now extinct. Even their languages are no longer accessible to most of us, except perhaps in obscure academic corridors.

What Simpson knew and what every other paleontologist recognizes is that the Earth, too, has a history. Life has a history, and the history of the Earth and its life are topics worthy of our study and understanding. That is why we study fossils: to understand the long history of life. This history helps put what we see today, for instance, the current environment of the planet, the rich diversity of living organisms found in many different habitats, into that historical, evolutionary, and geological context. It also helps us to understand where our species comes from, and to make predictions about where we and the other organisms that occupy this planet are headed.

**History**

Simpson defined history as “configurational change through time, i.e., a sequence of real, individual but related events.” These configurational changes have to do with changes in the state of the universe or any part of it through time. From our special point of view, those of interest to us are changes in the fossil record through time as organisms have evolved, been faced with environmental change, and coped—or failed to cope—with the forces of nature that at times in the past have caused the extinction of many kinds of organisms with which they shared their environments. Can we study in a scientific way these changes that have taken place through time? Is there such a thing as historical science? You can bet that the paleontologists think so. Their science is based on the idea of investigating the history of life in a scientific way.

**Science**

Simpson presented one of the most intriguing definitions of science that has ever been proposed. “Science” he wrote “is an exploration of the material universe that seeks natural, orderly relationships among observed phenomena and that is self-testing.” His definition says it all. It captures the excitement of science and implies that the exploration is far from being completed. It makes the important point that science deals with the natural world (not the supernatural), and it captures the essence of science as a self-testing, self-correcting enterprise. This means that when a scientist presents an idea—an hypothesis—he or she no longer owns it, and he or she should feel no compulsion to defend it. Instead, all qualified scientists, including the one who proposed the idea in the first place, are obligated to test the idea and to seek to reject it. If they are unable to reject the idea, it may be accepted. The idea, however, is always subject to further testing and to possible rejection. This implies another important point about ideas in science. Ideas in science are never proved. Mathematicians prove their theorems, but scientists seek only to test the ideas and to reject them when it is possible to do so.

If an idea in science is broad enough in scope to explain many different kinds of phenomena and if it has been tested repeatedly and accepted, the idea can be regarded as a scientific theory or even as a law of science. Simpson defined a scientific law as “a recurrent, repeatable relationship between variables that is itself invariable to the extent that the factors affecting the relationship are explicit in the law.” We shall come back to this idea later.
Historical science
Simpson defined historical science as “the determination of configurational sequences, their explanation, and the testing of such sequences and explanations.” History typically deals with unique events. There has been only one American Civil War, only a single origin of life more than 3.5 billion years ago (3.5 Ga, for giga annum), only a single invasion of the land by primitive Devonian amphibians, only one ultimate extinction of the dinosaurs at the end of the Cretaceous. It is the historical aspects of paleontology that continue to fascinate so many people interested in the history of life.

Process and Pattern
The way scientists like paleontologists connect history with science is through the study of processes. Indeed, following Simpson’s definition, a fundamental part of science is the search for orderly relationships: these are scientific processes that explain why certain phenomena occur. Further, the way scientists discover processes are from patterns: these patterns can be the results of an experiment or the distribution of species in the fossil record. That is, scientists seek to determine what processes are at work in nature from the patterns these processes produce—in the laboratory, in the stars, or in the fossil record preserved in ancient rock. The way of going about this in the historical sciences, however, is different from the procedures used in the physical sciences, where research often takes place in the laboratory. Years ago, before we realized how dangerous to health metallic mercury can be, a standard experiment in beginning chemistry laboratory classes was to heat mercuric oxide (HgO, an orange powder) to about 600° C. at which temperature it decomposed into metallic mercury (Hg, a silvery liquid) and free oxygen O₂. A property of mercuric oxide is that at 600° C. it decomposes in this manner. It has always done so, and it will do so anywhere in the universe where conditions are appropriate because the laws of science are invariant in time and space. By conducting this experiment, the beginning chemistry student demonstrated the process of thermal decomposition by the pattern it produced: change of an orange powder into a silvery liquid and a colorless gas.

Experiments of this sort lie at the heart of the physical sciences. In historical science, however, all the experiments have already been run by nature in the distant past. The task of the historical scientist is to determine what experiments nature has conducted. It is much as if you were to venture into a chemistry laboratory at the end of the day, poke around in the sink and waste containers, and try to determine what experiments had occupied the students in the laboratory that day. You would still be determining process from pattern, but the pattern would be little blebs of mercury, the remains of students’ playing about with free oxygen, and perhaps a broken test tube or two. The process that you would deduce is the same, but you would be establishing the historical, configurational fact that the chemistry course had just begun rather than making any profound discoveries about the chemical process of decomposition. Discovering the immanent properties and processes is the job of the physical scientist; applying the properties to understanding the process of history is what historical science is all about.

Fossils as a historical record
The early English scientist Robert Hooke (1635–1703) was a remarkable individual by any possible measure one could propose. Among his many accomplishments, he
studied springs and invented the hairspring, which led later to the invention of wristwatches and to ship’s chronometers, a discovery that made global navigation possible. While studying microscopically a thin slice of cork, he observed and named as cells the small compartments in the tissue, a term we still use for these structures today. We now know that all life is organized into cells, but it was Robert Hooke who started our thinking in this direction. From our special paleontological point of view, Hooke observed in 1688 that fossils could be used to record passing time. Evolution provides the process that explains the change in fossils through time that Hooke observed. It is interesting, therefore, that Hooke made this observation 171 years before Charles Darwin published his book *On the Origin of Species*.

As we shall see in some detail in the next section of this chapter, Hooke was absolutely correct. Fossils have recorded the chronicle of the history of life, and their study remains the best way we have of determining the past processes that have led to the patterns we see in the modern world.

**Time's cycle and time's arrow**

Conflicting adages abound. A common saying these days, “What goes around comes around,” implies some sort of cyclical recurrence of events. The Greek philosopher Heraclitus (ca. 540 to ca. 480 BCE) said, on the other hand, “You could not step twice into the same rivers; for other waters are ever flowing on to you.” Both are correct. Patterns in history and historical science can be thought of as comprising three components—trend, signal, and noise—the latter radio listeners refer to as static.

Trends, referred to as time’s arrow by paleontologist and evolutionary biologist Stephen Jay Gould, are unidirectional changes, patterns caused by long-term processes. In history they include such things as the flow of rivers mentioned by Heraclitus, the progressive and now alarming increase of human population, increased speed of computers, the growing levels of carbon dioxide (CO₂) in the atmosphere, and since the beginning of the 20th century, the increased effectiveness of weaponry and the consequent increased potential lethality of wars. In paleontology trends include such patterns as increased complexity of the most complex forms of life, movement of vertebrates from an aquatic to a terrestrial mode of life, and increased diversity of life—the number of different kinds of organisms that have lived at any one time.

Note that we do not include evolutionary trends here. In the past, the prevailing concept of evolution was as a gradual change of the form of organisms directed over a long time. As we shall see in a later chapter, paleontologists no longer think evolution produces a pattern of gradual change.

Signals, referred to as time’s cycle by Stephen Jay Gould, are events that recur in some more-or-less regular fashion. In our everyday lives, time’s cycle is manifest as diurnal cycles, tides that ebb and flow, the phases of the Moon, and the changing seasons. In historical science signals from nature include such patterns as the waxing and waning of glaciers over intervals of tens of thousands of years and, some evidence suggests, the recurrence of events of mass extinction in which a large proportion of life is eradicated.

Now, what about noise? In this context noise is configuration, the very kind of thing with which the historical sciences deal most often. Noise includes such chance events as predation, extinction events that are not periodic or cyclical, and the evolution of new species from ancestral forms. Often a clearer understanding of
events of the past can be gained if one is able to subtract out the trend and signal and focus on the noise as the stuff of history. It may seem a little funny to say so, but if we think of the history of life as being played on some sort of imaginary historical radio, as students of that history we are likely to be as interested in the static as in the music.

**Time, Life, and Stratigraphy**

Stratigraphy is the study of layered rock, most of which is conglomerate, sandstone, siltstone, shale, mudstone, limestone, or such evaporites as gypsum and rock salt. Geologists refer to all these types of rock as sedimentary rock, meaning that they were deposited by a fluid medium, either air or water. Paleontology is the study of fossils, nearly all of which occur in sedimentary rock. Because of the important roles organisms have played in the Earth’s history and because fossils provide the only information we have about the history of life, you would be correct in supposing that stratigraphy, understanding geological time, and the history of life are all closely intertwined.

**Some Principles**

As is true of most historical science, only a very few principles underlie the study of layered rock and the fossils it contains. Three of these principles were recognized by Nicholas Steno (1631–1687), a Dane working in Florence, Italy, as physician to the Grand Duke of Tuscany. In 1667 Steno was one of the first to understand that fossils were the remains of past life that had been deposited with the sediment, although he supposed that fossils had been deposited by the biblical deluge or, in the case of fossil elephants, were the remains of Hannibal’s army as it crossed the Alps to invade Rome in 218 BCE. Previously, many supposed that fossils grew in the rock under the influence of emanations from heaven or perhaps had been placed supernaturally into the rock as a test of religious faith.

Steno seems also to have been one of the first to understand that the Earth has a history that is worthy of study, and he applied his principles of stratigraphy in his attempts to understand the geological history of the area around Florence.

**Superposition**

If you are playing cards or tossing dirty laundry into a pile, you know that the first item played or tossed is the one at the bottom of the pile. As one moves up the stack or pile, the items were deposited more and more recently. This is all there is to the principle of superposition (Figure 1-1). Steno recognized that in any undisturbed sequence of sedimentary rock, the oldest is on the bottom and the youngest is on the top. It is not rocket science, but Steno’s recognition of this fact grew from his recognition that the rocks have a history, and it allowed him to begin interpreting that history.

**Original horizontality**

Steno recognized a further principle—that sediment is deposited from a fluid medium—air or water—and that the upper surface of a layer of sediment should be horizontal if the layer has not been disturbed subsequently.
Original lateral continuity
Finally, Steno understood the principle that layers of sedimentary rock are laterally continuous so that a layer of rock cropping out on opposite sides of a river valley was once continuous across the valley. Today his principle tells us that layers of rock continue until they reach the edge of a basin of deposition or thin to zero thickness as the supply of sediment runs out.

Unconformities
All the evidence we have of the Earth’s history comes from study of the rock. Where rock is not present, we have no means of grasping details of the Earth’s history—other than to say that sediment was not deposited or that it eroded away subsequently. On the basis of his observations of rocks in the field, James Hutton (1726–1797), a Scot regarded widely as the founder of the science of geology, recognized that in a sequence of rock one often sees steeply inclined layers of rock underlying flat-lying or more gently inclined strata. Such a configuration marks an important event in the history of the Earth, a place where folding of the older rock took place before deposition of the younger rock (Figure 1-2). Hutton called the
surface separating the two an unconformity, which is now defined as a surface of erosion or nondeposition, usually the former, that separates younger strata from older rock. We now apply the term unconformity to any such surface, even if the rock above and below the unconformity are not folded at all. In his three-volume work *Theory of the Earth* Hutton developed his ideas of the long history of the Earth marked by numerous cycles and summarized succinctly his views on the great age of the Earth: “We find no vestige of a beginning—no prospect of an end.”
Inclusions and cross-cutting relationships
You may not know how old your grandmother is, but you can be sure of two things: she is older than your mother, and your mother is older than you. Somewhere along the line in the development of geology this principle was applied to the rock, the idea that the sand grains that comprise a sandstone must pre-date the sandstone. Similarly, the chemicals that cement the sand grains together must be younger than the time of deposition of the sandy sediment. Finally, if one feature cuts across another, such as a fracture in the rock or a cave dissolved in limestone, it must be younger than the rock.

Faunal succession
William Smith (1769–1839) was a British surveyor and engineer involved in coal mining and in surveying and building canals. He observed that by taking note of the fossils in the rock and how one group of fossils succeeded another in layer after layer he could predict what layers of rock the canal builders and coal miners would encounter as they dug into the Earth. Because the characteristics of the rock have economic implications, Smith’s discovery was of great practical importance. The reason for the succession of fossils, of course, is that layers of rock represent time, and organic evolution has brought about change in the fossils from layer to layer. Smith had no idea of evolution, having worked some 50 years before Charles Darwin presented his views on evolution, but he observed the result of evolution and put it to work.

Extinction
Thomas Jefferson adhered strictly to the idea of uniformity in nature. In 1799, while John Adams was Vice President, he published a description of Megalonyx, a large ground sloth (Figure 1-3), which he supposed to be a gigantic lion. Ground sloths are extinct, but Jefferson, as was true of most of his contemporaries, had no concept of extinction. He wrote, “Such is the economy of nature, that no instance can be produced, of her having permitted any one race of her animals to become extinct; of her having formed any link in her great work, so weak as to be broken.” So confident in this principle was Jefferson that he instructed Lewis and Clark to be on the watch for living Megalonyx while on their expedition to open the American west.

In fact, three years before in 1796 Georges Cuvier presented the first irrefutable evidence of extinction among elephants, mammoths, and mastodons. Cuvier was a catastrophist and believed in worldwide extinction of nearly all animals, followed presumably by renewed creation of new forms. In spite of his catastrophic views, his recognition of extinction was an important step in the development of the use of fossils to compare the relative ages of rock units from widely separated areas.

Uniformitarianism and actualism
Charles Lyell (1797–1875), one of the pioneers of geology, was born the year James Hutton died. In his three-volume textbook, Principles of Geology, he developed his ideas on the uniformity of nature, a set of ideas that has since been termed uniformitarianism. The American paleontologist Stephen Jay Gould has shown that Lyell actually had two ideas in mind: related but logically distinct. The first of these
Gould labeled *substantive uniformitarianism*, the idea that rates of change have never in the past differed substantially from what they are at present. Lyell hoped to supplant the paroxysmal views of the catastrophists; the catastrophists envisaged the geological past as being marked by major catastrophic events rather than by the sort of slow change we see operating much of the time in the modern world. We now know that Lyell’s view of rates of change as uniform and constant is simply wrong. Rates at which processes have operated have sometimes been radically different in the past. Glaciers have covered the northern half of North America: they swiftly advanced over North America and later they swiftly receded. In the Paleozoic Era mountains were folded up in the eastern part of the United States in at least three major episodes of tectonic activity that produced what are today called the Appalachian Mountains. From the catastrophists’ perspective, it was hard to explain how such mountain belts might have been produced when the processes operating today seemed too slow and ineffectual to effect such vast changes. Substantive uniformitarianism has been tested and has found to be false when applied in general: in this respect, the catastrophists were correct.

The second aspect of uniformitarianism Gould labeled *methodological uniformitarianism*, the idea that the laws of nature are invariant in space and time. Lyell asserted this rule in the hope of establishing geology as a science in its own right; laws of nature could be discovered and invoked to explain geological phenomena: for example, the existence of a mountain range or a small river at the bottom of a deep river valley. This was in distinction to the catastrophist’s who invoked supernatural intervention via catastrophes to explain such phenomena,
for example, a catastrophic flood had produced the deep river valley. The idea that there are invariant natural laws is now a part of all science, including geology. However, this does not preclude the fact that major cataclysms can and do occur—the eruption of volcanoes, the occurrence of earthquakes of staggering intensity, or the in-crashing of a comet or meteorite. Such events, although catastrophic, are not catastrophism in the original sense because these catastrophes are not the result of supernatural miracles.

**Facies**

_Facies_ is a Latin and French word that means aspect. The term was first applied in geology by Nicholas Steno, but the modern concept of facies of sedimentary rock was developed in 1838 by the Swiss geologist Armanz Gressly. To refer to the facies of a sedimentary rock unit is to refer to some distinctive aspect or feature of it. Perhaps it is sandy in one area and muddy in another, in which instance it could be said to have a sandy and a muddy facies. Perhaps one part of the rock unit was deposited near the shoreline (the nearshore facies) and another part was deposited farther out to sea (the offshore facies). Perhaps it has a fossiliferous facies and an unfossiliferous facies or a clam facies and a snail facies. The idea of facies is important in reconstructing the history of life because it brings home the idea that different environmental conditions exist in different places, often with profoundly different effects on the sediment and the organisms that live in and on them.

**Geological Time**

Understanding deep time—the immense age of the Earth—and subdividing geological time into manageable units that can be studied is one of the great intellectual achievements of Western Civilization. Paleontologists look at the ages of rocks and fossils in two ways: absolute time and relative time.

**Absolute time**

Absolute time is the term used when the age of a rock or fossil is expressed in years. Strictly speaking, it is not precisely absolute because absolute ages always involve some error, and even the best ages are expressed with an error term, such as $320 \pm 3$ Ma, which means that the best estimate of the age is 320 Ma but that the rock could be as old as 323 Ma or as young as 317 Ma.

The absolute age of certain rocks can be determined because of the phenomenon of radioactive decay, where one parent atom the rock contains transforms into a daughter atom at a constant, even rate (Figure 1-4). This graph implies the loss of a constant percentage of atoms through time. It can be converted to a semi-logarithmic plot by taking the logarithm of the values on the y-axis; applying such a conversion shows how the clock works in more detail (Figure 1-5). Here the straight line indicates a constant decay rate. At a certain amount of time half the atoms will be remaining; that time is called the half-life of the atom. If you know the decay rate of an atom, which can be determined in a lab, and you know how much of the parent and how much of the daughter atom is present in a rock (again, this can be determined in a lab) you can estimate the age of the rock. Some atoms, called radioisotopes, are better for determining the age of very old rocks. For instance,
potassium–40 decays to argon–40 with a half-life of 1.3 billion years: that is, after 1.3 billion years half of the potassium–40 originally in a rock will have decayed to argon–40. Because of its very long half-life, this would be an excellent radioisotope to use if you were trying to calculate the age of a very old rock. However, if you wanted to determine the age of a very young rock, or even a skeleton of a fossil human, it would not be a good isotope to use. This is because only a tiny amount of potassium–40 would have decayed out of the sample, and only a tiny amount of argon–40 would have been produced by the decay, such that these quantities would be very hard to measure accurately. For a particularly young volcanic rock, or a recent skeleton, one could use the radioisotope carbon-14: it decays to nitrogen-14 with a half-life of 5,730 years. Such an isotope, while good for dating fairly young things, is not useful for determining the age of really old rocks, because all of the carbon-14 will have decayed away.
Radioactive dating methods have been successfully applied literally tens of thousands of times. One interesting application of these methods is when they are applied to determine the age of the oldest objects known on Earth. These oldest objects actually turn out to have originally came from outer space: they are meteorites and they typically are about 4.5 billion years old. These meteorites have a composition similar to that of the Earth, and they were the primordial objects in the solar system. They coalesced out of a swirling mass of dust and gas centered around a large object which was to become our Sun.

It is generally accepted that the Earth formed at around the same time as these meteorites. However, as of yet no rocks have been discovered on the Earth that are quite so old (although tiny crystals once part of rocks nearly this old may exist). Perhaps all of the rocks that were this old have subsequently been eroded away or they may still be present but are buried at great depths. It is more likely though that the Earth was mostly molten at this time and thus completely inhospitable to life as we know it. Still, the oldest Earth rocks are exceedingly old: they date from 3.9 billion years ago (Figure 1-6). These oldest Earth rocks are heavily metamorphosed and altered and thus could not contain any record of ancient life from quite so early in our planet’s history, because any fossils or other organic matter present in the rocks would have been baked away. Still, there are sedimentary rocks (which are discussed in Chapter 2 and are the types of rocks that can potentially contain organic

Figure 1.6 Very old rock. A 3.8+ billion year old rock from Greenland. Image courtesy of Harald Furnes, University of Bergen, Norway.
remains) that are nearly as old as these rocks. These oldest sedimentary rocks, which date from around 3.8 billion years and hail from modern day Greenland, appear to contain evidence of organic activity. The implications of this will be explored more fully in Chapter 12, but it is worth recognizing that life had already evolved shortly after our Earth had solidified from its molten state.

Relative time
Most geological ages of rocks and fossils are given as relative ages. There are two principal ways of expressing relative ages. The simplest is the kind of relative ages we use in our everyday lives. You are younger than your parents. World War I occurred before World War II. The Victorian era came after the Elizabethan era. Paleontologists get this kind of information from such principles of stratigraphy as superposition, cross-cutting relationships, and inclusions. In a series of layered rock that has not been disturbed by subsequent geological activity, the oldest layer is on the bottom and the youngest is on the top.

Relative geological time is how we determine if a rock is older or younger than another rock when we lack an absolute age for the rocks. This determination can be accomplished through the use of fossils, recognizing the principle of faunal or biological succession which stipulates that life forms are unique to particular time intervals. Fossils principally occur in sedimentary rocks and these contain various facies (described earlier). Differences in the way a sedimentary rock looks, it feels, and yes, even it tastes reflect differences in the type of environment it was deposited. Generally, the original environment will be under water, either seawater or freshwater, and conditions vary from place to place, or with the depth of the water, if there was a river nearby, etc. Because layers of rock tend to have a distinctive appearance, we can follow them for several miles. Following Steno’s principle of superposition (also described earlier), an overlying layer of rock must be younger than the rock underlying it, at least in any one region. One might be tempted to think of any one layer of rock, for example, throughout the Grand Canyon, as representing a constant time line, but this is incorrect, especially if we were to follow a single layer over many miles as can be done in the Canyon. Why don’t sedimentary rock layers represent constant time lines? Because any layer of rock represents a particular environment. Let’s imagine the type of environment where some of the layers of rocks in the Grand Canyon were originally deposited: in an ocean somewhere near the shoreline at a beach (Figure 1-7).

At any time near this shoreline, depending on if one was looking nearer or further from the shore, there were actually several different types of environments on the seafloor where sediments were being deposited; each one of these places would eventually become one of the layers of rock seen in the Grand Canyon. Thus, to summarize, at any one time, several of the different rock layers we see today in places like the Grand Canyon were forming. Of course, the diagram shown is schematic, and the slope and spacing between the different rock types and the different sedimentary environments is exaggerated to make things clearer. However, the basic principle conveyed is still valid: sedimentary rock layers represent different environments, and at anyone time several environments and thus several future rock layers are being deposited.

In most marine settings like the one we’ve shown you, the level of the ocean tends to rise and fall through time. The result is that environments move back and forth, toward and away from the shoreline. Similar environments tend to end up being, much
later, similar looking rocks. Thus, you cannot simply use the physical characteristics of a rock to say that this rock and that rock, because they look alike, were formed at the same time. There needs to be something to impart a direction or vector of change to such a cycling system in order to determine the relative age of a rock. This something is biology: the fossils provide a unidirectional vector or arrow of change within such cycles of rock because simply put life has evolved and a species can only evolve once. The idea that evolution is irreversible was codified as a law by the Belgian paleontologist Louis Dollo in the early part of the 20th century. His notion was not that there was some force or principle that prevented evolution from reversing but rather that organisms were so complex that it was extremely unlikely that the same type of organism could evolve more than once. The fact of evolution, discussed more fully in Chapter 4, and the fact that some animals and plants are preserved as fossils, provides us with that arrow we can use to tell relative time in the rock record.

Returning to the case of the Grand Canyon, to provide a concrete example, there are a set of trilobites that always occur in rocks of a certain age. They are found to cut across or occur in several of the individual rock layers in the Grand Canyon (Figure 1-8). They later are succeeded by a different set of trilobites that again cut across the rock units and define a later interval of time that can be recognized over great distances.

The Geological Time Scale

The more common and more useful way of dealing with relative ages of rock is to express ages in terms of the geological time scale, which is presented in Figure 1-9. Instead of saying, “This fossil is from 354 to 417 million years old,” a paleontologist would say, “This fossil is Devonian.” There are several reasons for this use of relative time. For one thing, the paleontologist rarely has direct knowledge of the absolute age of a fossil (unless it is a very young fossil and can be dated using carbon-14). Moreover, to express ages in terms of the geological time scale links the item to a great many other ages and events. To say, “This fossil is Devonian” is
Figure 1.8 Cambrian trilobites. (a) An Early Cambrian trilobite from Vermont, USA, in the collections of the American Natural History Museum. (b) Middle Cambrian trilobites from Antarctica, in the collections of the University of Kansas Museum of Invertebrate Paleontology. Images by B. S. Lieberman.
rather like saying, “This event occurred in Victorian times.” Both statements link the fossil or event to a host of well-understood historical events that are different in nature, scope, and duration from those of other times in history.

The history of the development of the geological time scale has been laid out in a very interesting book by William B. N. Berry (see Additional Reading at the end of this chapter). The time scale has been developed over the past 180 years by geologists and paleontologists. The principles as to how to tell relative time in the geological record, when combined with the methods for determining absolute time, have allowed construction of a detailed geological time scale. In fact, the time scale was originally largely produced through the techniques of relative dating, but it was given expanded meaning with the addition of absolute dates.

**Divisions within the geological time scale**
The geological time scale is an encapsulated history of the Earth, and contains many intervals broken up by distinct boundaries which reflect major episodes of origination and extinction in the history of life. These episodes of origination and extinction can be thought of as the birth and death of various types of animals and plants. Thus, the time scale is not only a means of telling time in the geological record, but it actually represents an idealized history of life on Earth. If you worked for an advertising agency that was hired to create a one page ad summarizing life on Earth, to be distributed to a newly discovered alien civilization, you couldn’t do any better than to show the geological time scale; if you wanted to be fancy about it you might also add some small images of the major animal and plant groups that were alive next to the various boundaries.
At any one place, it is not possible to find rocks that preserve the entire time scale; not even at places like the Grand Canyon where there is a lot of rock present and thus a lot of time preserved. However, because of the nature of the geological record, different parts of the time scale are present in different places, such that if we add up the rock from these places, globally, we can get a very complete picture of geological time.

It is worth noting that the geological time scale is hierarchically structured. For example, the time scale is broken up, at the largest scale, into three major eons. The Archean Eon and the Proterozoic Eon are often lumped informally into the Precambrian. The Archean Eon and the Proterozoic Eon combine a very large proportion of the history of the Earth (about 85%), but if we consider the geological time scale (Figure 1-9) there are far fewer boundaries during these time intervals than the succeeding, but far shorter Phanerozoic Eon. Archean is derived from the Greek word for ancient, bespeaking to the nature of these rocks, the oldest known from our planet; the Proterozoic succeeds the Archean, starting 2.5 billion years ago and ending 543 million years ago; the word translates in Greek, roughly, to early life. Fossils are quite rare in Archean rocks; these rocks typically have been intensively metamorphosed because they are so ancient; the fossils known from these rocks always represent the remains of microscopic bacteria. Proterozoic fossils are also scarce, though not as scarce as their Archean brethren, especially late in the Proterozoic. Again, just about all of the fossils known from the Proterozoic Eon consist of various microscopic life forms, principally bacteria, with a few important exceptions. We will discuss Archean and Proterozoic life more fully in Chapter 12, but in effect during these intervals there was not much going on evolutionarily in terms of large, multicellular life, though many evolutionary changes were transpiring among important and distinct bacterial lineages. In the absence of the origination, or extinction, of major fossil groups it is difficult to divide up geological time, and this is why these eons are not prominently subdivided.

The Phanerozoic, which began 543 million years ago, represents a prominent break from the Archean and Proterozoic. Its name is derived from the Greek words for visible life. This name encapsulates why there are many more divisions in the geological time scale during the third, but shortest, eon. A lot more is happening evolutionarily, especially when we consider the fossil remains of large, multicellular organisms. Abundant fossils of large organisms basically (with a few exceptions that will be considered in Chapter 12) do not appear in the record before 543 million years ago, at the start of the Phanerozoic (in fact at what is called the Cambrian Period, which we will discuss soon). During this eon there were many major origination and extinction events, first in animal life and later in plant life. For this reason the eon can be finely subdivided. For example, the Phanerozoic is further divided into three eras, the Paleozoic or time of ancient life, the Mesozoic or time of middle life, and the Cenozoic or time of new life. The boundaries separating the different eras represented times of major change in life on Earth. Between the Paleozoic and Mesozoic, maybe as many as 95 percent of all the species alive were wiped out. At the end of the Mesozoic the large terrestrial dinosaurs, along with many other species, went extinct; the mammals, the group we belong to, really started to become diverse in the Cenozoic. Within each of these eras there are also periods. Each period is also an interval of time defined by a characteristic set of animals, plants, or even microfossils.

The differences between the types of life forms present in any adjacent two periods is less than the difference between the life forms of adjacent eras, except in
the case when period boundaries also correspond to era boundaries. For example,
the boundary between the Permian and Triassic periods is equivalent to the
boundary between the Paleozoic and Mesozoic. The boundary between
the Cretaceous and Tertiary periods is equivalent to the boundary between the
Mesozoic and Cenozoic eras.

The rocks that contain the fossils that were used to define the time interval
representing any given geological period were originally defined by geologists in
a relatively small region. For example, the rocks representing Cambrian time take
their name from Cambria, the Latin name for Wales. There are rocks rich in
Cambrian fossils in Wales, and this was a place where many early geological studies
were conducted. Subsequently it was found that Cambrian fossils occur in rocks
throughout the globe. There are now several places known to have a more complete
record of Cambrian aged rocks then Wales.

It is very useful to learn the geological time scale because we will refer to the
various intervals in it throughout the book. It is also very handy to learn because in
a significant way this time scale corresponds to the history of life. Darwin is known
for referring to the geological record as a book containing many chapters. Each one
of the chapters or intervals in the geological time scale represents a time when a
distinct set of life forms walked, crawled, or passively sat on the face of the Earth.

What is a Fossil?
A fossil is the remains or evidence of life from a previous geological time. That is
a pretty loose definition, and it is intentionally so. What kinds of remains qualify as
fossils? What kinds of evidence are sufficient? And how old does something have to
be to be regarded as a fossil—that is, to be from a previous geological time?

Fine Tuning the Definition
In terms of our definition, there are two kinds of fossils. One comprises the actual
remains of past life, typically the shells, bones, and teeth that occur in the rock.
These are referred to usually simply as fossils, but they are more precisely termed
body fossils. Paleontologists often refer to skeletal material as hard parts and to
organic tissue as soft parts. They also refer to animals without mineralized skeletons
as soft-bodied organisms, although in actuality the bodies of all organisms are soft.
These terms, although jargon, are a useful way to refer to the skeletons and tissues
of animals.

The tracks, trails, burrows, borings, nests, and coprolites (fossil excrement) of
ancient organisms are called trace fossils, which are especially useful as a record
of the behavior of ancient organisms, and we shall discuss these in greater detail
in Chapter 2. Any remains of an organism and any sort of track or trail, even if the
paleontologist cannot identify it or the plant or animal that made it, qualifies as
a fossil if it was formed by a life form from the geological past.

Most fossils are very old, millions of years old at least and sometimes more than
a billion years old, but technically any remains or evidence of life that is older than
about 10,000 years is a fossil.

Far more important is the manner in which the object is studied. No matter how
old an object is, if it is studied in the same manner as a very old fossil, as something
that has come from rock or sediment, then it is often regarded as a fossil. Thus,
because the frozen remains of the ice man found some years ago in the Alps are
studied by the methods of biology and anthropology, most paleontologists would not regard the ice man as a fossil. On the other hand, a paleontologist interested in interpreting the interactions between organisms and their environments might study modern sea shells as if they were fossils, even if the organism that made them died only a few days ago. The term subfossil is sometimes used to refer to the remains of an organism that died recently if it is to be studied as if it were a fossil.

Kinds of Organisms Preserved as Fossils

The five principal kinds of body fossils are invertebrate fossils, vertebrate fossils, microfossils, fossil plants, and palynomorphs (fossil spores and pollen and thus both plant fossils and microfossils).

Invertebrate fossils

By far the greatest number of paleontologists are those who study invertebrate fossils, the remains of animals that do not have backbones (Figure 1-10). This is because these kinds of fossils are abundant and well preserved in many kinds of rocks; because they come from a wide variety of different kinds of organisms, many with long geological ranges; and because they are often preserved as whole organisms rather than as fragments. We shall deal with the many kinds of invertebrate fossils throughout the rest of this book.

Vertebrate fossils

The fossils of animals with backbones—the fishes, the amphibians, the various groups of reptiles, the birds, and the mammals—are termed vertebrate fossils (Figure 1-11). Their bones and teeth are hard and thus likely to be resistant to erosion, but they come apart readily so that most vertebrate fossils occur as isolated bones and teeth. In general, the more complete the fossil, the rarer its occurrence, but of course a vertebrate paleontologist gets a lot more information from a complete skeleton that has been preserved intact than from a few scattered bones and teeth.

Microfossils

Paleontologists use microscopes to study all kinds of fossils, even the bones of gigantic dinosaurs that may be more than a meter long and weigh many tens of kilograms. A microfossil is one that can be studied only with a microscope because it is so small. The most common microfossils are the remains of tiny, single-celled forms of algae, and many people are surprised to learn that even such tiny organisms sometimes secrete complicated mineralized skeletons that are often beautifully preserved (Figure 1-12). Those who study microfossils are called micropaleontologists, and many of them work for petroleum companies because, as we shall see, microfossils are useful for determining the ages of rocks, and they are likely to be the only kinds of fossils that are not ground up when oil wells are drilled.

Bacteria are preserved as fossils far more often than one would expect, perhaps because they are so abundant and hardy and because they alter their environments in such significant ways. The study of the interactions of bacteria with rocks and
Figure 1.10 Invertebrate fossil. A Devonian trilobite from Morocco. Image by A. Modell.

sediment—termed geobiology—is one of the most promising and rapidly growing fields of geology.

Fossil plants
Most kinds of plants do not have any sort of mineralized skeleton, although some kinds of grass secrete tiny grains of opal that wreak havoc on the teeth of grazing animals. It is surprising, therefore, that the plants have such a good fossil record. In fact, the chances of any individual plant being fossilized are slim, but the abundance of plants in most environments ensures that when conditions are right plants will be fossilized (Figure 1-13). The sizes of tree trunks and the abundance of leaves also contribute to the abundance of the fossil record of plants. Large tree trunks can fossilize before they have time to rot; and if a great many leaves accumulate in an environment, they can actually alter the environment so as to enhance the likelihood of their fossilization. One surprising fact is that although vertebrate organisms and plants are interdependent in many ways, it is rather unusual to find both vertebrate fossils and fossil plants preserved together in the same kind of rock. The conditions necessary for their preservation are sufficiently different so that they are unlikely to occur together as fossils, even though we know that they generally lived together in the same places.

Palynomorphs
It is surprising that anything as tiny as a spore or pollen grain could be preserved in the rock for geologically long periods of time, especially since they have no mineralized covering of any sort. Nevertheless, fossil pollen grains are abundant enough (Figure 1-14) and resistant enough that a whole science has grown up around them, the science of palynology, and for this reason we distinguish fossil pollen grains from “fossil plants” even though they are of course parts of fossil plants. Different kinds of plants have different sorts of spores and pollen that can be distinguished by studying them with a microscope. They provide a lot of information about the evolutionary history of plants and, because plants are very picky about where they live, about ancient environments as well.
How do Fossils Form?
Paleontologists are often approached by people who have found fossils and would like to know more about them. One of the first questions they ask is, “Has it been fossilized?” Remember that a fossil is the remains or evidence of life from a previous geological time. All that has to happen, then, is that the remains have to persist for a long time: there is not a single process called fossilization. Anything that keeps the remains from being destroyed by geological processes is a type of fossilization.

Preservation of Original Material
All fossils have been modified to one degree or another from how they were when the organism was alive. It is just not possible to bury the remains of an organism deep in the Earth, perhaps for millions of years, without having some changes
occur. Some kinds of fossils, however, are much more stable than others and are remarkable for how little change they have undergone. Some kinds of fossils that have changed very little we shall discuss below in the section on special preservation. Here we deal with more common, less spectacular instances of preservation.

Mineralized skeletons of organisms—including both shells and bones—are more likely to be preserved with little alteration if they are chemically stable. The spicules of many sponges are siliceous, being made of the mineral opal—silicon dioxide with varying amounts of water included (SiO$_2$.nH$_2$O)—which is quite stable for long periods of time, even when buried deeply in the Earth. For this reason, sponge spicules are likely to be preserved with little change. The same is true of the skeletons of other kinds of organisms with siliceous skeletons, including the microfossil diatoms and radiolarians.
Among the most common Paleozoic fossils are the brachiopods (Figure 1-15), most of which secrete shells made of the mineral calcite—calcium carbonate (CaCO$_3$). Calcite is quite stable. The skeletons of brachiopods, moreover, are dense and contain very little magnesium (Mg), an element that is abundant in the calcite skeletons of many other kinds of organisms. Magnesium forms a very tiny ion that is easily removed from the calcite crystal lattice. As a result, it is not unusual to find fossil brachiopod shells that have almost the same chemical composition as that of living brachiopods. When a fossil shell hasn’t been altered it tends to preserve many details.

**Permineralization**

Most skeletons are porous to one degree or another. Our bones are quite porous, the pores being occupied by soft tissue, and the shells of many kinds of invertebrates are also porous. When groundwater seeps through porous fossils after their burial, it typically deposits mineral matter into the pores, a process referred to as permineralization. The permineralizing material can be of the same composition as the skeleton, or it can be quite different.
Petrification

Petrification means literally to turn to stone. Its use implies that the substance being petrified must have started out without mineralized hard parts. That is, the organisms was probably soft bodied. The process of petrifaction involves typically the replacement of soft parts with mineral matter, usually silica in the form of microcrystalline quartz ($\text{SiO}_2$), calcite, or, more rarely, apatite—a calcium phosphate mineral with some other elements included, most notably fluorine $[\text{Ca}_5\text{F(PO}_4)_3]$. In some instances the preservation occurs on such a fine scale that individual cells are preserved, as occurs especially in some petrified wood.

Recrystallization

Recrystallization is a process of fossilization that interferes with good preservation. The most easily understood example is when shells made of one type of mineral recrystallize to a different type of mineral. This happens most frequently between two types of closely similar but not identical minerals, aragonite and calcite. Many invertebrate organisms secrete skeletons of the mineral aragonite; it has the same chemical composition as calcite ($\text{CaCO}_3$) but there are subtle differences in the molecular structure of these minerals. Most snails, clams, cephalopods, and corals from the Mesozoic and Cenozoic eras have skeletons made of aragonite. It turns out that the mineral aragonite is less stable than calcite, especially when it is removed from seawater. Further, molecular changes occur to aragonite (slowly perhaps but inevitably) when it is removed from seawater that cause it to be converted to calcite. That means that in the long term aragonite converts to calcite—which has the same chemical composition but a more stable crystal structure. As crystallization proceeds, much of the fine detail of the skeleton is lost, but the external form is likely to be preserved.

Casts and Molds

Sometimes a skeleton may dissolve before there is time for the replacement to occur. This can result in fossil-shaped openings in the rock that are called molds. When the opening is filled, the fossil is called a cast. A cast may have the same shape as the original fossil, but the composition is likely to be completely different and usually little of the fine detail is preserved. Snails, which have aragonite shells, are especially likely to dissolve away. Sometimes the spiral shape of the inside of the snail shell is filled with calcite mud before the shell dissolves. The resultant shape, sometimes called a steinkern (a German word meaning stone kernel), is an internal mold—not a cast—because it is not a replica of the fossil but is a sort of negative, showing the shape of the interior of the shell.

Carbonization

Sometimes organisms are buried quickly before they have time to rot. As successive layers of sediment accumulate above them, they are buried deeper and deeper in the Earth. There, the heat of the Earth drives out all the volatile material, leaving behind a carbon film, often with excellent preservation of detail. Leaves are commonly preserved by carbonization. Animals are carbonized less frequently, but
such fossils, when they occur, provide a unique glimpse into the ancient communities of the past, showing the nature of soft-bodied animals that have otherwise little likelihood of preservation. The most famous carbonized fossils are from the Burgess Shale of British Columbia, with which we shall deal in more detail in a later chapter.

Special Preservation

In the category special preservation we include instances of fossilization that preserve incredible detail, especially details about the soft parts of ancient organisms. Sometime, as we shall see, carbonization provides such detail, but here we have in mind kinds of preservation that take place under very unique circumstances.

Mummies

Mummies of Egyptian pharaohs preserved in the pyramids are not regarded usually as fossils, but the remains of ancient organisms are sometimes preserved in similar ways. Paleontologists think of mummies forming by having dried up before they have a chance to rot. Naturally, this sort of preservation is rare and can occur only under very dry conditions—in a desert or in a dry cave, perhaps. Mummies do not last very long, so no fossilized mummies are very old, and few of them qualify as true fossils. Climates change; caves collapse; bacteria invade and destroy the mummy. Nevertheless, when they occur they give a lot of information about the soft parts of ancient organisms.

Frozen mammoths

Freeze-drying is a special kind of mummification, but more spectacular are fossils that have frozen solid but not dried out. In 1900 some men hunting for fossil ivory from mammoth tusks in northern Siberia discovered a well-preserved mammoth embedded in the permafrost of a river bank (Figure 1-16). Such fossils, which are many thousands of years old and thus date from the Pleistocene Epoch, had been known for years, but this one was especially well preserved. Scientists visited the site, thawed the mammoth, cut it into manageable pieces, refroze it, and transported it to St Petersburg for study. In recent years scientists have proposed producing a living mammoth by collecting the DNA of frozen mammoths and combining it with elephant DNA. So far this project has not made much headway, but it lurks on the horizon as an interesting possibility.

Fossils in amber

Amber is fossil tree sap. Some kinds of trees, when damaged, ooze copious sap, an evolutionary defense mechanism that keeps insects from boring into the wood. Usually it is an insect that touches the sap and is entrapped, though sometimes lizards and even feathers can be trapped as well. More sap flows over it, and in time the bleb of sap may lose its volatile material, solidify, and become amber, with the fossil organism (or part of the organism) preserved inside it in exquisite detail. The oldest known amber is a tiny piece found in rock of the Midcontinent of North America that is nearly 300 million years old. Amber is more common in rock that is a few tens of millions of years old.
Phosphatization
Minerals rich in phosphate, especially calcium phosphate minerals, sometimes permeate the pore space in rock, forming phosphate nodules. In certain instances shells and even the soft tissues of organisms can be replaced. When this happens, the preservation can be remarkably good. Muscle fibers of fishes, larvae of invertebrates, and even individual bacteria can all be preserved by phosphatization.

Conclusions: Fossils as Curious Stones
The term fossil was originally applied to anything dug up from the earth. The word comes from the Latin verb fodere, meaning to dig. What we now regard as fossils—the remains or evidence of life from a previous geological time—were not yet recognized as being any different in nature from gemstones, ore, and other curiously shaped objects dug from the ground. One early attempt at a scientific explanation of rocks shaped like seashells—i.e., fossils—was that such shapes grew as a result of emanations from heaven—a vis plastica or plastic force that caused such things to form. Where the emanations impinged upon the water, marine animals grew. Emanations impinging on solid rock, however, caused nonliving shapes to grow in the rock. Of course we now realize that this early attempt was seriously inaccurate.

One of the things that is the most fun for a professional paleontologist is the opportunity to deal with members of the interested public who have unearthed curious stones. Sometimes the best and most important fossils found are discovered by so-called amateur paleontologists. They are called “amateur paleontologists.”

Figure 1.16 Frozen mammoth. This frozen carcass was discovered in Siberia in 1900. Image from R. Cowen (2005) History of Life, 4th Edn, Blackwell Publishing.
because they do not receive pay for their prospecting, yet their diligence and work ethic often exceeds those of the so-called professionals. Sometimes though, the finders of these objects attribute more interesting properties to such objects than their true nature merits. Rounded concretions in the rock have been interpreted as turtles or dinosaur eggs; stems of crinoids are mistaken for fossil sea serpents; in ancient times the heavy shells of fossil oysters were described as the devil’s toenails (Figure 1-17). Once your textbook authors were asked to inspect an alleged fossil baby’s head. Although the purveyor of this alleged fossil never showed up, it was likely to be simply a round rock with three holes—two eyes and a mouth—but one never knows just what curious stones might turn up.

**Additional Reading**


