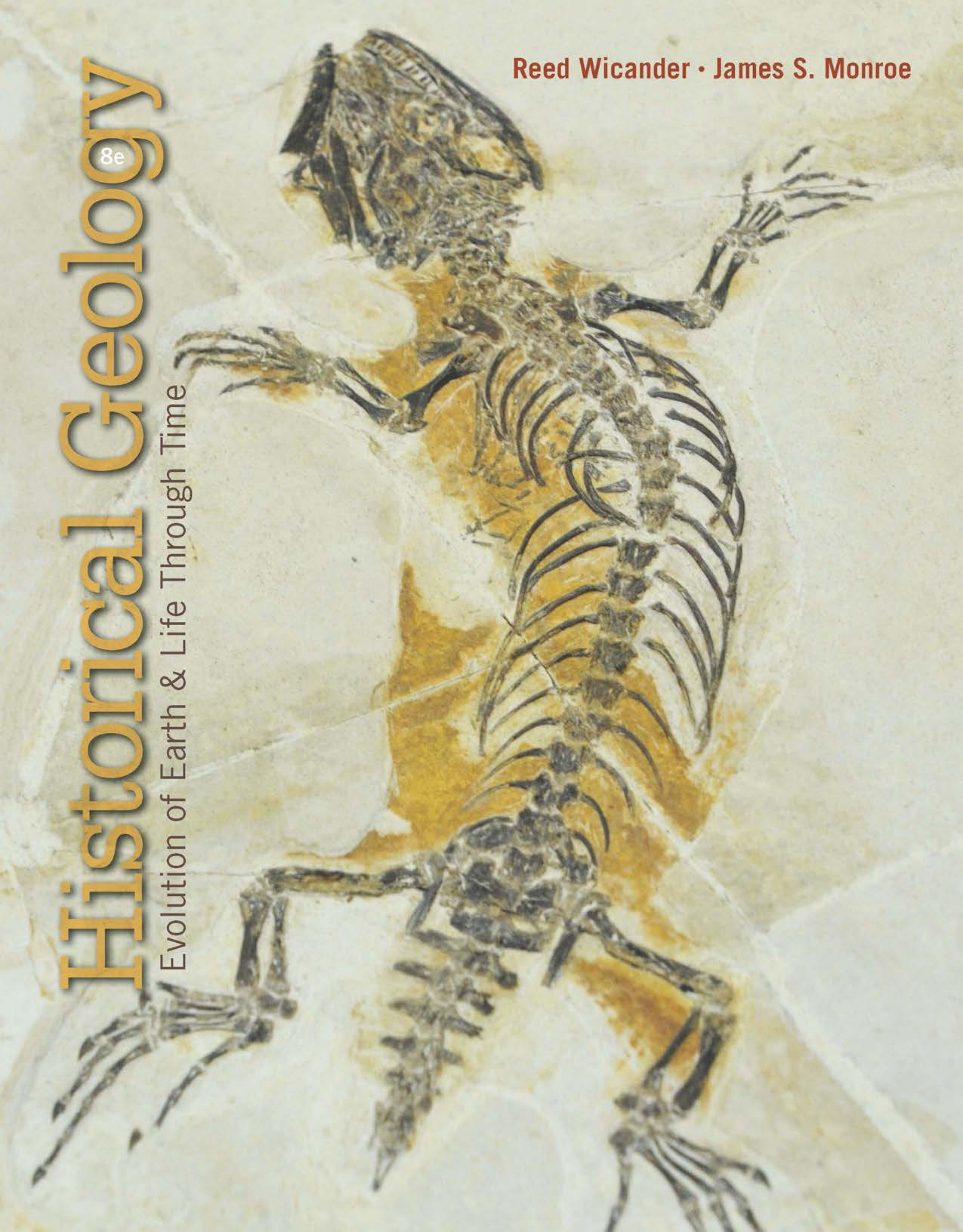

Reed Wicander • James S. Monroe

Historical Geology

8e

Evolution of Earth & Life Through Time

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Evolution of Earth & Life Through Time

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Courtesy of Melanie G. Wicander

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Brief Contents

Contents

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Preface

Earth is a dynamic planet that has changed continuously during its 4.6 billion years of existence. The size, shape, and geographic distribution of the continents and ocean basins have changed through time, as have the atmosphere and biota. As scientists and concerned citizens, we have become increasingly aware of how fragile our planet is and, more importantly, how interdependent all of its various systems and subsystems are.

We have also learned that we cannot continually pollute our environment and that our natural resources are limited and, in most cases, nonrenewable. Furthermore, we are coming to realize how central geology is to our everyday lives. For these and other reasons, geology is one of the most important college or university courses a student can take.

Historical geologists are concerned with all aspects of Earth and life history. They seek to determine what events occurred during the past, place those events into an orderly chronological sequence, and provide conceptual frameworks for explaining such events. Equally important is using the lessons learned from the geologic past to understand and place in context some of the global issues facing the world today, such as depletion of natural resources, global climate warming, and decreasing biodiversity. Thus, what makes historical geology both fascinating and relevant is that, like the dynamic Earth it seeks to understand, it is an exciting and ever-changing science in which new discoveries and insights are continually being made.

Historical Geology: Evolution of Earth & Life Through Time, eighth edition, is designed for a one-semester geology course and is written with students in mind. One of the problems with any introductory science course is that students are overwhelmed by the amount of material that must be learned. Furthermore, most of the material does not seem to be linked by any unifying theme and does not always appear to be relevant to their lives. This book, however, is written to address that problem in that it shows, in its easy-to-read style, that historical geology is an exciting science, and one that is increasingly relevant in today's world.

The goals of this book are to provide students with an understanding of the principles of historical geology and how these principles are applied in unraveling Earth's history. It is our intent to present the geologic and biologic history of Earth, not as a set of encyclopedic facts to memorize, but rather as a continuum of interrelated events reflecting the underlying geologic and biologic principles and processes that have shaped our planet and life upon it.

Instead of emphasizing individual, and seemingly unrelated, events, we seek to understand the underlying causes of why things happened the way they did, and how all of Earth's systems and subsystems are interrelated. Using this approach, students will gain a better understanding of how everything fits together and why events occurred in a particular sequence.

Because of the nature of the science, all historical geology textbooks share some broad similarities. Most begin with several chapters on concepts and principles, followed by a chronological discussion of Earth and life history. In this respect, we have not departed from convention. We have, however, placed greater emphasis on basic concepts and principles, their historical development, and their importance in deciphering Earth history: in other words, how do we know what we know? By approaching Earth history in this manner, students come to understand Earth's history as part of a dynamic and complex integrated system, and not as a series of isolated and unrelated events.

Features in the Eighth Edition

Just as Earth is dynamic and evolving, so too is *Historical Geology: Evolution of Earth & Life Through Time*. The eighth edition has undergone significant rewriting and updating, resulting in a book that is still easy to read, yet contains a high level of current information. The new edition features many new photographs and figures, as well as numerous new *Perspectives*, all of which are designed to help students maximize their learning and understanding of their planet's history. Drawing on the comments and suggestions of reviewers and users of the book, we have expanded and retained many of the features that were successful in the previous edition.

- The *Chapter Objectives* outline at the beginning of each chapter has been retained to alert students to the key points that the chapter will address.
- Chapter 2 (Mineral and Rocks), which provides the necessary background for those students who are unfamiliar with minerals, rocks, and the rock cycle, has been retained, as well as *Appendix C* on Mineral Identification.
- A new *Perspective* on "The Industrial Minerals" has been added to Chapter 2, which previously didn't have a Perspective.

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- Chapter content has been extensively updated and rewritten to (1) help clarify concepts, (2) emphasize underlying processes, and (3) make the material more exploratory.
- An added emphasis has been placed on global climate warming throughout the text, with both new material added and previous sections rewritten and updated.
- Eleven of the eighteen previous *Perspectives* are new, and many of the previous eight are rewritten and updated.
- New, bold, and dramatic photos have been added to open eleven of the nineteen chapters. In addition, numerous new images have been added to the text of each chapter, and many figures have been updated.
- The *Review Questions* section at the end of each chapter has been changed to five multiple-choice questions and five short-essay questions. Question #10 in a number of the chapters asks the student to interpret a photograph or illustration and apply the lessons learned from that chapter to the image. A significant number of the questions have been rewritten or are new. Answers to all of the multiple-choice questions are provided at the back of the book.
- The *Epilogue* has been updated. The *Epilogue* is designed to tie together current issues with the historical perspective of geology presented in the previous nineteen chapters.
- Based on user comments, a new *Appendix D*, titled "A Refresher on Structural Geology" has been added to help students review the many structural features discussed in the text.

It is our strong belief that the significant rewriting and updating done in the text, as well as the addition of new and dramatic photos and figures, have greatly improved the eighth edition of *Historical Geology: Evolution of Earth & Life Through Time*. We think that these changes and enhancements make this textbook easier to read and comprehend, as well as making it a more effective teaching tool that engages students in the learning process, and thereby fostering a better understanding of the material and how it relates to Earth today.

Text Organization

As in the previous editions, we develop three major themes in this textbook that are essential to the interpretation and appreciation of historical geology. These themes are introduced early and reinforced throughout the book. The themes are *plate tectonics* (Chapter 3), a unifying theory for interpreting much of Earth's physical history and, to a large extent, its biologic history; *time* (Chapter 4), the dimension that sets historical geology apart from most of the other sciences; and *evolutionary theory* (Chapter 7), the explanation for inferred relationships among living and fossil organisms. Additionally, we have emphasized the intimate interrelationship existing between physical and biologic events, and the fact that Earth is a complex, dynamic, and evolving planet whose history is best studied by using a systems approach.

This book was written for a one-semester course in historical geology to serve both majors and non-majors in geology and in the Earth sciences. We have organized *Historical Geology: Evolution of Earth & Life Through Time*, eighth edition, into the following informal categories:

- Chapter 1 reviews the principles and concepts of geology and the three themes this book emphasizes. The text is written at an appropriate level for those students taking historical geology with no prerequisites, but the instructor may have to spend more time expanding some of the concepts and terminology discussed in Chapter 1.
- Chapter 2, "Minerals and Rocks," can be used to introduce those students who have not had an introductory geology course to minerals, rocks, and the rock cycle, or as a review for those students that have had such a course. In addition to a new *Perspective* titled "The Industrial Minerals," a new section on economic geology has been added to call attention to minerals and rocks as resources.
- Chapter 3 explores plate tectonics, which is the first major theme of this book. Particular emphasis is placed on the evidence substantiating plate tectonic theory, why this theory is one of the cornerstones of geology, and why plate tectonic theory serves as a unifying paradigm in explaining many apparently unrelated geologic phenomena.
- The second major theme of this book, the concepts and principles of geologic time, is examined in Chapter 4. The *Perspective* "The Anthropocene: A New Geologic Epoch?" shows how humans' impact on Earth might show up in the geologic record, possibly necessitating a new geologic epoch: the Anthropocene.
- Chapter 5 expands on the theme of geologic time by integrating it with rocks and fossils. A new *Perspective* titled "Mesa Verde National Park, Colorado" calls attention to the geological and cultural aspects of the park.
- Depositional environments are sometimes covered rather superficially (perhaps with little more than a summary table) in some historical geology textbooks. However, Chapter 6, "Sedimentary Rocks: The Archives of Earth History," is completely devoted to this topic, with a reworked section on sedimentary structures and a new *Perspective*; it contains sufficient detail to be meaningful while avoiding an overly detailed discussion more appropriate for advanced courses.
- The third major theme of this book, organic evolution, is examined in Chapter 7. In this chapter, the theory of evolution is covered, as well as its supporting evidence. It has been updated with new material including a new *Perspective*.

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- Precambrian time—fully 88 percent of all geologic time—is sometimes considered in a single chapter in other historical geology textbooks. In this book, however, Chapter 8 is devoted to the geologic and biologic histories of the Hadean and Archean Eon, whereas Chapter 9 covers the same topics for the Proterozoic Eon. Both chapters contains new *Perspectives*, with some of the previous *Perspectives* material being incorporated into the text. Furthermore, both chapters have undergone major updating based on the latest research from this period of Earth history.
- Chapters 10 through 19 constitute our chronological treatment of the Phanerozoic geologic and biologic history of Earth. These chapters are arranged so that the geologic history of an era is followed by a discussion of the biologic history of that era. We think that this format allows easier integration of life history with geologic history. All 10 of these chapters have undergone updating, new *Perspectives*, many new figures, and a discussion on glaciers and global warming.
- The *Epilogue* summarizes the major topics and themes of this book, with an updated and added emphasis on global climate warming.

In these chapters, there is an integration of the three themes of this textbook, as well as an emphasis on the underlying principles of geology and how they have helped us decipher Earth's history. We have found that presenting the material in the order just discussed works well for most students. We also know, however, that many professors prefer an entirely different order of topics, depending on the emphasis in their course. Therefore, we have written this book so that instructors can present the chapters in whatever order suits the needs of a particular course.

Chapter Organization

All chapters have the same organizational format as follows:

- Each chapter opens with a photograph relating to the chapter material, many of which are new and dramatic, followed by an *Outline* of the topics covered, and a list of *Chapter Objectives* that alerts students to the learning-outcome objectives of the chapter.
- An *Introduction* follows that is intended to stimulate interest in the chapter and show how the chapter material fits into the larger geologic perspective. Many of the *Introductions* have been rewritten and updated in this edition.
- The text is written in a clear, informal style, making it easy for students to comprehend.
- Numerous color diagrams and photographs complement the text and provide a visual representation of the concepts and information presented.
- Each chapter contains a *Perspective*, many of which are new to this edition, presenting a brief discussion of an interesting aspect of historical geology or geologic research pertinent to that chapter.
- Each of the chapters on geologic history in the second half of this book contains a final section on mineral resources characteristic of that time period. These sections provide applied economic material of interest to students.
- The end-of-chapter materials begin with a concise review of important concepts and ideas in the *Summary*.
- The *Important Terms*, which are printed in boldface type in the chapter text, are listed at the end of each chapter for easy review, along with the page number where that term is first defined. A full *Glossary* of important terms appears at the end of the text.
- The *Review Questions* are another important feature of this book. They include five multiple-choice questions with answers, as well as five short-essay questions, some of which require interpretation of an image, and are related to the principles and material presented in the chapter. Many of both types of questions are new in each chapter of this eighth edition.
- The global paleogeographic maps that illustrate in stunning relief the geography of the world during various time periods have been retained in this edition. These maps enable students to visualize what the world looked like during the time period being studied and thus add a visualization dimension to the text material.
- As in the previous editions, end-of-chapter summary tables are provided for the chapters on geologic and biologic history. These tables are designed to give an overall perspective of the geologic and biologic events that occurred during a particular time interval and to show how these events are interrelated. The emphasis in these tables is on the geologic evolution of North America. Global tectonic events and sea-level changes are also incorporated into these tables to provide global insights and perspective.

Ancillary Materials

We are pleased to offer a full suite of text and multimedia products to accompany the eighth edition of *Historical Geology: Evolution of Earth & Life Through Time*.

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Earth Science MindTap for Historical Geology MindTap is a new approach to highly personalized online learning. Beyond an eBook, homework solution, digital supplement, or premium website; MindTap is a digital learning platform that works alongside your campus LMS to deliver course curriculum across the range of electronic devices in your life. MindTap is built on an "app" model allowing enhanced digital collaboration and delivery of engaging content across a spectrum of Cengage and non-Cengage resources.

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As the authors, we are, of course, responsible for the organization, style, and accuracy of the text, and any mistakes, omissions, or errors are our responsibility. The finished product is the culmination of many years of work during which we received numerous comments and advice from many geologists who reviewed parts of the text. We wish to express our sincere appreciation to the many users of the seventh edition who generously provided us with many helpful comments that have led to the improvements seen in this eighth edition.

We would also like to thank the reviewers of the previous editions. Their comments and suggestions resulted in many improvements and pedagogical innovations, making this book a success for students and instructors alike.

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True color satellite image of Asia (partly in shadow), the Arctic ice cap, and the Sun. In this book, we examine Earth and its history as a system of interconnected components that interact with each other. The atmosphere, biosphere, hydrosphere, and lithosphere are four of Earth's major subsystems that are visible in this image. The complex interactions among these subsystems and Earth's interior have resulted in a dynamically changing planet since its origin 4.6 billion years ago.

The Dynamic and Evolving Earth

OUTLINE

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CHAPTER OBJECTIVES

At the end of this chapter, you will have learned that

- Earth is a complex, dynamic planet that has continuously evolved since its origin some 4.6 billion years ago.
- Earth can be viewed as an integrated system of interconnected components that interact and affect one another in various ways.
- Theories are based on the scientific method and can be tested by observation and/or experiment.
- The universe is thought to have originated approximately 14 billion years ago with a Big Bang, and the solar system and planets evolved from a turbulent, rotating cloud of material surrounding the embryonic Sun.
- Earth consists of three concentric layers—core, mantle, and crust—and this orderly division resulted during Earth's early history.
- Plate tectonics is the unifying theory of geology, and it revolutionized the science.
- The theory of organic evolution provides the conceptual framework for understanding the evolution of Earth's fauna and flora.
- An appreciation of geologic time and the principle of uniformitarianism are central to understanding the evolution of Earth and its biota.
- Geology is an integral part of our lives.

Introduction

A major benefit of the space age has been the ability to look back from space and view our planet in its entirety. We are able to see not only the beauty of our planet, but also its fragility. Even though we did not witness it firsthand, we can still tell the story of Earth's long and turbulent 4.6-billion-year history by deciphering the clues preserved in its geologic record. So let's tell that story in a full-length feature film we'll call *The History of Earth*.

In this movie, we will see a planet undergoing remarkable change as continents move about its surface. As a result of these movements, ocean basins will open and close and mountain ranges will form along its continental margins. Oceanic and atmospheric circulation patterns will shift in response to the moving continents, sometimes causing massive ice sheets to form, grow, and then melt away. At other times, extensive swamps or vast interior deserts will appear.

We will also witness the first living cells evolving from a primordial organic soup sometime between 4.4 billion years ago, when Earth was cool enough to support life, and 3.5 billion years ago, which is the oldest fossil record of life. Cells with a nucleus will make their first appearance around 1.2 billion years ago, and not long thereafter, multicelled soft-bodied animals will begin populating the world's oceans, followed in relatively short order by animals with skeletons and then by animals with backbones.

Until about 450 million years ago, Earth's landscape was essentially barren and devoid of color. At about that time, however, plants and animals began moving from their home in the seas and oceans to take up residency on land. Viewed from above, Earth's landmasses took on new hues and colors as different life-forms began inhabiting the terrestrial environment. From this point on, Earth will never be the same as plants, insects, amphibians, reptiles, birds, and mammals made the land their home. Near the end of our film, humans will evolve and we will see how their activities greatly impact the global ecosystem. It seems only fitting that the movie's final image will be Earth as a shimmering blue-green oasis outlined against the black void of space and a voiceover saying, "To be continued."

Every good movie has a theme, and the major theme of *The History of Earth* is that Earth is a complex, dynamic planet that has changed continuously since its origin some 4.6 billion years ago. Furthermore, because of the epic nature of our movie, three interrelated subthemes run throughout *The History of Earth*. The first is that Earth's outermost part is composed of a series of moving plates (*plate tectonics*) whose interactions have affected the planet's physical and biological history. The second is that Earth's biota has evolved or changed throughout its history (*organic evolution*). The third is that the physical and biological changes that occurred did so over long periods of time (*geologic* or *deep time*). These three interrelated subthemes are central to our understanding and appreciation of our planet's history, as told in our imaginary movie, and as discussed in this book.

By viewing Earth as a whole—that is, thinking of it as a *system*—we not only see how its various components are interconnected, but can also better appreciate its complex and dynamic nature. The system concept makes it easier for us to study a multifaceted subject, such as Earth, because it divides the whole into smaller components that we can easily understand without losing sight of how the separate components fit together as a whole. In the same way, you can think of this book as a large, panoramic landscape painting. Each chapter fills in the details of the landscape, thereby enhancing the overall enjoyment and understanding of the entire painting.

A **system** is a combination of related parts that interact in an organized manner. We can thus consider Earth as a system of interconnected components, or subsystems, that interact and affect each other in many different ways. The principal subsystems of Earth are the *atmosphere*, *biosphere*, *hydrosphere*, *lithosphere*, *mantle*, and *core* (▶Figure 1.1). The complex interactions among these subsystems result in a dynamically changing planet in which matter and energy are continuously recycled into different forms. For example, the movement of

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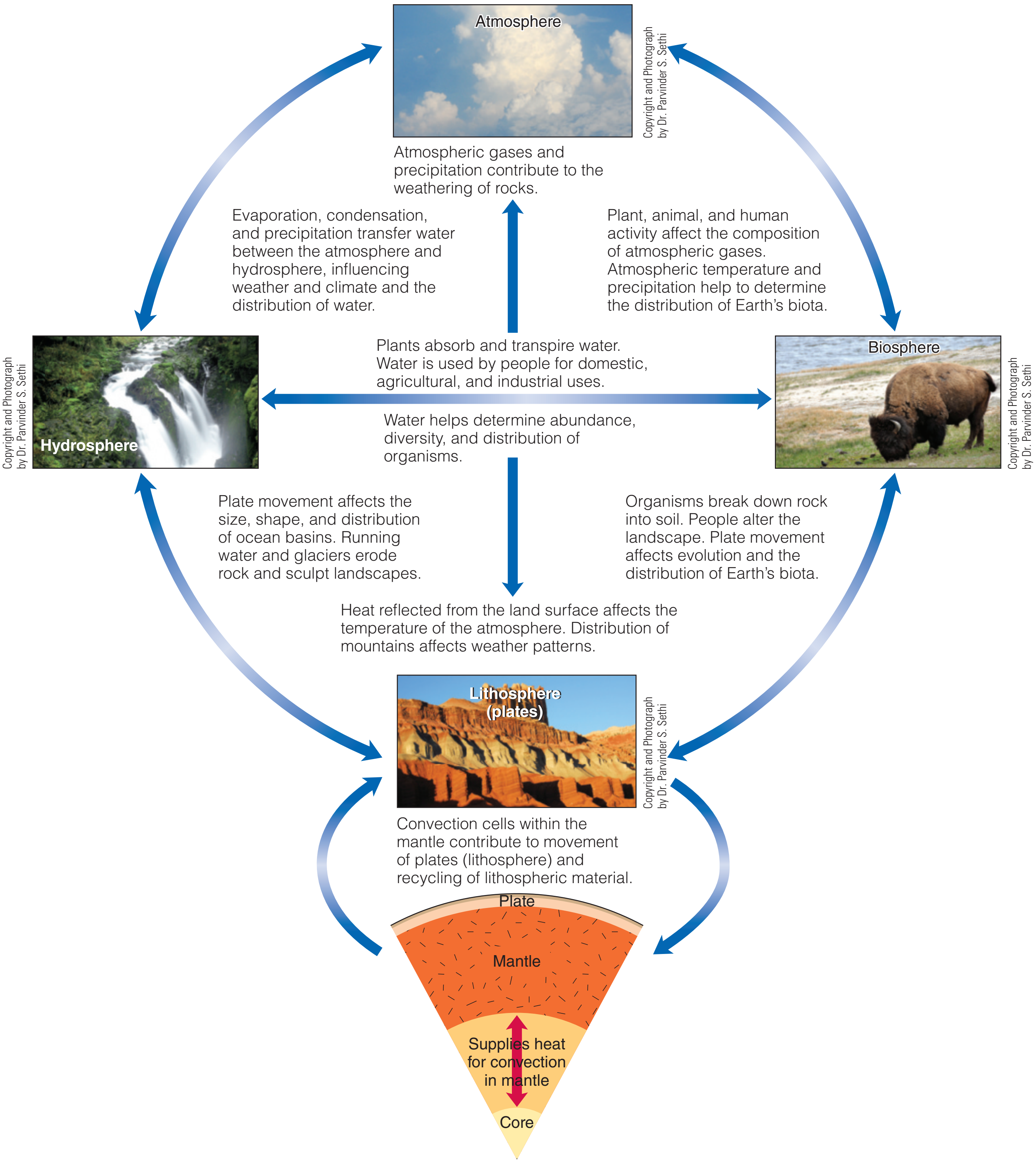

▸**Figure 1.1** **Subsystems of Earth** The atmosphere, hydrosphere, biosphere, lithosphere, mantle, and core are all subsystems of Earth. This simplified diagram shows how these subsystems interact and includes some examples of how materials and energy are cycled throughout the Earth system. The interactions among these subsystems make Earth a dynamic planet that has evolved and changed since its origin 4.6 billion years ago.

plates has profoundly affected the formation and evolution of Earth's surface features and the distribution of mineral resources, as well as atmospheric and oceanic circulation patterns, which, in turn, have affected global climate changes. Examined in this manner, the continuous evolution of Earth and its life is not a series of isolated and unrelated events, but rather a dynamic interplay among its various subsystems.

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What Is Geology?

Geology, from the Greek *geo* and *logos*, is defined as the study of Earth, but now it must include the study of the planets and moons in our solar system—and even beyond our solar system. The discipline of geology is generally divided into two broad areas—physical geology and historical geology. *Physical geology* is the study of Earth materials, such as minerals and rocks, as well as the processes operating within Earth and on its surface. *Historical geology* examines the origin and evolution of Earth, its continents, oceans, atmosphere, and life.

Historical geology is, however, more than just a recitation of past events. It is the study of a dynamic planet that has changed continuously during the past 4.6 billion years. In addition to determining what occurred in the past, geologists are also concerned with explaining how and why past events happened. It is one thing to observe in the fossil record that dinosaurs went extinct, but quite another to ask how and why they became extinct—and perhaps more importantly, what implications that holds for today's global ecosystem.

The basic principles of historical geology not only aid in interpreting Earth's history, but they also have practical applications. For example, William Smith, an English surveyor and engineer, recognized that by studying the sequences of rocks and the fossils they contained, he could predict the kinds and thicknesses of rocks that would have to be excavated in the construction of canals. The same principles Smith used in the late 18th and early 19th centuries are still used today in mineral and oil exploration and also in interpreting the geologic history of the planets and moons of our solar system.

Historical Geology and the Formulation of Theories

The term **theory** has various meanings and is frequently misunderstood and consequently misused. In colloquial usage, it means a speculative or conjectural view of something—hence the widespread belief that scientific theories are little more than unsubstantiated wild guesses. In scientific usage, however, a theory is a coherent explanation for one or several related natural phenomena supported by a large body of objective evidence. From a theory, scientists derive predictive statements that can be tested by observations and/or experiments so that their validity can be assessed.

For example, one prediction of plate tectonic theory is that oceanic crust is youngest near spreading ridges and becomes progressively older with increasing distance from ridges. This prediction has been verified by observations (see Chapter 3). Likewise, according to the theory of evolution, fish should appear in the fossil record before amphibians, followed by reptiles, mammals, and birds—and that is indeed the case (see Chapter 7).

Theories are formulated through the process known as the **scientific method**. This method is an orderly, logical approach that involves gathering and analyzing facts or data about the problem under consideration. Tentative explanations, or **hypotheses**, are then formulated to explain the observed phenomena. Next, the hypotheses are tested to see whether what was predicted actually occurs in a given situation. Finally, if one of the hypotheses is found, after repeated tests, to explain the phenomena, then that hypothesis is proposed as a theory. Remember, however, that in science, even a theory is still subject to further testing and refinement as new data become available.

The fact that a scientific theory can be tested and is subject to such testing separates it from other forms of human inquiry. Because scientific theories can be tested, they have the potential for being supported or even proved wrong. Accordingly, science must proceed without any appeal to beliefs or supernatural explanations, not because such beliefs or explanations are necessarily untrue, but because we have no way to investigate them. For this reason, science makes no claim about the existence or nonexistence of a supernatural or spiritual realm.

Each scientific discipline has certain theories that are of particular importance. For example, the theory of organic evolution revolutionized biology when it was proposed in the 19th century. In geology, the formulation of plate tectonic theory changed the way geologists viewed Earth. Geologists now view Earth from a global perspective in which all of its subsystems and cycles are interconnected, and Earth history is seen as a continuum of interrelated events that are part of a global pattern of change.

Origin of the Universe and Solar System and Earth's Place in the Cosmos

How did the universe begin? What has been its history? What is its eventual fate, or is it infinite? These are just some of the basic questions people have asked and wondered about since they first looked into the nighttime sky and saw the vastness of the universe beyond Earth.

Origin of the Universe—Did It Begin with a Big Bang?

Most scientists think that the universe originated about 14 billion years ago in what is popularly called the **Big Bang**. The Big Bang is a model for the evolution of the universe in which a dense, hot state was followed by expansion, cooling, and a less dense state.

According to modern *cosmology* (the study of the origin, evolution, and nature of the universe), the universe has no edge and therefore no center. Thus, when the universe

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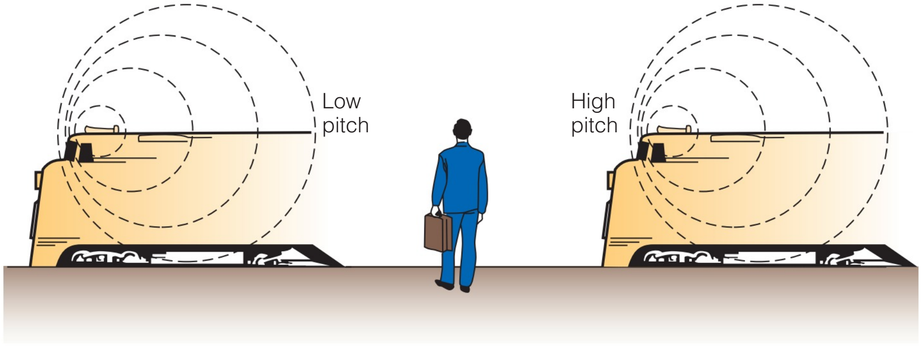
began, all matter and energy were compressed into an infinitely small high-temperature and high-density state in which both time and space were set at zero. Therefore, there is no "before the Big Bang," only what occurred after it. As demonstrated by Einstein's Theory of Relativity, space and time are unalterably linked to form a space–time continuum—that is, without space, there can be no time.



▶**Figure 1.2** **The Doppler Effect** One way to understand the Doppler effect is by analogy to the sound of a passing train's whistle. As the train approaches, the sound waves are compressed slightly so that the individual hears a shorter-wavelength, higher-pitched sound. As the train passes and recedes from the individual, the sound waves are slightly expanded and a longer-wavelength, lower-pitched sound is heard.

How do we know that the Big Bang took place approximately 14 billion years ago? Why couldn't the universe have always existed as we know it today? Two fundamental phenomena indicate that the Big Bang occurred: (1) The universe is expanding, and (2) it is permeated by background radiation.

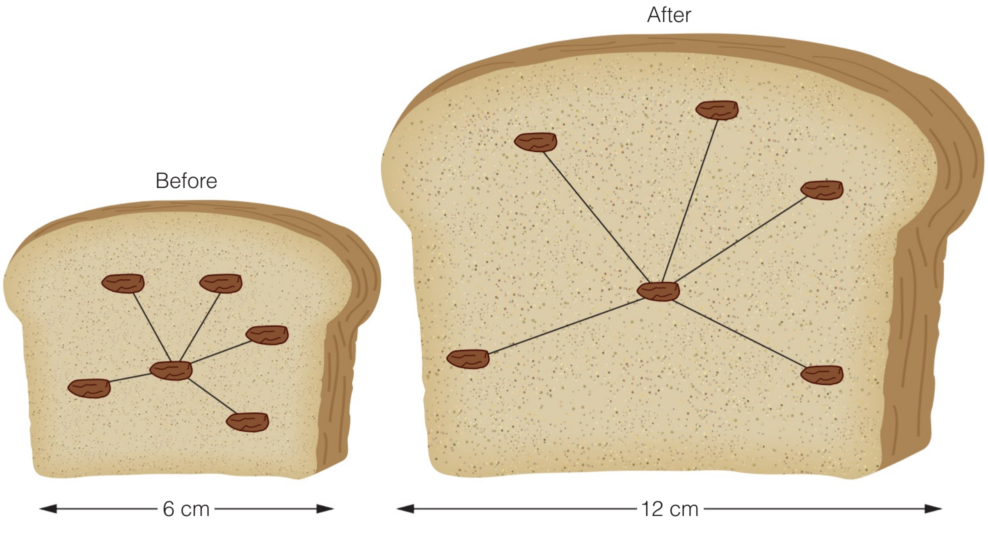
When astronomers look beyond our own solar system, they observe that everywhere in the universe, galaxies are moving away from each other at tremendous speeds. Edwin Hubble first recognized this phenomenon in 1929. By measuring the optical spectra of distant galaxies, Hubble noted that the velocity at which a galaxy moves away from Earth increases proportionally to its distance from Earth. He observed that the spectral lines (wavelengths of light) of the galaxies are shifted toward the red end of the spectrum; that is, the lines are shifted toward longer wavelengths. Galaxies receding from each other at tremendous speeds would produce such a redshift. This is an example of the *Doppler effect*, which is a change in the frequency of a sound, a light, or another wave caused by movement of the wave's source relative to the observer (▶Figure 1.2).

An easy way to envision how velocity increases with increasing distance is by reference to the popular analogy of a rising loaf of raisin bread in which the raisins are uniformly distributed throughout the loaf (▶Figure 1.3). As the dough rises, the raisins are uniformly pushed away from each other at velocities directly proportional to the distance between any two raisins. The farther away a given raisin is to begin with, the farther it must move to maintain the regular spacing during the expansion, and hence the greater its velocity must be.

In the same way that raisins move apart in a rising loaf of bread, galaxies are receding from each other at a rate proportional to the distance between them, which is exactly what astronomers see when they observe the universe. By measuring this expansion rate, astronomers can calculate how long ago the galaxies were all together at a single point, which turns out to be about 14 billion years, the currently accepted age of the universe.

In 1965, Arno Penzias and Robert Wilson of Bell Telephone Laboratories made the second important observation that provided evidence of the Big Bang.

▶**Figure 1.3** **The Expanding Universe** The motion of raisins in a rising loaf of raisin bread illustrates the relationship that exists between distance and speed and is analogous to an expanding universe. In this diagram, adjacent raisins are located 2 cm apart before the loaf rises. After one hour, any raisin is now 4 cm away from its nearest neighbor and 8 cm away from the next raisin over, and so on. Therefore, from the perspective of any raisin, its nearest neighbor has moved away from it at a speed of 2 cm per hour and the next raisin over has moved away from it at a speed of 4 cm per hour. In the same way that raisins move apart in a rising loaf of bread, galaxies are receding from each other at a rate proportional to the distance between them.



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They discovered that there is a pervasive background radiation of 2.7 Kelvin (K) above absolute zero (absolute zero equals −273°C; 2.7 K = −270.3°C) everywhere in the universe. This background radiation is thought to be the fading afterglow of the Big Bang.

Currently, cosmologists cannot say what it was like at time zero of the Big Bang because they do not understand the physics of matter and energy under such extreme conditions. However, it is thought that during the first second following the Big Bang, the four basic forces—(1) *gravity* (the attraction of one body toward another), (2) *electromagnetic force* (combines electricity and magnetism into one force and binds atoms into molecules), (3) *strong nuclear force* (binds protons and neutrons), and (4) *weak nuclear force* (is responsible for the breakdown of an atom's nucleus, producing radioactive decay)—separated and the universe experienced enormous expansion.

As the universe continued expanding and cooling, stars and galaxies began to form and the chemical makeup of the universe changed. Initially, the universe was 100% hydrogen and helium, whereas today it is 98% hydrogen and helium and 2% all other elements by weight (see Perspective).

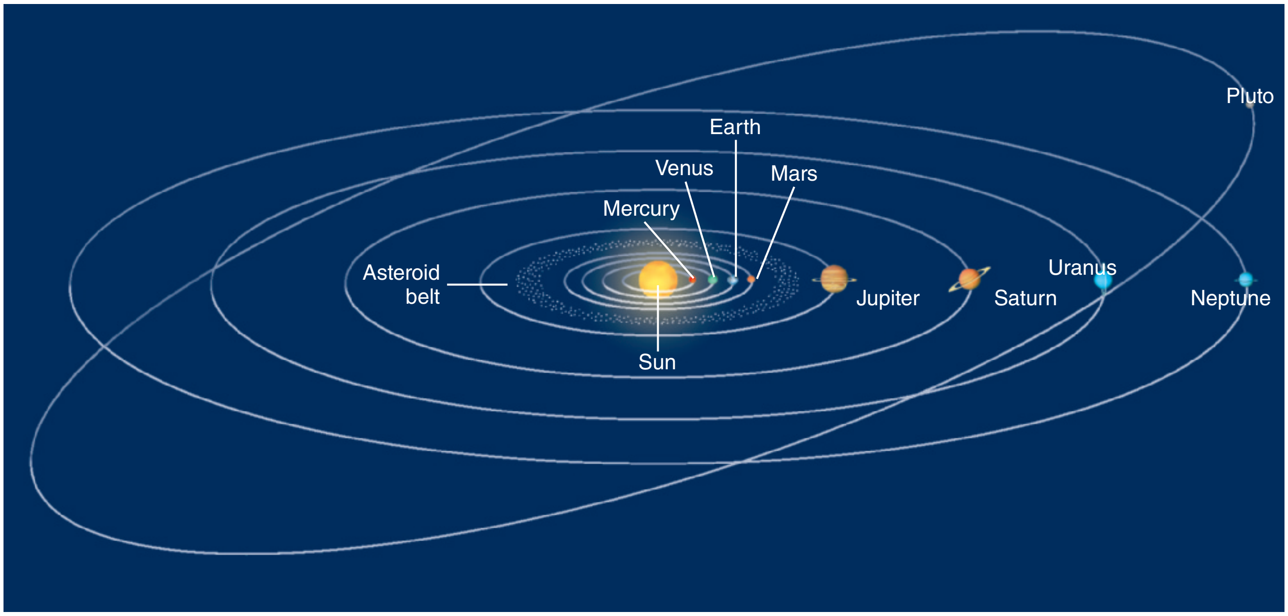
How did such a change in the universe's composition occur? Throughout their life cycle, stars undergo many nuclear reactions in which lighter elements are converted into heavier elements by nuclear fusion. When a star dies, often explosively, the heavier elements that were formed in its core are returned to interstellar space and are available for inclusion in new stars. In this way, the composition of the universe gradually is enhanced by heavier elements.

Our Solar System—Its Origin and Evolution

Our solar system, which is part of the Milky Way Galaxy, consists of the Sun; 8 planets; 5 known dwarf planets (including Pluto); at least 100 known moons or satellites (this number keeps changing with the discovery of new moons and satellites surrounding the Jovian planets); a tremendous number of asteroids—most of which orbit the Sun in a zone between Mars and Jupiter; the Kuiper Belt—a disc-shaped region beyond Neptune where such icy worlds as Pluto reside; and the even more distant Oort Cloud, which is thought to be the source of many of the millions of comets that orbit our Sun (▸Figure 1.4). Any theory formulated to explain the origin and evolution of our solar system must, therefore, take into account all of its various features and characteristics.

Many scientific theories for the origin of the solar system have been proposed, modified, and discarded since the French scientist and philosopher René Descartes first proposed in 1644 that the solar system formed from a gigantic whirlpool within a universal fluid. Today, the **solar nebula theory** for the formation of our solar system not only best explains its features, but also provides a logical explanation for its evolutionary history (▸Figure 1.5).

According to the solar nebula theory, the condensation and subsequent collapse of interstellar material in a spiral arm of the Milky Way galaxy resulted in a counterclockwise-rotating disk of gases and small grains. About 90% of the material was concentrated in the central part of the disk, thus forming an embryonic Sun, around which swirled a rotating cloud of material called a *solar nebula*. Within this



▸**Figure 1.4 Diagrammatic Representation of the Solar System** This representation of the solar system shows the planets and the dwarf planet Pluto and their orbits around the Sun. Pluto orbits among the icy debris of the Kuiper Belt, a disc-shaped region beyond Neptune, in which it and four other dwarf planets are known.

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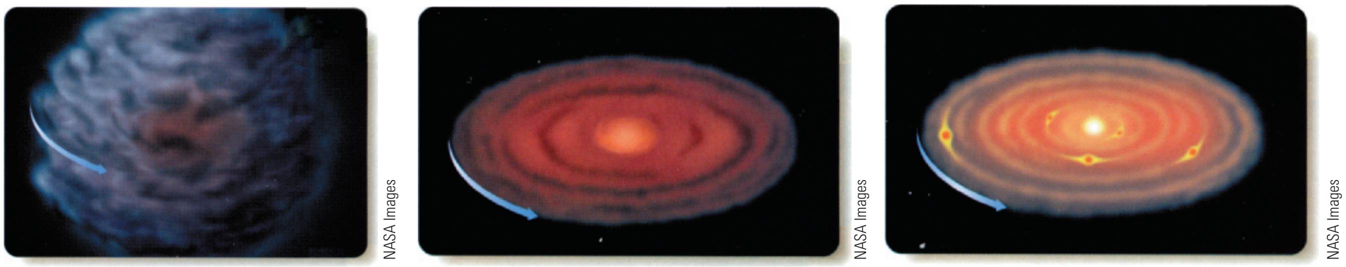


(a) A huge rotating cloud of gas contracts and flattens

(b) to form a disk of gas and dust with the sun forming in the center,

(c) and eddies gathering up material to form planets.

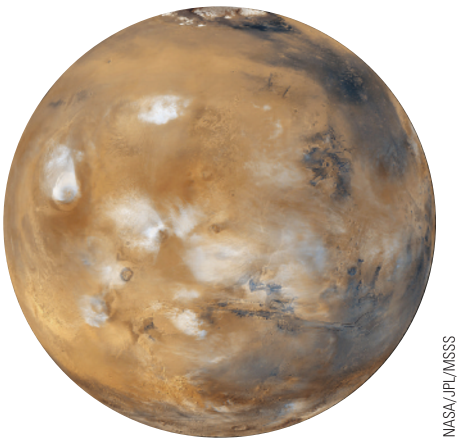
▶**Figure 1.5** **Solar Nebula Theory** According to the currently accepted theory for the origin of our solar system, the planets and the Sun formed from a rotating cloud of gas.

solar nebula were localized eddies where gases and solid particles condensed. During the condensation process, gaseous, liquid, and solid particles began accreting into ever-larger masses called *planetesimals*, which collided and grew in size and mass until they eventually became planets.

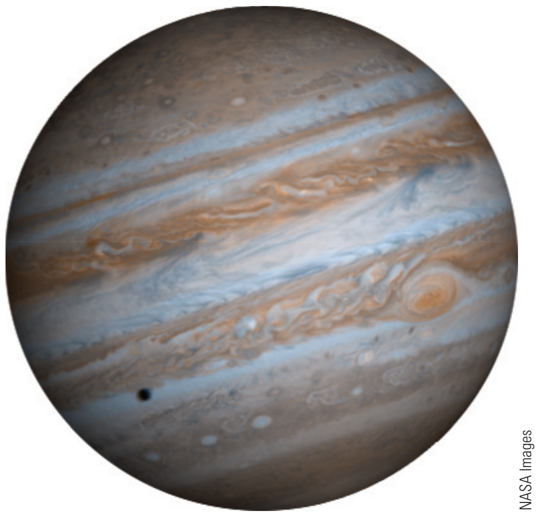
The composition and evolutionary history of the planets are a consequence, in part, of their distance from the Sun. The four inner planets—Mercury, Venus, Earth, and Mars—are the **terrestrial planets**, so named because they are similar to *terra*, Latin for "Earth" (▶Figure 1.6). All of the terrestrial planets are small and dense (composed of a metallic core and silicate mantle-crust), having condensed at the high temperatures of the inner nebula. The **Jovian planets**—Jupiter, Saturn, Uranus, and Neptune—so named because they resemble Jupiter (the Roman god was also named *Jove*), all have small, rocky cores compared to their overall size, and are composed mostly of hydrogen, helium, ammonia, and methane, which condense at low temperatures (▶Figure 1.7).

While the planets were accreting, material that had been pulled into the center of the nebula also condensed, collapsed, and was heated to several million degrees by gravitational compression. The result was the birth of a star, our Sun.

During the early accretionary phase of the solar system's history, collisions between various bodies were common, as indicated by the craters on many planets and moons (▶Figure 1.8). Asteroids probably formed in much the same way as other planetesimals did, but in a localized eddy between what eventually became Mars and Jupiter. The tremendous gravitational field of Jupiter, however, prevented this material from ever accreting into planets. Comets, which are interplanetary bodies composed of loosely bound rocky and icy materials, are thought to have condensed beyond the orbit of Neptune.



▶**Figure 1.6** **Terrestrial Planets** Mars is one of the terrestrial planets, so named because they are similar to Earth. Mars has a thin atmosphere, little water, and distinct seasons. Its southern hemisphere is heavily cratered like the surfaces of Mercury and the Moon. The northern hemisphere has large, smooth plains; fewer craters; and evidence of extensive volcanism. The largest volcano in the solar system is found in the northern hemisphere. Huge canyons, the largest of which, if present on Earth, would stretch from San Francisco to New York, also occur in the northern half of the planet.



▶**Figure 1.7** **Jovian Planets** Jupiter is the largest of the Jovian planets. With its moons, rings, strong magnetic field, and intense radiation belts, it is the most complex and varied planet in our solar system. Jupiter's cloudy and violent atmosphere is divided into a series of different-colored bands and a variety of spots (the Great Red Spot) that interact in incredibly complex motions.

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Exoplanets

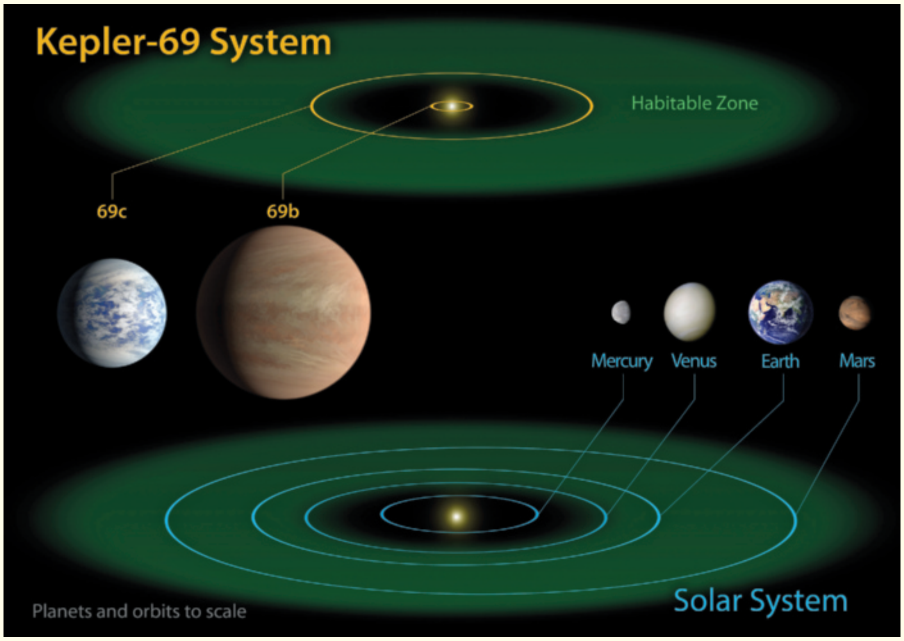
Exoplanets, also known as extrasolar planets, are planets located outside our solar system. Originally hypothesized for several centuries by astronomers and philosophers, it was not until 1988 that the first published discovery of an exoplanet was made by a team of astronomers at the University of Victoria and the University of British Columbia, Canada. Their findings were independently and definitively confirmed in 2003 using improved techniques of detection. Since that initial discovery, there are now more than 1,700 confirmed exoplanets.

Although some exoplanets can be viewed through telescopes, the vast majority are discovered by various indirect methods. This is because the exoplanets do not reflect as much light as stars emit, making them hard to find by traditional telescopic observation. The two most common indirect methods of detecting exoplanets are the (1) *transit method*, in which the amount of visual brightness of a star drops slightly when a planet crosses in front of its parent star disk, and the (2) *radial-velocity method*, by which the variation of a star's orbit, caused by the effect of a planet's gravity, can be measured using the Doppler effect. Both methods have their advantages and disadvantages. Now, however, astronomers have a new statistical technique that they can apply to the transit method to detect stars with multiple planets, thus increasing their accuracy in confirming the presence of new exoplanets.

Besides knowing that there are other planets circling stars in the Milky Way Galaxy, the possibility of discovering Earthlike planets that might support life as we know it is exciting astronomers and scientists throughout the world. To find such planets, astronomers look for planets rotating around a star in what is known as the *habitable zone* or "Goldilocks zone," a region where the temperature allows liquid water to exist. That region would not be too close to a star where it is so hot that water would evaporate, yet not too far away where it is so cold that water would freeze—in other words, just the right distance. This distance varies with the size of the star. For larger and hotter stars, that distance is farther than for smaller and cooler stars. In addition, the components necessary for life would also have to be present for Earthlike life to be able to exist.

Thus far, most of the stars that have exoplanets are similar to our own Sun. Furthermore, the majority of exoplanets tend to be massive, gaseous bodies, the size of Jupiter or larger. However, the latest discoveries point to a significant number of exoplanets that are smaller and more terrestrial-like in nature, with a handful that are Earthlike and orbit within their star's habitable zone (Figure 1).

In February 2014, the United States National Aeronautics and Space Administration (NASA) announced that the Kepler space telescope had discovered 715 new exoplanets orbiting 305 different stars, many of which are multiplanet systems like our own solar system (Figure 2). NASA further reported that nearly 95% of these planets were smaller than Neptune, marking a significant increase in the number of known small-size planets, more similar to the terrestrial rather than



NASA Ames/JPL-Caltech

Figure 1 This diagram compares the planets of our inner solar system (the terrestrial planets) to that of Kepler-69, a two-planet system in the constellation Cygnus, approximately 2,700 light-years away. Kepler-69c is about 70% larger than Earth and is the smallest exoplanet found to date to orbit the habitable zone of a sunlike star. The image of the two Kepler-69 planets is an artistic rendition based on what scientists think the exoplanets might look like.

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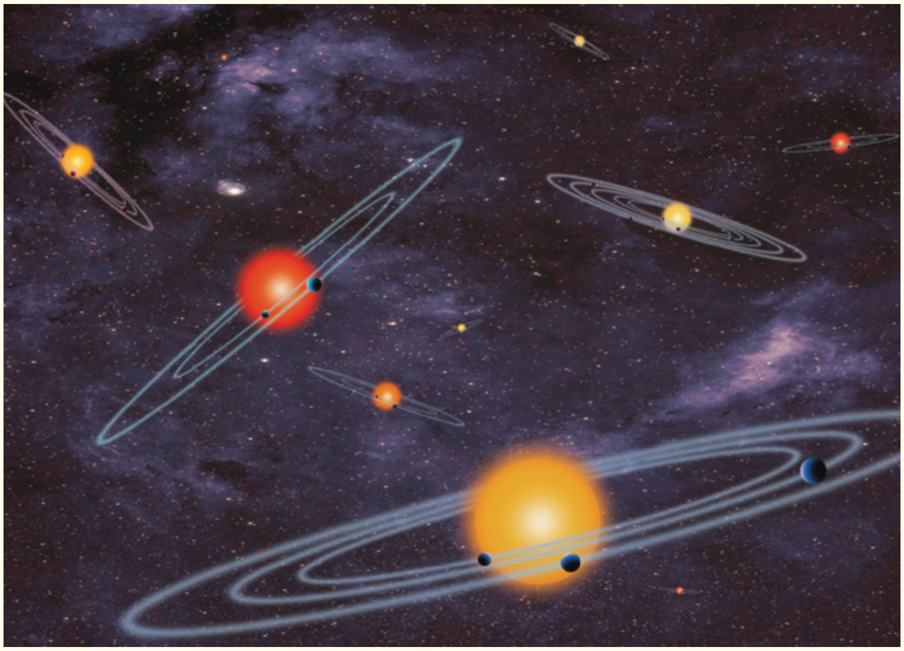

Figure 2 This artistic representation portrays a number of multiple-exoplanet systems, which are stars with more the one exoplanet. This edge-on view shows the exoplanets from the viewpoint of the observer eclipsing or transiting their host star.

the Jovian planets. What made this announcement most exciting was that four of these planets were less than 2.5 times the size of Earth, and orbited within their star's habitable zone.

One of these exoplanets, named Kepler-296f, is twice the size of Earth and orbits a star half the size and 5% as bright as our own Sun. Like the four other habitable-zone exoplanets discovered by the orbiting Kepler space telescope (Figure 3), it is not yet known whether Kepler-296f is a body with a thick hydrogen-helium atmosphere or one that is water-rich, and thus an oceanlike world.

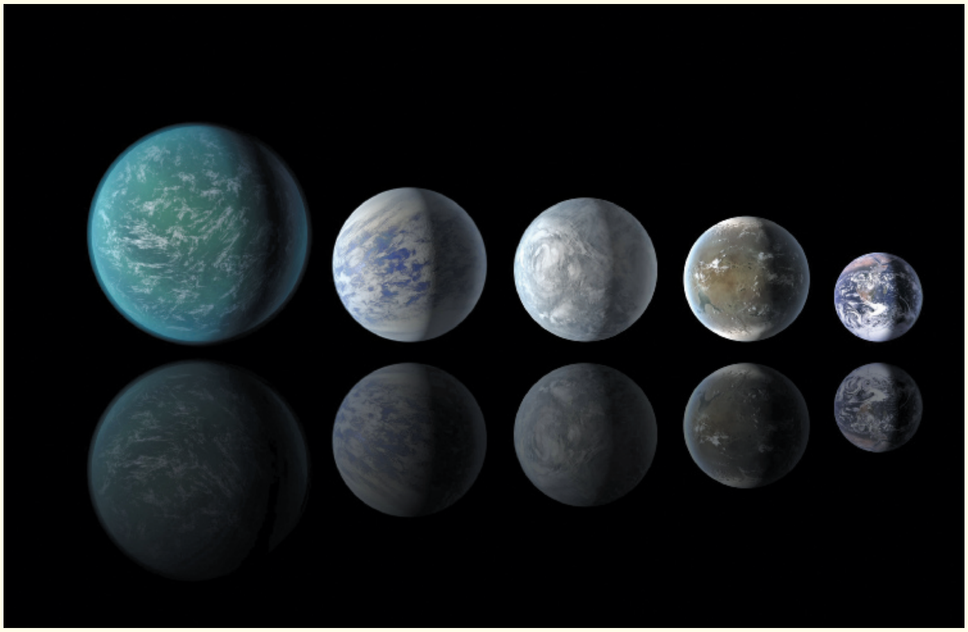

Figure 3 Shown next to Earth for comparison, are the relative sizes of the four habitable-zone exoplanets found to date. From left to right are Kepler-22b, Kepler-69c, Kepler-62e, Kepler-62f, and Earth. All but Earth are artistic renditions. Although scientists do not know whether these exoplanets could support life, they all fall in the habitable-zone orbit of their respective star and thus, could contain liquid water.

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