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PALEONTOLOGY

Paleontology is the study of prehistoric life through fossils, the remains of once living organisms that are preserved in the sediments of the earth's crust. Although evolutionary biology has made enormous strides studying living organisms, these studies see evolution only in the thin slice of time known as "the recent." Fossils provide the only direct evidence of 3.5 or more billion years of the history of life, and in many cases they suggest processes that might not be explained by what is known from living organisms. Fossils provide a fourth dimension (time) to the biology of many living organisms. Although indirect techniques such as morphological and molecular reconstruction of phylogenies can be used to infer the past history of life on earth, many groups of organisms, such as conodonts and graptolites, are extinct and would be unknown were it not for the fossil record.

Since paleontology is the study of biological objects (fossils) in a geological context (the sediments in which they were preserved), it is on the border between, and draws from, two major branches of science. Paleontologists must be interdisciplinary in their interests and competent in both geology and biology. Most paleontologists specialize in a particular subdiscipline. Sometimes these subdisciplines are defined by the group of organisms studied. Vertebrate paleontologists study the remains of extinct backboned animals, including fish, amphibians, reptiles, birds, and mammals. Invertebrate paleontologists study the remains of animals without backbones (such as arthropods, molluscs, echinoderms, brachiopods, bryozoans, corals, and sponges). Paleobotanists study the remains of ancient plants. Micropaleontologists specialize in a wide variety of microscopic organisms. These include plants (pollen, diatoms, calcareous algae), animals (ostracods, conodonts, pteropods), and single-celled organisms (foraminifers, radiolarians, and many other Protists). Micropaleontology is useful in locating fossil fuels, and many micropaleontologists are employed by the petroleum industry. Paleontologists who study "megascopic" fossils, on the other hand, tend to be employed by colleges and universities, since their research is more academic in scope.

Paleontologists also define themselves by areas of theoretical interest. Paleobiology describes any application of biological principles to the fossil record; paleobiologists study biological phenomena across many taxonomic groups. Paleobiogeography is the study of the past distribution of organisms in an attempt to understand their origin and dispersal around the world, and sometimes to decipher the motions of continents and land bridges. Paleogeography seeks to determine, by means of the fossil record, ancient continental positions and connections. Some of the earliest evidence for continental drift came from the similarities of fossils on different continents.

Paleoecology is the study of ecological principles as they apply to the fossil record. Paleoecologists try to reconstruct ancient environments and the ecology of extinct organisms. Paleoclimatology is the study and reconstruction of ancient climates; the discipline uses fossils as indicators of past environments, as well as information from geochemistry, climatic modeling, and many other fields.

Fossils are often the only practical means of telling time in geology. Radioisotopic decay methods, such as potassium-argon and uranium/lead dating, work only in rocks that have cooled down from a very hot state, such as igneous or metamorphic rocks. Most of geological history is contained in sedimentary rocks, which cannot be dated by radioisotopes. Biostratigraphy uses the distribution of fossils in stratified sedimentary rocks to correlate and date those rocks. Most paleontologists who are employed by oil and coal companies as economic paleontologists use their knowledge of the fossil record (especially biostratigraphy) to predict the location, quality, and quantity of oil and coal resources.

History of Paleontology. The ancient Greeks interpreted the giant bones of mammoths as the remains of mythical giants, but were puzzled by seashells found hundreds of feet above sea level and miles inland. Had the sea once covered the land, or had these objects grown within the rocks like crystals do? In the sixth century B.C., Xenophanes of Colophon saw the seashells high in a cliff on the island of Malta and suggested that the land had once been covered by the sea.

During the Middle Ages and Renaissance, learned men began to speculate on the meaning of fossils, producing a wide range of interpretations. Originally, the word *fossil* (from the Latin *fossilis*, "dug up") applied to any strange object found within a rock. These in-

PROCESSES OF FOSSILIZATION

The fossil record preserves only a small fraction of the organisms that have existed in the past, and does so in a very selective manner. Some groups of organisms with hard parts (such as shells, skeletons, wood) tend to fossilize readily and much is known about their past. Many others are soft-bodied and rarely if ever fossilize, and paleontology has little to say about their history. The study of how living organisms become fossilized is known as *taphonomy* (Greek for "laws of burial").

From the moment an organism dies, there is a tremendous loss of information as it decays and is trampled, tumbled, broken, and buried. The more of that lost information that can be reconstructed, the more reliable scientific hypotheses are likely to be. In this sense, every paleontologist must act as a forensic pathologist, and determining what killed the victim and trying to reconstruct the events at the "scene of the crime."

The first step is to determine just what type of fossilization has taken place. Most fossils have been dramatically altered from the original composition of the specimen; it is often difficult to determine their original shape and texture, unless one has some idea of the circumstances leading to fossilization.

In a few exceptional cases, organisms are preserved with most of their original tissues intact. Ice Age woolly mammoths have been found thawing out of the Siberian tundra with all their soft tissues essentially freeze-dried and their last meals still in their digestive tracts. Some were so fresh that humans and animals could eat the 30,000-year-old meat with no ill effects. An Ice Age woolly rhinoceros was found intact in a Polish oil seep; the petroleum pickled the specimen and prevented decay. These examples are extremely rare, but when they occur, they give us insight into color, diet, muscles, hair texture, and other anatomical features that paleontologists seldom see.

Some organisms are fossilized when tree resin oozes downward and entraps insects, spiders, and even frogs and lizards. The resin then hardens and forms a tight seal of amber around the organism. Most specimens are only carbonized films, but some are so well preserved that some of their original biomolecules are still intact.

Another mode of fossilization is called permineralization. Many biological tissues contain pores and canals. The bones of animals are highly porous, especially in their marrow cavity, and most wood is full of canals and pores. After the soft parts decay, these hard parts are buried and then permeated with groundwater that flows through them. In the groundwater are dissolved calcium carbonate or silica, which precipitate out and fill up the pores, completely cementing the bone or wood into a solid rock. Although new material comes in, none of the original material is removed. Permineralization can be so complete that even the details of the cell structure are preserved.

Yet another process is called dissolution and replacement. As water seeps through sediments filled with shells or bone, there is a tendency for the original material to dissolve. If the fossil dissolves and leaves a void, then the shape of the fossil is preserved in the surrounding sediments. The internal filling of this specimen is known as an internal mold; the external mold of the specimen is often also preserved. In other cases, the void is filled with sediment and a natural cast of the fossil is formed, mimicking the original in surprising detail. Original bone or shell material can also be replaced without leaving a void. In these cases, the original mineral is dissolved away, and another mineral precipitates almost immediately in its place. This is easiest to detect when a fossil is made of some mineral that is clearly not original.

Finally, remains are preserved through carbonization. Many fossils are preserved as thin films of carbon on the bedding planes of sandstones and shales. When the organism dies, most of the volatile organic materials disperse and leave a residue of coal-like carbon, in the form of a black film that preserves the outline and sometimes the detailed structures of an organism. This kind of preservation is typical of most plant fossils; indeed, coal is the accumulated carbonized films of countless plants.

—DONALD R. PROTHERO

cluded not only the organic remains that we call fossils, but also crystals and concretions and many other structures that were not organic in origin. Most scholars thought that fossils had formed spontaneously within the rock; those that resembled living organisms were thought to have crept or fallen into cracks and then been converted to stone. Others thought that they were grown in rocks from seeds, or were grown from fish spawn washed into cracks during Noah's Flood. Many scholars thought that they were supernatural, "pranks of nature" (*lusus naturae*), or "figured stones" produced by mysterious "plastic forces." Still others considered them to be works of the devil, placed in the rocks to shake religious faith. As quaint and comical as these ideas seem to us today, in their own time they were perfectly rational for people who believed in a literal interpretation of Genesis, and thought that the earth had been created 6,000 years previous and undergone little or no change except for decay and degradation due to Adam's sin.

Essentially modern concepts about fossils were first proposed by Nicholaus Steno. Steno was the court physician to the Grand Duke of Tuscany, so he had ample opportunity to see the shells in the rocks of the Apennine Mountains above Florence, Italy. In 1666 he dissected a large shark caught near the port town of Leghorn. A close look at the mouth of the shark showed that its teeth closely resembled fossils known as "tongue stones," which had been considered the petrified tongues of snakes or dragons. Steno realized that tongue stones were actually ancient shark teeth, and that fossil shells were produced by once living organisms. In 1669 Steno published *De solido intra solidum naturaliter contents dissertationis prodromus* (Forerunner to a dissertation on a solid naturally contained within a solid). The title may seem peculiar at first until the central problem that Steno faced is appreciated: how did these solid objects get inside solid rock? Steno realized that the enclosing material must have once been loose sand, later petrified into sandstone. With this idea, he overturned the long-standing assumption that rocks were permanently formed during the first days of Creation. Steno extended this insight into a general understanding of the relative age of geological features. Fossils that were enclosed in rock that had been molded around them must be older than the rock in which they were contained. On the other hand, crystals that clearly cut across the preexisting fabric of a rock must have grown within the rock after it formed. From this, Steno generalized the principles of superposition, original horizontality, and original continuity that are the fundamental principles of historical geology and stratigraphy.

Although supernatural concepts of the origin of fossils persisted for another century, by the mid-1700s naturalistic concepts of fossils began to prevail. When the Swedish botanist Linnaeus published his landmark classification of all life, *Systema Naturae*, in 1735, fossils were treated and named as if they were living animals. By the time of the publication of Darwin's *On the Origin of Species* in 1859, the realization of the complexity of the fossil record had reached the point where few scholars took Noah's Flood literally.

The Paleontological Perspective. The fossil record provides a unique perspective on life. Without the fossil record, who would have imagined that the world was once ruled by such immense creatures as the dinosaurs, and that the seas were home to equally impressive marine reptiles? Who would have dreamed of some of the bizarre creatures that are now extinct, from the trilobites and ammonites that once dominated the seas, to the incredible plants and animals of the land and air that once existed? Without the fossil record, who would have guessed that through 3 billion years (85 percent of life's history) there were no organisms on earth more sophisticated than bacteria, and no organic structures larger than algal mats? Through most of life's history, much simpler ecological patterns than are seen today prevailed. At one time, the land was not dominated by flowering plants, insects, mammals, and birds (which are all relatively late arrivals on this planet), but by simple plants and (if there were land animals at all) millipedes and spiders and scorpions, and eventually by amphibians and reptiles. Today the sea is the realm of fish and clams and snails and crustaceans, but in the past it was dominated by groups that are either extinct or alive but relatively rare in the modern ocean: trilobites, nautiloids, brachiopods, bryozoans, and crinoids. The air was inhabited by flying insects hundreds of millions of years before the first birds or bats, and even flying reptiles preceded the first birds.

[*See also* Origin of Life, *article on* The First Fossils.]

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