
EARTH AND LIFE THROUGH TIME
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TO NELL

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Preface

Major developments in the study of earth history during the past few years have, for the first time, made it possible to integrate descriptions of such diverse elements of our planet's evolution as earth movements, climatic and oceanographic changes, and the transformation of life by evolution and extinction. I have written this book in the conviction that the physical history and the biological history of the earth are inextricably intertwined. Not only has the evolutionary play been performed in the ecological theater, to borrow G. Evelyn Hutchinson's metaphor, but the players themselves, albeit unwittingly, have changed the stage upon which they have acted.

This integrated view of earth history has led me to write a text which can serve as a self-contained introduction to both the biological and the geological aspects of our planet's evolution. Unlike many other historical geology texts, *Earth and Life Through Time* requires no previous knowledge of physical geology in order to be fully comprehended; yet it may also be easily adapted for use in courses with different emphases and requirements for enrollment, and can therefore be used by majors and nonmajors alike, by students who have had a previous course in physical geology, and by those who are being introduced to geologic techniques and concepts for the first time.

Broadly, the first portion of the text (Chapters 1 through 8) provides facts and principles necessary to understand the second (Chapters 9 through 18), which is a chronological review of the earth and its biota. Unlike comparable segments in the traditional earth history text, however, the introductory chapters are not merely a summary of relevant topics in physical geology. They also contain much additional material that is essential for understanding modern concepts of earth history and that, to date, has been insufficiently covered in the available texts. Chapter 2, for example, presents an overview of ecological principles and the nature of our planet's ecosystem. I hope that the material here will prove generally enlightening to students, quite apart from its immediate purpose of serving as a basis for understanding life and environments of the past. Chapters 3 and 4 are also without counterpart in previous historical geology texts. They review a modest number of important nonmarine and marine depositional settings that account for the bulk of the sedimentary record. I have placed Chapter 5, which introduces correlation and other stratigraphic procedures and principles, ahead of the chapter on evolution (Chapter 6). This ordering may run counter to the inclinations of some teachers. My rationale is that understanding the elements of biostratigraphy requires knowledge of faunal and floral succession but not knowledge of the nature of evolution. Furthermore, only students who first know something about correlation and radiometric dating will be able to appreciate what the fossil record can tell us about rates and patterns of evolution and extinction.

To introduce plate tectonics (Chapter 7), I have employed a largely historical approach in order to give students the opportunity both to share in the excitement that this new paradigm has generated and to learn how scientific theories germinate and develop. The final "background" chapter (Chapter 8), also a new feature for a book of this type, reviews mountain-building processes through analysis of four case studies: the Alps, the Himalayas, the Andes, and the Appalachians. I later refer to these examples in the second part of the book, where each has a place in the chronological sequence. Additional basic information concerning minerals, rocks, and deformational structures in the earth's crust is summarized in Appendixes I and II.

Throughout the book I have relied heavily on figures and figure legends to introduce students to ancient animals and plants. In Chapters 12 through 18, this approach provides a chronological picture of life on earth. Complementing this perspective, Appendix III places important fossil groups in a taxonomic context; alongside nearly every taxon listed is a cross-reference to one or more figures in the text illustrating one or more members of the taxon. Study of Appendix III and the figures (and figure legends) cited within it will provide the student with a general picture of ancient life.

The broad coverage of this book is designed to give teachers the freedom to lecture only on specific topics that they find appealing. Believing that students are most comfortably immersed in history by degrees, I have organized the chapters on Phanerozoic time so that the general features of each interval (its biological and paleogeographic developments) appear first, and more localized aspects (selected regional events) follow. This arrangement also allows for flexibility in the use of the book: Instructors whose courses are dominated by students not majoring in geology may wish to omit some or all of the "Regional Events" sections of the final seven chapters—or these instructors might recommend that students merely scan those portions of the book; Chapter 11, which describes Proterozoic cratons, might also be omitted or scanned. Such courses would then focus on global events, paleogeography, and the history of life.

Because of its comprehensiveness and flexibility, *Earth and Life Through Time* can also serve as a text for courses on the History of Life. In this role, the book will surely not be assigned in its entirety. Chapters 7 and 8, covering plate tectonics and mountain building, might be scanned rather than read; other expendable sections would include parts of Chapter 9 (which covers Archean time), all of Chapter 11 (which describes Proterozoic cratons), and the "Regional Events" sections of later chapters.

In writing this book I have relied on the criticisms and suggestions of many experts and capable critics. None of these persons has seen a final version of anything he or she has reviewed, so, in the proper tradition, I accept blame for any errors, but I also express much gratitude to all:

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In the course of preparing the manuscript and developing the extensive illustration program, I was assisted by able persons too numerous to name separately here. Some of the outstanding contributions nevertheless merit special acknowledgment: Anne Boersma, J. M. Pulsford, and Don Baird, for making exceptional efforts in providing illustrative material; Gregory Paul, whose beautiful drawings speak for themselves; Kate Francis and Susan Lubonovich, for their excellent typing; and Robert T. Bakker, for enriching my intellectual life during the past ten years and enlightening me about many things described in the following pages.

I also thank the many people at W. H. Freeman and Company who have aided in this project. John H. Staples has long been a friend and valued advisor, Moira Lerner has been the best and most cheerful developmental editor anyone could wish for, Georgia Lee Hadler coordinated the long transition from manuscript to bound book with great skill, and Lisa Douglis designed what I think is an exceptionally beautiful book.

Finally, I offer apologies and appreciation to my wife, Nell, for tolerating my horrendous daily schedule for more years at work on this book than I wish to count.

I would be grateful if readers would notify me of errors or offer suggestions for improvement, preferably with literature citations where these would be helpful.

Steven M. Stanley

EARTH AND LIFE THROUGH TIME

Contents

CHAPTER 1

Introduction to the 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 those geologic facts and principles to give the student an understanding of the general history of our planet and its life. The chapters that follow will describe how the physical world assumed its present form and where the inhabitants of the modern world came from. They will 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.

The San Andreas Fault in California is a great break within the earth's crust separating large segments, or plates, of the crust. The Pacific plate is on the left, and the North American plate is on the right. As indicated by the arrows, the Pacific plate periodically slides northwestward in relation to the North American plate. Movement along this fault led to the San Francisco earthquake of 1906. Many faults transect California, although movement has not occurred along most of these during recorded history. (*R. E. Wallace, U.S. Geological Survey.*)

Knowledge of the earth's history can also be of great practical value. For example, geologists have learned to locate petroleum reservoirs by ascertaining where the porous rocks of these reservoirs tend to form in relation to other bodies of rock. Early in this century, vast stores of natural gas and petroleum were discovered trapped in rocks that lay adjacent to buried pillars of salt in the Gulf Coast region of the United States. It is now known that natural gas, petroleum, and sulfur are trapped in rocks above salt domes. By studying waves of earth movement produced by artificial explosions, geologists can locate salt domes deep below the surface and guide petroleum companies in their extraction of valuable resources from the rock. Geologists have also helped discover many additional kinds of petroleum reservoirs, as well as coal deposits, ore deposits, and other natural resources buried within the earth. Occurrences of some of these resources will be analyzed in the chapters that follow. Before we launch into our detailed examination of the history of the earth and its life, however, an introduction to some of the basic facts and unifying concepts of geology is in order. This chapter will be devoted to laying that groundwork.

THE PRINCIPLE OF UNIFORMITARIANISM

Fundamental to the modern science of geology is the principle of **uniformitarianism**, which is 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 the principle of uniformitarianism 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**. As an example, when we see ripples on the surface of an ancient rock composed of hardened sand (sandstone), we assume that these ripples formed in the same manner 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.

Commonly, actualism is described 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 in recent times. Many researchers, for example, believe 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 great tidal wave, but 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 the earth for many days. As we will learn in Chapter 16, 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 cannot be applied.

Similarly, geologists have found that certain types of rocks cannot be observed in the process of forming today. When this is the case, 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 the earth's surface that we cannot observe them; or (3) the conditions exist today but produce the rocks only after 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, but it does present geologists with a problem that cannot be solved by application of the principle of actualism, since they will not have the opportunity to interpret the rocks by studying their development during a modern human lifetime.

In an attempt to address some of these problems, geologists have learned to form rocks in the laboratory by duplicating the conditions that prevail at great depths within the earth. To accomplish this, they expose simple chemical components to temperatures many times higher—and to pressures many times greater—than those of the 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 of the past.

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 the 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 earth's surface. These ideas were entirely speculative; they were unsupported by evidence from the physical world.

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 presently operating at or near the earth's surface—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 entitled *Principles of Geology*. Let us briefly examine the uniformitarian view of how rocks form.

Rocks consist of interlocking or attached 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 form the materials we call mica, clay, and asbestos. Rocky surfaces that stand exposed and are readily accessible for study are generally designated as **outcrops** or **exposures**, although some geologists restrict the first term to rocks laid bare by natural processes and the second to rocks exposed by human activities such as quarrying or road building. Scientists also have access to rocks that are not visible in outcrops or exposures. Well drilling and mining, for example, allow geologists to sample rocks that are still buried beneath the earth's surface.

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 thepoint at which it hardens, or freezes (much as ice forms when water freezes in a refrigerator), are composed of interlocking grains, each consisting of a particular mineral. The most familiar igneous rock to the nongeologist is granite. The molten material, or **magma**, that turns into igneous rocks comes from great depths within the earth, where temperatures are very high. This material may reach the 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 the earth to form **intrusive** igneous rock (Figure 1-2). Igneous rock that solidifies deep within the earth is sometimes uplifted by subsequent earth movements along with surrounding rock and eventually exposed at the earth's surface by **erosion**, which is the group of processes that loosen rock and move pieces of loosened rock downhill.

Sedimentary rocks form from **sediments**, which are materials deposited at the earth's surface by water, ice, or air. Most sediments are accumulations of distinct mineral grains. Some of these grains are products of weathering

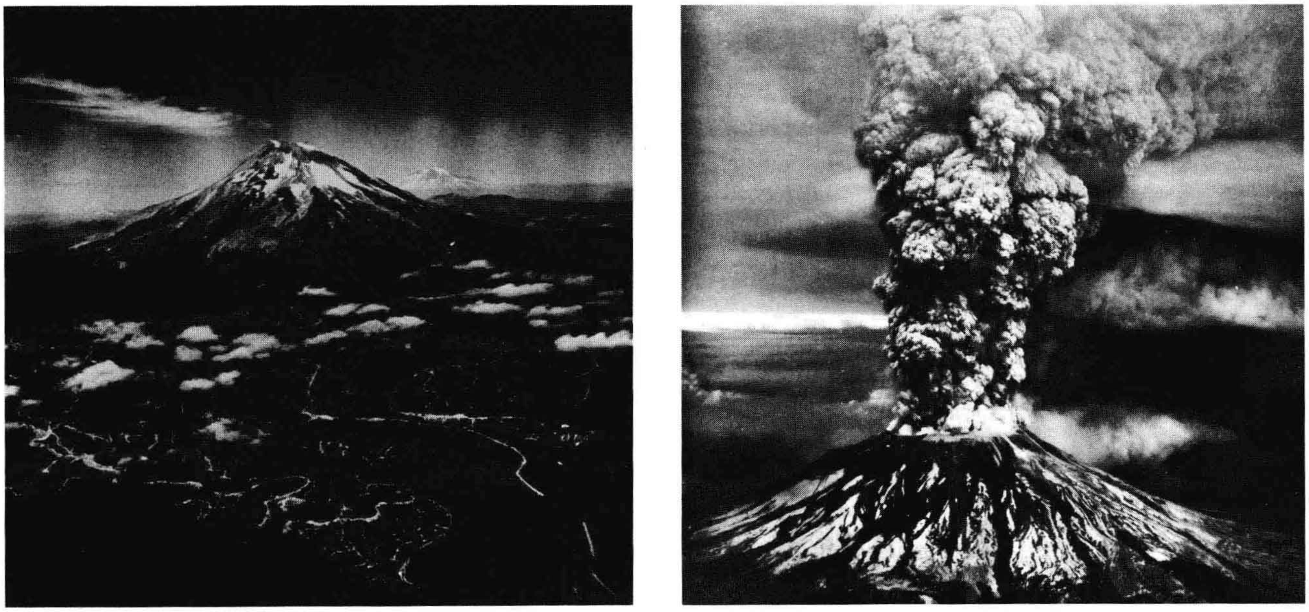

FIGURE 1-1 Mount St. Helens in a peaceful state (*left*) and erupting in 1980 (*right*). The cone of the volcano is itself formed of volcanic igneous rock extruded from the volcano. (*U.S. Geological Survey.*)

FIGURE 1-2 Igneous rock that formed by cooling of magma within the earth. The mineral grains of this type of igneous rock are larger than those of volcanic igneous rock, giving the rock a coarser texture. The hammerhead rests against an inclusion—a piece of older rock that was trapped within the magma and "frozen" into it as it cooled. (*J. J. Witkind, U.S. Geological Survey.*)

(i.e., decay and breakup) of older rocks, while others result from the chemical precipitation of minerals from water. Grains of sediment seldom become mutually attached to form a 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 precipitation of mineral cement from solutions that flow between the grains. Lithification is a form of **diagenesis**, which is the full set of processes, including solution, that alter sediments at low temperatures after burial. Alteration at high temperatures constitutes metamorphism, which will be described shortly.

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 the earth's crust.

Sediments usually accumulate during episodes of deposition, 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. The result is that sedimentary rocks exposed at the earth's surface often have a steplike configuration when viewed from the side (Figure 1-3). **Stratification** is the word used to describe the layered character of sedimentary rocks. **Bedding** is stratification in which layers exceed one centimeter (~0.4 inches) in thickness, and **lamination** is stratification on a finer scale.

Metamorphic rocks form by the alteration, or **meta-**

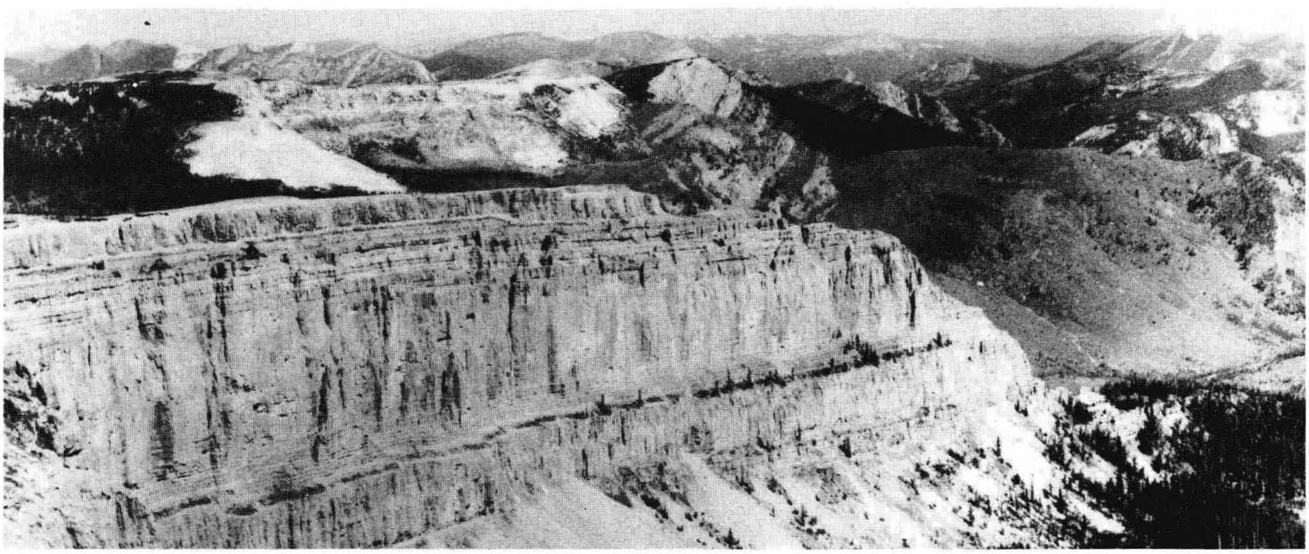

FIGURE 1-3 Horizontal bedding in sedimentary rocks of the Bob Marshall Wilderness Area in Montana. Erosion of these rocks has produced a steplike outcrop pattern. Sediment loosened by erosion forms a sloping deposit at the foot of the cliff. (*M. R. Mudger, U.S. Geological Survey.*)

morphism, of rocks within the 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 subsequently 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).

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.

FIGURE 1-4 Metamorphic rock showing parallelism of mineral grains that formed at high pressure and high temperature. (*M. H. Staatz, U.S. Geological Survey.*)

LIFE ON EARTH

The organisms that have inhabited the 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 during the history of the earth and that its transformation has been intimately associated with changes in physical conditions on earth —in climates or in the position 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 the earth today, all entities that are self-replicating and self-regulating also share the quality of being cellular, which means that 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 DNA molecule, which we will examine more closely in Chapter 6. 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. They are illustrated in Figure 1-5.

A more detailed classification of many forms of life can be found in Appendix III of this book. As examination of this appendix will indicate, 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). 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.

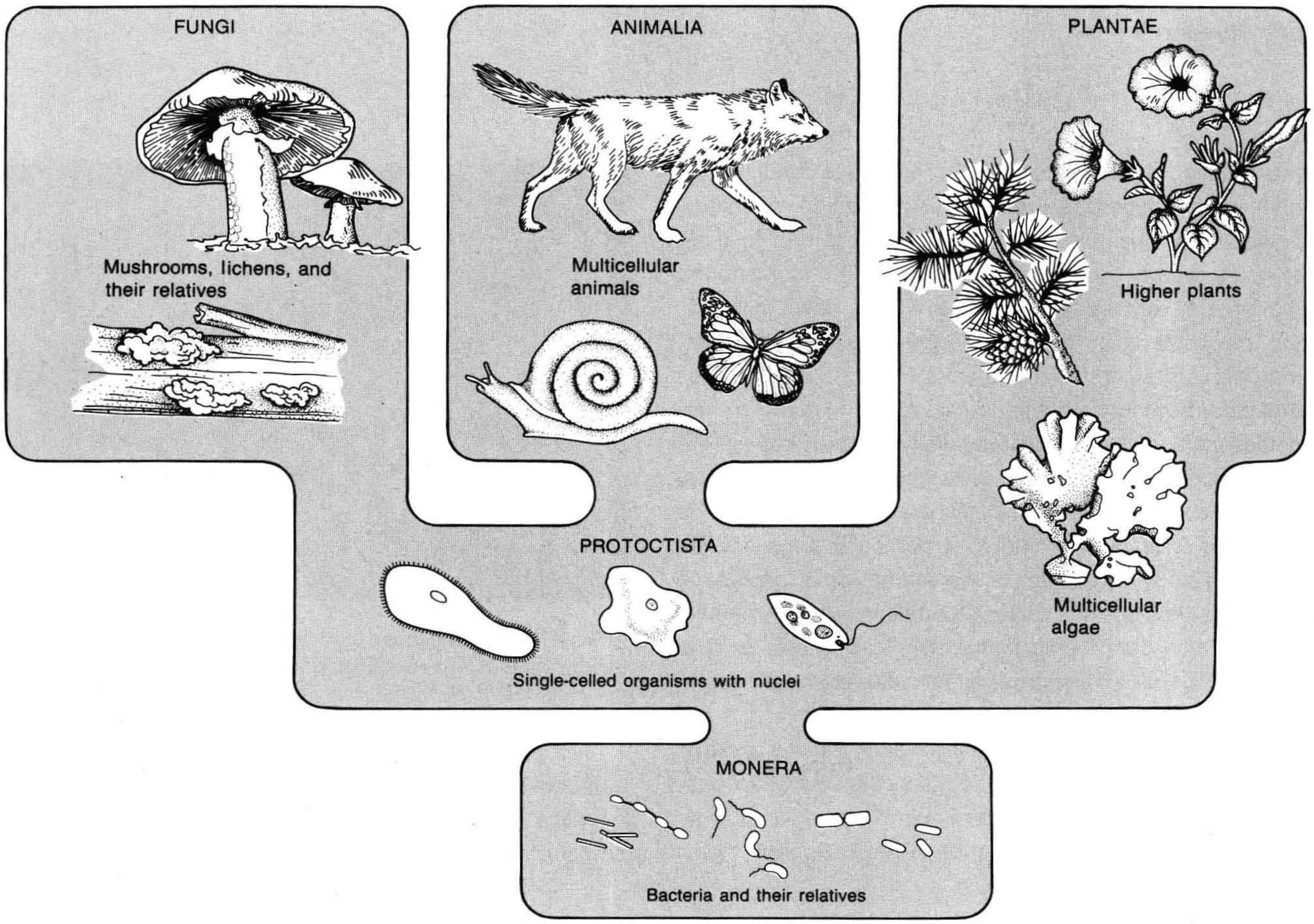

FIGURE 1-5 The five kingdoms of living things. The Monera include simple forms whose cells lack the internal organization represented by subcellular bodies such as nuclei and chromosomes. Some experts divide the Monera into two kingdoms andhence recognize six kingdoms altogether. The Protoctista include single-celled organisms that possess nuclei and chromosomes; animal-like protists eat other organisms, while plantlike 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 protists, 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 include mushrooms and molds; they absorb food from their environment.

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 degree of biological similarity. Humans and gorillas, for example, have enough in common to be assigned to the same superfamily, but humans and gorillas are grouped with monkeys only within the broader suborder category. Within this suborder, monkeys are placed in a superfamily of their own. 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 ex-

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

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

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

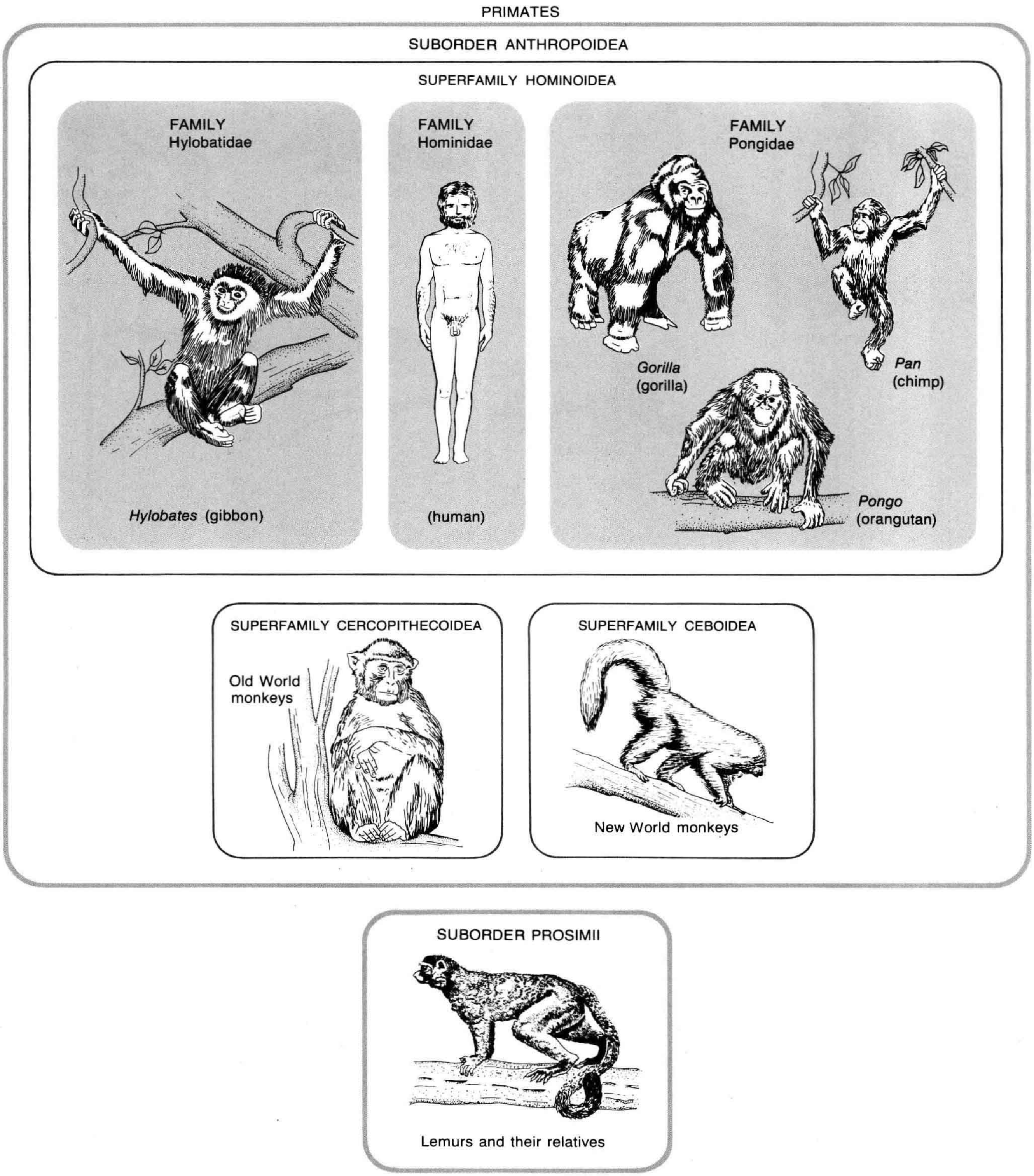

FIGURE 1-6 The taxonomic position of the human genus *Homo* within the order Primates. There are four other genera in the superfamily Hominoidea: three ape genera of the family Pongidae and one genus of the family Hylobatidae.