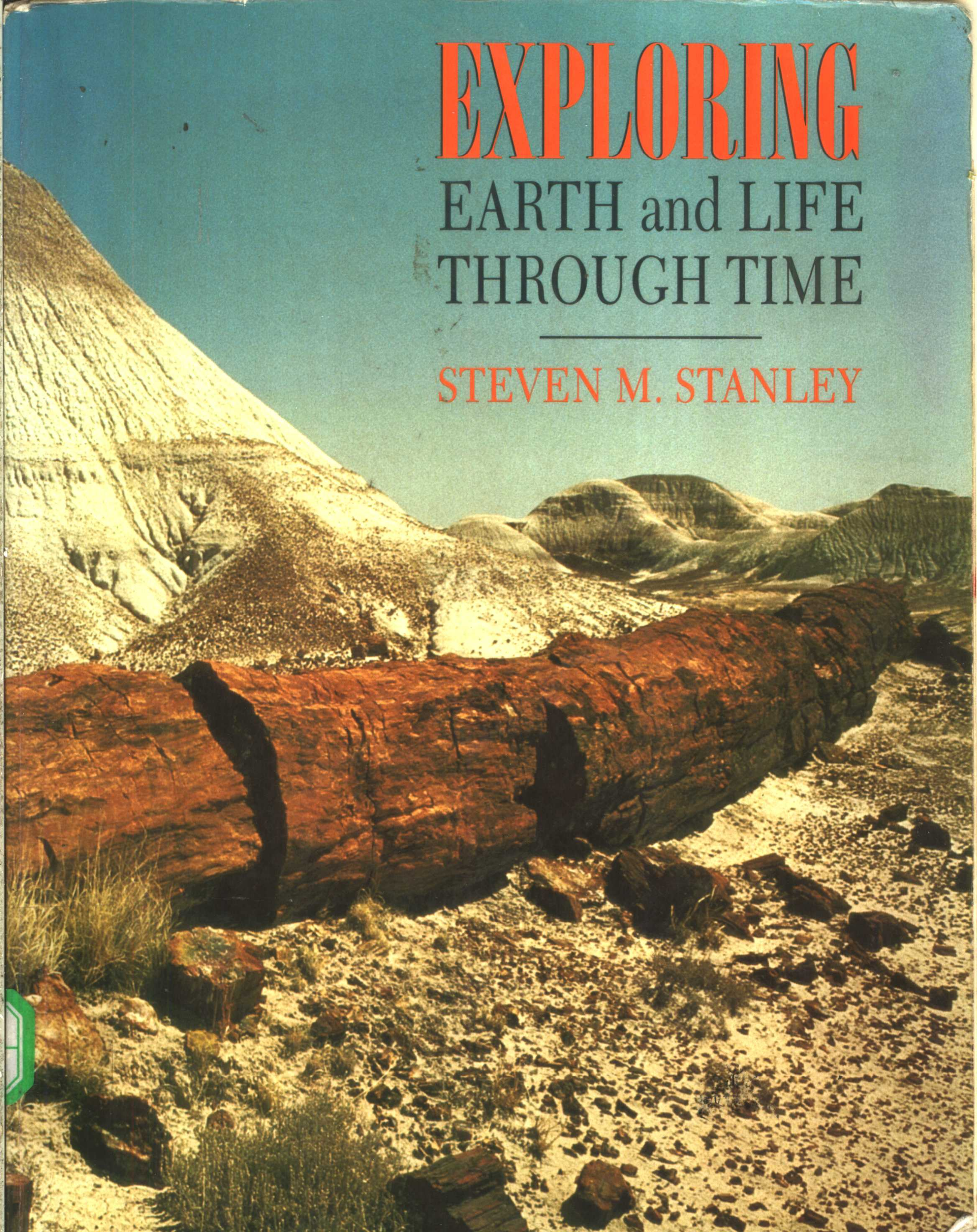
EXPLORING EARTH and LIFE THROUGH TIME

STEVEN M. STANLEY



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Cover image: This fossilized tree trunk has weathered out of the Triassic Chinle Formation in the Petrified Forest National Park in Arizona. *(Photograph by Harry Foster. Reproduced by permission of the Canadian Museum of Nature, Ottawa, Canada.)*

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PREFACE

We humans are inherently curious about our roots — not only about our ancestry during the past few decades or centuries but also about our animal origins and the history of the world our four-legged ancestors inhabited. Now that we are damaging the global environment in ways that may harm our own species along with many others, our curiosity heightens. This book, unlike other textbooks that introduce historical geology, shows the student how Earth's ecosystem has changed through time and how events of the past provide a perspective for dealing with changes that are taking place now or may take place in the future.

In fact, the geologic record uniquely documents not only the history of Earth's habitats far back in time but also the events of the past few million years that have shaped the modern ecosystem. What lessons can we learn from "natural" changes of the past? One issue is how we exercise our unrivaled powers to alter environments on Earth. Another is how we cope with the changes that we do produce. Thanks to exciting advances in the study of ancient oceans, climates, and land areas, the geologic record now reveals that many of the kinds of change that may loom ahead have occurred before. In addition, the fossil record reveals many ways in which life has responded. Ultimately, extinction has been the helpless response of nearly all species to certain environmental changes that have been beyond their control: Only a tiny fraction of the species that were alive halfway through the Age of Mammals survive today. Farther back in time, mass extinctions have occasionally decimated life on Earth. Thus, the geologic record reveals that environments and life are transitory. As the French adage has it, the more things change, the more they stay the same. Nonetheless, we cannot justify the crisis that we may soon inflict on rainforests and grasslands and coral reefs by arguing that it will simply mimic "natural" mass extinctions of the past. Events of the distant past do not provide an ethic for our behavior, but they do offer us the opportunity to predict some of the consequences of our potential actions so that we can make choices and adjustments.

Study of Earth's history has other practical benefits as well. Geologists have been able to locate important natural resources such as coal and petroleum by understanding the record of rocks and fossils. They have also come to understand the origins of valuable but nonrenewable sources of fresh water far below Earth's surface. By learning how events of the past have created and concentrated resources, a student of Earth history comes to appreciate the limited supply and inevitable depletion of materials that he or she might otherwise take for granted.

ORGANIZATION AND CONTENT

My aim in writing this concise version of *Earth and Life through Time* has been to make the history of our planet and its inhabitants accessible to a wider range of students. To accomplish this goal, I have eliminated specialized topics, especially ones focusing on regional geologic events outside North America. I have also abbreviated the discussion of sedimentary environments, confining it to a single chapter, and the review of Precambrian geology, covering it in two chapters rather than three.

Exploring Earth and Life through Time is not simply a reduced version of its parent, however. New boxes in Chapters 2 to 16 show students how Earth's history sheds light on contemporary issues. Nine of the boxes discuss modern environmental issues that relate to subjects in the chapters where the boxes appear; the issues range from loss of wetlands to future extinctions to global warming. Three of the remaining boxes shed light on the process of biological evolution, and the other two focus on natural resources.

A Major Events diagram on the third page of each of the final eight chapters helps students comprehend the global events that took place during each major interval of Proterozoic and Phanerozoic time. Each diagram provides a graphic summary of events that occurred during an interval of time, and it can serve as a handy guide to the rest of the chapter.

Scientific terms are printed in boldface where they first appear and are also defined in the Glossary or, if they are names of major groups of organisms, in Appendix III.

Numerous innovative features of *Earth and Life through Time* that have been well received are retained in this book. Chapter 2 reviews the structure of modern ecosystems. Without such an introduction, no student who is not already well versed in ecological principles could understand environments and life of the past. Chapter 3 explains how we recognize ancient environments. Lacking this kind of review, no student could appreciate how we reconstruct the ancient world. Similarly, Chapters 6 and 7 explain plate tectonics and mountain building in ways that teach students how lateral and vertical movements of the lithosphere have caused Earth's geography to evolve over millions of years. As in the parent volume, these and other early chapters provide the raw material for understanding the history of Earth and its biota. Appendix I and Appendix II provide additional background on minerals, rocks, and fossils for the student who has not previously studied physical geology.

Chapters 8 through 16, like comparable chapters of *Earth and Life through Time,* integrate the history of life with the physical history of Earth, including plate-tectonic events. During the past decade, paleogeography, paleoceanography, and paleoclimatology have emerged as new disciplines that are revolutionizing the Earth sciences. Without labeling these disciplines, I have attempted to accord them their newly earned status.

SUPPLEMENTS

The following supplemental materials for *Exploring Earth and Life through Time* are available to adopters:

The **Instructor's Manual,** prepared by Robert D. Merrill of California State University, Fresno, contains chapter outlines, summaries, and objectives; teaching tips; answers to end-of-chapter text exercises; additional questions and answers; and additional resource references, including audio visual aids, for each chapter.

A set of **120 slides** contains a selection of color line diagrams from the text.

For more information and to request copies of these supplements, please contact

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Steven M. Stanley

TO THE STUDENT

I use my own understanding of the past to gain insight into the present and the future. Nearly all students will live much longer than I, so they will have greater opportunities to employ lessons from the past. I want to address a few comments to you, the student, to help you gain useful insights as you use this book to explore Earth and life through time.

First, I urge you not to treat this book as a compendium of facts. It is the major events and concepts and themes that matter most, and I exhort you to focus on them. Here are some of the kinds of important questions that you should ask yourself in organizing the material that the book presents: When did major ice ages begin in the course of Earth's history, and how were continents arranged when they began? When and where have mountains risen up in North America and what caused them to form? What evolutionary breakthroughs have led to dramatic expansions of various groups of plants and animals, and how have these expansions changed the biosphere? What have been the patterns and probable causes of the great extinctions of the past? Forty million years ago, southern England was tropical and Alaska was subtropical; how did the world's climate come to be as it is today?

The Major Events figure near the beginning of each of the final eight chapters will help you to identify and review major events and themes, and so will the exercises at the ends of chapters. If you can complete these exercises, you will have mastered the broad outlines of the subject.

As you first venture into the subject of Earth's history, the vastness of geologic time may seem daunting, but this reaction is misleading. It is actually quite easy to come to grips with the geologic time scale. There is no need to connect intervals that span millions of years to the much shorter intervals by which we measure our everyday lives: seconds, minutes, days, weeks, months, and years. In fact, we seldom try to relate seconds or minutes to years, but instead maintain separate time scales in our heads. You must simply make this kind of leap to establish the scale of geologic time in your thinking. Except for the most recent interval of geologic time, the basic unit is a million years, and it is often convenient to round geologic dates or intervals off to units of tens or hundreds of millions of years. At the start of your study of Earth's history, you should learn the elements of the geologic time scale — the eons, the Phanerozoic periods, and the Cenozoic epochs. By this strategy you will establish a framework for positioning major events so that a general picture of Earth's history will emerge.

Many forms of life have come and gone during our planet's history. The basic types are easier to keep track of if you have a sense of how they lived. I have therefore tried to convey useful information about the mode of life of each major group of animals or plants, either in the text or in a figure caption, when I first introduce it. Appendix III also allows you to see where a particular group fits into the general classification of life. Boldfaced names of groups of animals or plants that do not appear in this appendix are defined in the Glossary.

I wish you a pleasant voyage through the history of our planet and its inhabitants. This is as close as you will get to entering a time machine!

Steven M. Stanley

CONTENTS

CHAPTER 1

Introduction to Earth, Life, and Geologic Time

Few people recognize, as they travel down a highway or hike along a mountain trail, that the rocks they see around them have rich and varied histories. Unless they are geologists, they have probably not been trained to identify a particular cliff as rock formed on a tidal flat that once fringed a primordial sea, to read in a hillside's ancient rocks the history of a primitive forest buried by a fiery volcanic eruption, or to decipher clues in lowland rocks telling of a lofty mountain chain that once stood where the land is now flat. Geologists can do these things because they have at their service a wide variety of information gathered during the two centuries that the modern science of geology has existed. The goal of this book is to introduce enough of these geologic facts and principles to give students an understanding of the general history of our planet and its life. The chapters that follow describe how the physical world assumed its present form and where the inhabitants of the modern world came from. They also reveal the procedures through which geologists have assembled this information. Students of Earth history inevitably discover that the perspective this knowledge provides changes their perception of themselves and of the land and life around them.

Knowledge of Earth's history can also be of great practical value. Geologists have learned to locate petroleum reservoirs, for example, by ascertaining where the porous rocks of these reservoirs tend to form in relation to other bodies of rock. Geologists have also helped discover deposits of coal and ore and other natural resources buried within Earth.

An understanding of Earth history helps us to address problems caused by changes that are now taking place in the world, or that will be occurring soon. The rock record also sheds light on ways in which a broad array of factors cause environmental change and on the rates at which various kinds of change occur. The shifting of coastlines as sea level rises or falls represents one example. The geologic record of the past few thousand years documents a general rise in sea level as huge glaciers have melted and released water into the ocean. The geologic record near the edge of the

A geyser in the Black Rock Desert of Nevada: The green cyanobacteria that thrive in the warm water that issues from the geyser resemble ones that lived more than 2 billion years ago and are preserved in Precambrian rocks. *(Stephen Trimble.)*

sea reveals how coastal marshes have shifted as sea level has changed. These marshes are very important to humankind; they cleanse marginal marine waters and sustain valuable forms of animal life. Study of the geologic history of coastal marshes will help us to predict their fate as sea level continues to change in the decades and centuries to come.

The geologic record of the history of life also provides a unique perspective on the numerous extinctions of animals and plants that are now resulting from human activities. Humans are causing extinction by destroying forests and other habitats, but our collective behavior also affects life profoundly in less direct ways. Very soon human activities will cause average temperatures at Earth's surface to rise in many areas of the world. The geologic record of ancient life reveals how climatic change has affected life in the past — how some species have survived by migrating to favorable environments, for example, and how others that failed to migrate successfully have died out. To the surprise of many biologists, geologic evidence has revealed that many of the natural assemblages of species that populate the world today are not ancient associations of interdependent species. Instead, they are associations that have developed very recently (on a geologic scale of time) as climates have changed in ways that have caused species to shift their distributions. Today spruce trees grow naturally in the United States only in the cold climates of eastern New England. Pollen preserved in clay shows that about 20,000 years ago spruce trees grew as far south as southern Georgia. At that time, areas close to Washington, D.C., were covered with frozen tundra, closely resembling the habitat that now occupies broad areas of northern Canada. Early humans — members of our own species — lived through similar changes that were occurring simultaneously in Europe.

As we come to understand the speed and profundity of natural environmental change and the transience of assemblages of species, we begin to appreciate the fragility of the world we live in. More generally, having studied the past, we can make more intelligent choices as we contemplate the future of our changing planet.

Before we launch into our detailed examination of the history of Earth and its life, however, an introduction to some of the basic facts and unifying concepts of geology is in order. The first seven chapters lay this groundwork.

THE PRINCIPLE OF UNIFORMITARIANISM

Fundamental to the modern science of geology is the principle of **uniformitarianism** — the belief that there are inviolable laws of nature that have not changed in the course of time. Of course, uniformitarianism applies not only to geology but to all scientific disciplines — physicists, for example, invoke the principle of uniformitarianism when they assume that the results of an experiment will be applicable to events that take place a day, a year, or a century after the experiment is conducted — but geologists hold this principle in particularly great esteem because, as we shall see, it was the widespread adoption of uniformitarianism during the first half of the nineteenth century that signaled the beginning of the modern science of geology.

Actualism: The Present as the Key to the Past

The principle of uniformitarianism governs geologists' interpretations of even the most ancient rocks on Earth. It is in the present, however, that many geologic processes are discovered and analyzed, and the application of these analyses to ancient rocks in accordance with the principle of uniformitarianism is sometimes called **actualism.** When we see ripples on the surface of an ancient rock composed of hardened sand (sandstone), for example, we assume that these ripples formed in the same way that similar ripples develop today — under the influence of certain kinds of water movement or wind. Similarly, when we encounter ancient rocks that closely resemble those forming today from volcanic eruptions of molten rock in Hawaii, we assume that the ancient rocks are also of volcanic origin.

Actualism is commonly expressed by the phrase "The present is the key to the past." This idea is only partly true, however. Although it is universally agreed that natural laws have not varied in the course of geologic time, not all past events have been duplicated within the time span of human history. Many researchers believe, for example, that the impact of very large meteorites may explain certain past events, such as the extinction of the dinosaurs 65 million years ago. They can calculate that the impact of a huge meteorite—one something like 10 kilometers (6 miles) in diameter—if it were to land in the ocean, would produce a huge wave that would crash over coastlines thousands of kilometers from the impact site. Nonetheless, because we have never observed the arrival of such a large meteorite, we do not know exactly what else would happen. It has been suggested that the fine dust injected into the upper atmosphere might block the sun's rays from Earth's surface for many days. As we will learn in Chapter 14, there is some evidence to support this contention, but because we cannot observe the consequences of such an event today, the idea is difficult to verify. In other words, in this case actualism does not apply.

Similarly, geologists have found that certain types of rocks cannot be observed in the process of forming today. In such cases, geologists usually assume that

1 The rocks in question formed under conditions that no longer exist;

2 The conditions responsible for the formation of these rocks still exist, but at such great depths beneath Earth's surface that we cannot observe them; or

3 The conditions exist today but produce the rocks only over a long interval of geologic time.

Many iron ore deposits more than 2 billion years old, for example, are of types that cannot be found in the process of forming today. It is believed that when the iron ore formed, chemical conditions on Earth differed from those of the present world and, furthermore, that the rocks underwent slow alteration after they were formed. The existence of these iron ore deposits does not necessarily negate the principle of uniformitarianism inasmuch as there is no evidence that natural laws were broken. It does, however, present geologists with a problem they cannot solve by applying the principle of actualism, because a human lifetime is only a small fraction of the time needed to study the rocks' development.

In an attempt to address some of these problems, geologists have learned to form certain kinds of rocks in the laboratory by duplicating the conditions that prevail at great depths within Earth. They expose simple chemical components to temperatures and pressures many times greater than those at Earth's surface. Such experiments indicate the range of conditions under which a particular type of rock could have formed in nature. In conducting these experiments, geologists are, in a sense, expanding the domain of actualism by using as a model not only what is happening in nature today, but also what happens under artificial conditions and may have happened under natural conditions long ago.

The Uniformitarian View of Rocks

Until the early nineteenth century, many natural scientists subscribed to a concept known as **catastrophism.** According to this idea, floods caused by supernatural forces formed most of the rocks visible at Earth's surface. Late in the eighteenth century, Abraham Gottlob Werner, an influential German professor of mineralogy, claimed that most rocks formed as a result of the precipitation of minerals from a vast sea that periodically flooded and retreated from the surface of Earth. These ideas were largely speculative.

Not long after Werner published his ideas, James Hutton, a Scottish farmer, established the foundations of uniformitarianism by writing about the origins of rocks in Scotland. Hutton concluded that rocks formed as a result of a variety of processes currently operating at or near the surface of Earth—processes such as volcanic activity and the accumulation of grains of sand and clay under the influence of gravity. It was only after extensive debate that Hutton's interpretation of the origins of rocks was generally accepted by the scientific community. Once established, however, uniformitarianism soon dominated the science of geology, gaining almost total acceptance after Charles Lyell, an Englishman, popularized it in the 1830s in a three-volume book titled *Principles of Geology.* Let us briefly examine the uniformitarian view of how rocks form.

Rocks consist of interlocking or bonded grains that are typically composed of single minerals. A **mineral** is a naturally occurring inorganic solid element or compound with a particular chemical composition or range of compositions and a characteristic internal structure. Quartz, which forms most grains of sand, is probably the most familiar and widely recognized mineral; other minerals constitute the materials we call limestone, clay, and asbestos. Most rocks consist of two or more minerals. Rocky surfaces that stand exposed and are readily accessible for study are generally designated as **outcrops** or **exposures.** Scientists also have access to rocks that are not visible in outcrops. Well drilling and mining, for example, allow geologists to sample rocks that lie buried beneath Earth's surface.

Basic Kinds of Rocks On the basis of modes of origin, many of which can be seen operating today, early uniformitarian geologists, led by Hutton and Lyell, came to recognize three basic types of rocks: igneous, sedimentary, and metamorphic. **Igneous rocks**, which form by the cooling of molten material to the point at which it hardens, or freezes (much as ice forms when water freezes), are composed of interlocking grains, each consisting of a particular mineral. The igneous rock most familiar to the nongeologist is granite. Molten material, or **magma**, that turns into igneous rock comes from great depths within Earth, where temperatures are very high. This material may reach Earth's surface through cracks and fissures in the crust and then cool to form **extrusive, or volcanic, igneous rock** (Figure 1-1), or it may cool and harden within Earth to form **intrusive igneous rock** (Figure 1-2). Igneous rock that solidifies deep within Earth is sometimes uplifted by subsequent movements of earth and eventually exposed at Earth's surface by **erosion,** which is a group of processes that loosen rock and move pieces of it downhill.

Sedimentary rocks form from **sediments,** which are materials deposited at Earth's surface by water, ice, or air. Most sediments are accumulations of distinct mineral grains. Some of these grains are products of weathering (i.e., decay and breakup) of older rocks, while others result from the chemical precipitation of minerals from water. Grains of sediment seldom become bonded to form hard rock until long after they have accumulated. The two important agents of this rock-forming process, which is known as **lithification,** are **compaction** of sediment under the influence of gravity and **cementation** of grains by the pre-

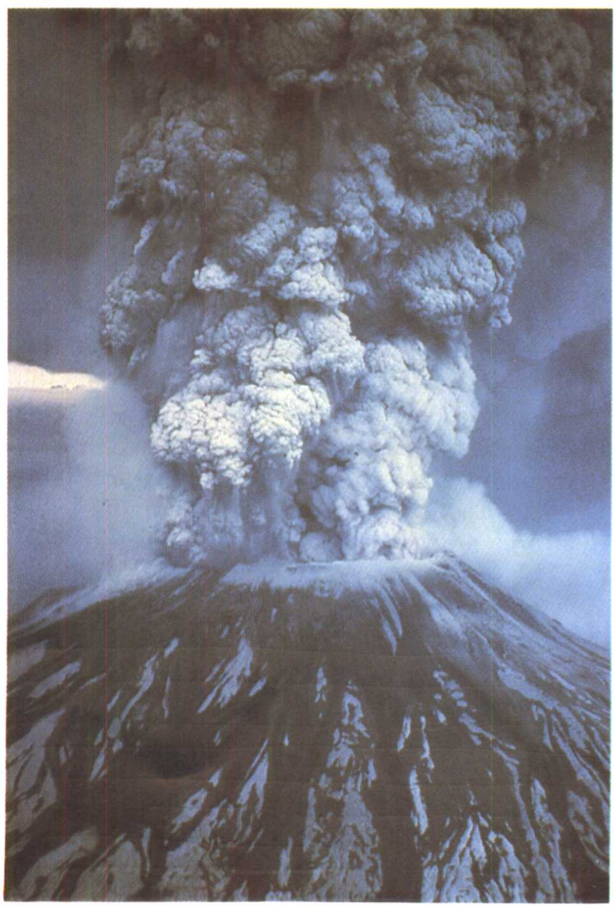

FIGURE 1-1 Mount St. Helens erupting in 1980. The cone of the volcano is itself formed of volcanic igneous rock extruded from the volcano. *(U.S. Geological Survey.)*

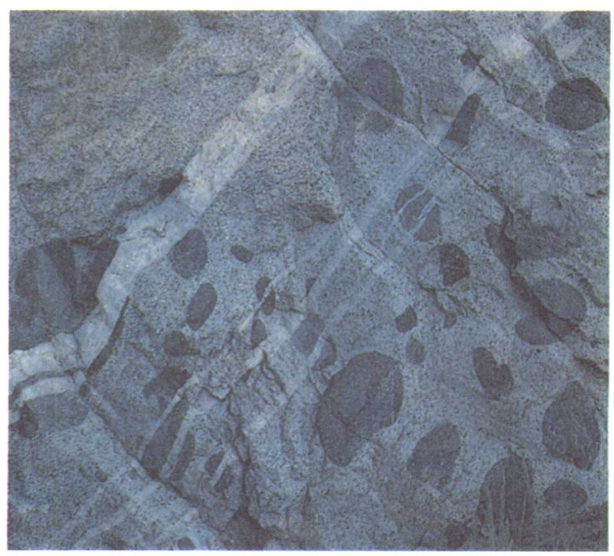

FIGURE 1-2 Intrusive igneous rock. The dark bodies are pieces of the surrounding rock that the magma that formed the igneous rock incorporated before it solidified. The light-colored diagonal bands on the left are veins that formed when a second body of magma intruded the main body of igneous rock. *(Martin G. Miller.)*

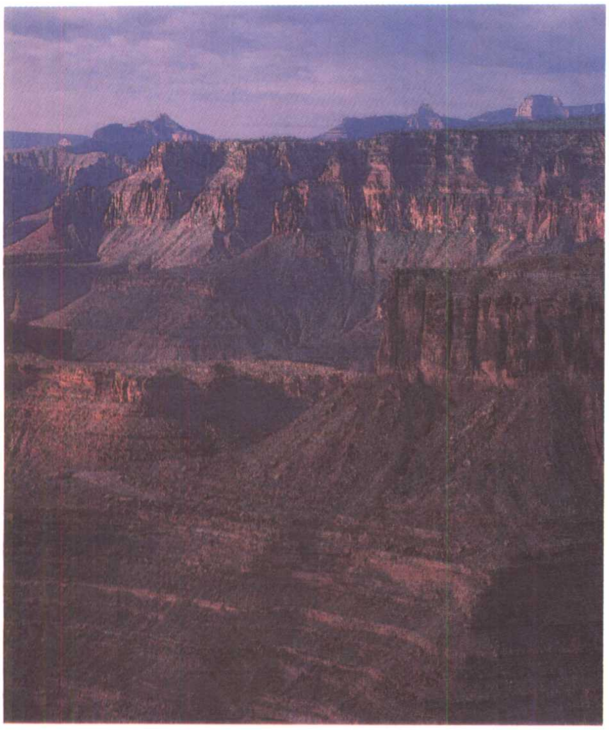

FIGURE 1-3 Horizontal bedding in sedimentary rocks bordering the Grand Canyon. *(Peter Kresan.)*

cipitation of mineral cement from solutions that flow between the grains. Lithification is a form of **diagenesis,** which is the full set of processes, including dissolution, that alter sediments at low temperatures after they have been buried. Cementation that transforms sand into sandstone is an example of diagenesis.

Most igneous rocks consist of silicate minerals (see Appendix I) and so do most sedimentary particles, or **clasts,** derived from them. Sedimentary rocks formed primarily of silicate minerals are thus known as **siliciclastic** rocks, and these are the most abundant sedimentary rocks of Earth's crust.

Sediments usually accumulate during discrete episodes, each of which forms a tabular unit known as a **stratum** (plural, **strata**). Strata tend to remain distinct from one another even after lithification because the grains of adjacent beds usually differ in size or composition. Because of their differences, the contacting surfaces of the strata usually adhere to each other only weakly, and sedimentary rocks often flake or fracture along these surfaces. As a result, sedimentary rocks exposed at Earth's surface often can be seen to have a steplike configuration when they are viewed from the side (Figure 1-3). **Stratification** is the word used to describe the arrangement of sedimentary rocks in discrete layers. **Bedding** is stratification in which layers exceed 1 centimeter (~0.4 inch) in thickness, and **lamination** is stratification on a finer scale.

Metamorphic rocks form by the alteration, or **metamorphism,** of rocks within Earth under conditions of high temperature and pressure. By definition, metamorphism alters rocks without turning them to liquid. If the temperature becomes high enough to melt a rock and the molten rock later cools to form a new solid rock, this new rock is by definition igneous rather than metamorphic. Metamorphism produces minerals and textures that differ from those of the original rock and that are characteristically arrayed in parallel wavy layers (Figure 1-4). The two groups of rocks that

FIGURE 1-4 Metamorphic rock. This is a coarsely crystalline kind of rock known as gneiss. *(Peter Kresan.)*

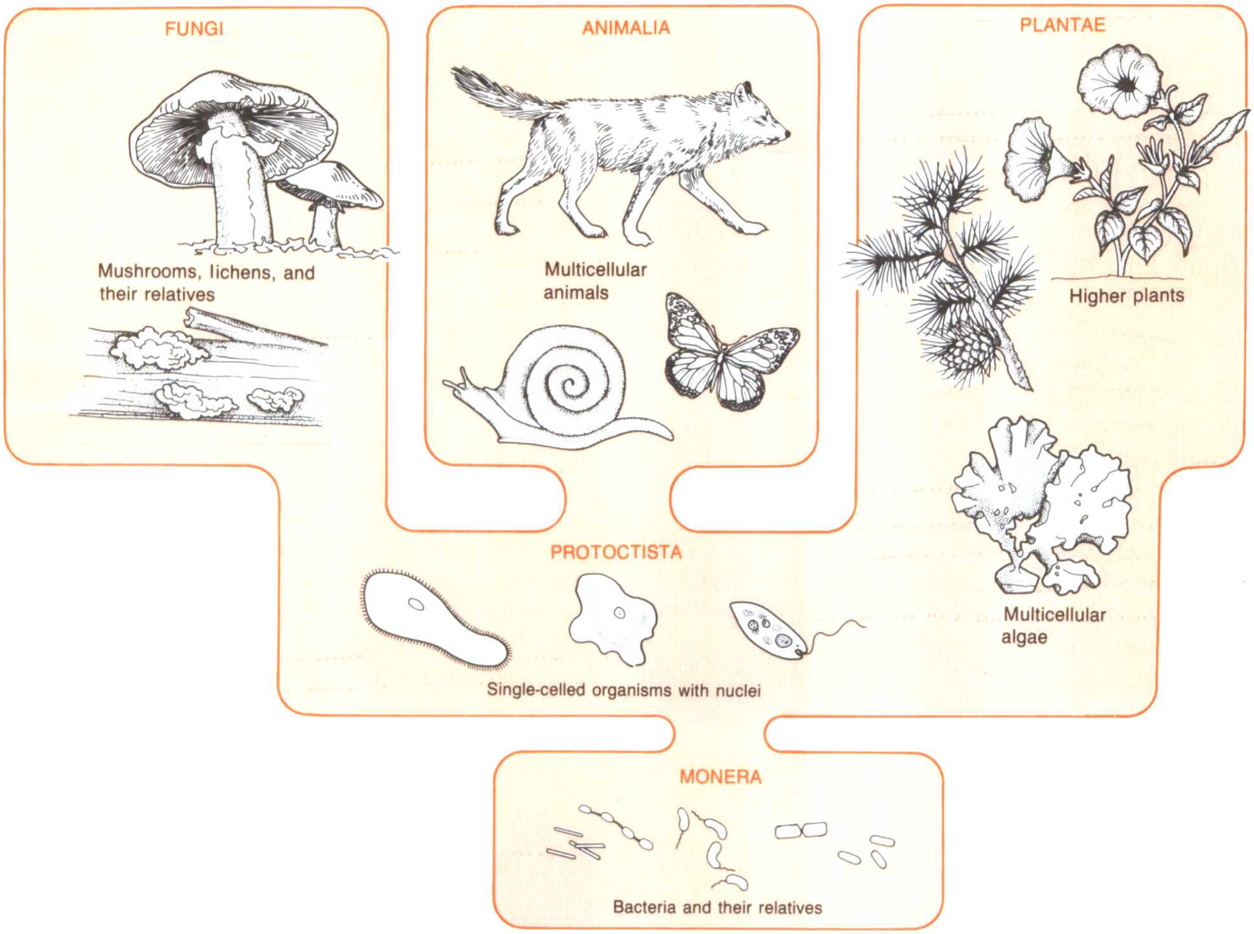

FIGURE 1-5 The five kingdoms of living things. The Monera include simple forms whose cells lack the internal organization represented by subcellular bodies such as nuclei and chromosomes. Some experts divide the Monera into two kingdoms and hence recognize six kingdoms altogether. The Protoctista include single-celled organisms that possess nuclei and chromosomes; animal-like protoctists eat other organisms, while plant-like protists manufacture their own food. Red, green, and brown algae are multicellular, but their cells are not differentiated into tissues of discrete cell types; some experts classify these algae as protoctists, while others classify them as members of the Plantae. Plantae are multicellular organisms that manufacture their own food, and animals are multicellular organisms that ingest food and digest it within their bodies. Fungi, which include mushrooms, lichens, and molds, absorb food from their environment.

form at high temperatures—igneous and metamorphic rocks—are sometimes referred to as **crystalline rocks.**

Classification of Bodies of Rock Geologists also classify rocks into units called **formations.** Each formation consists of a body of rocks of a particular type that formed in a particular way—for example, a body of granite, of sandstone, or of alternating layers of sandstone and shale. A formation is formally named, usually for a geographic feature such as a town or river where it is well exposed. Smaller rock units called **members** are recognized within some formations. Similarly, some formations are united to form larger units termed **groups,** and some groups, in turn, are combined into **supergroups.**

More about the nature and origin of minerals and the three basic types of rocks can be found in Appendix I.

LIFE ON EARTH

Organisms that have inhabited Earth in the course of geologic time have left a partial record in rock of their presence and their activities. This record reveals that life has changed dramatically since it first arose on Earth and that its transformation has been intimately associated with changes in physical conditions on Earth — in climates or in the positions of continents, for example.

It is not easy to provide a precise definition of *life*, but two attributes that are generally regarded as essential to life are the capacity for self-replication and the capacity for self-regulation. Viruses are simple entities that can replicate themselves (or reproduce), but they do not regulate themselves — that is to say, they do not employ raw materials from the environment to sustain orderly, internal chemical reactions. Thus viruses are not considered to be living things. On Earth today, all entities that are self-replicating and self-regulating are also cellular; that is, they consist of one or more discrete units called cells. A living cell is a module that includes a number of distinct features, including apparatuses that facilitate certain chemical reactions. The chemical "blueprint" for a cell's operation is coded into the chemical structure of the gene. An essential feature of this blueprint is the cell's built-in ability to duplicate itself so that a replica can be passed on to another cell or to an entirely new organism.

Taxonomic Groups

Until well into the nineteenth century, scientists divided all living things into two categories: the animal kingdom and the plant kingdom. As various forms of life came to be better understood, however, these distinctions became increasingly difficult to maintain. Today five kingdoms are recognized — the Monera, Protoctista, Fungi, Animalia, and Plantae (Figure 1-5).

A more detailed classification of many forms of life can be found in Appendix III. As this appendix indicates, each of the five kingdoms is divided into numerous subordinate groups. These kingdoms and their subordinate groups are known as **taxa,** or **taxonomic groups,** and the study of the composition and relationships of these groups is known as **taxonomy.** Taxa within kingdoms range from the broad category known as the phylum (plural, phyla) to the narrowest category, the **species** (Table 1-1), which consists of a group of individuals that interbreed or have the potential to interbreed in nature and that do not breed with other interbreeding groups. The basic categories of higher taxa — the kingdom, phylum, class, order, family, and genus (plural, genera) — are sometimes supplemented by categories such as the subfamily and the superfamily. Names of genera are printed in italics, as are species designations. Actually, the name of the species consists of two words, the first of which is the name of the genus to which the species belongs.

Figure 1-6 further illustrates how humans are classified within the order Primates of the class Mammalia. In general, the narrower the taxonomic category, the greater the biological similarity of its members. Humans and gorillas, for example, have enough in common to be assigned to the same superfamily, but monkeys differ from these groups in several ways and are assigned to other superfamilies. All of these superfamilies are nonetheless similar enough to be united in a single suborder. Often one or a small number of biological features serve to distinguish one higher taxon from other closely related taxa of the same rank. Dinosaurs, for example, are divided into two orders on the basis of pelvic structure (Figure 1-7).

TABLE 1-1 Major taxonomic categories within a kingdom, as illustrated by the classification of humans

Kingdom	Animalia
Phylum	Chordata
Class	Mammalia
Order	Primates
Family	Hominidae
Genus	*Homo*
Species	*Homo sapiens*

NOTE: Between these categories, intermediate ones (e.g., superorders, suborders, superfamilies, and subfamilies) are sometimes recognized.