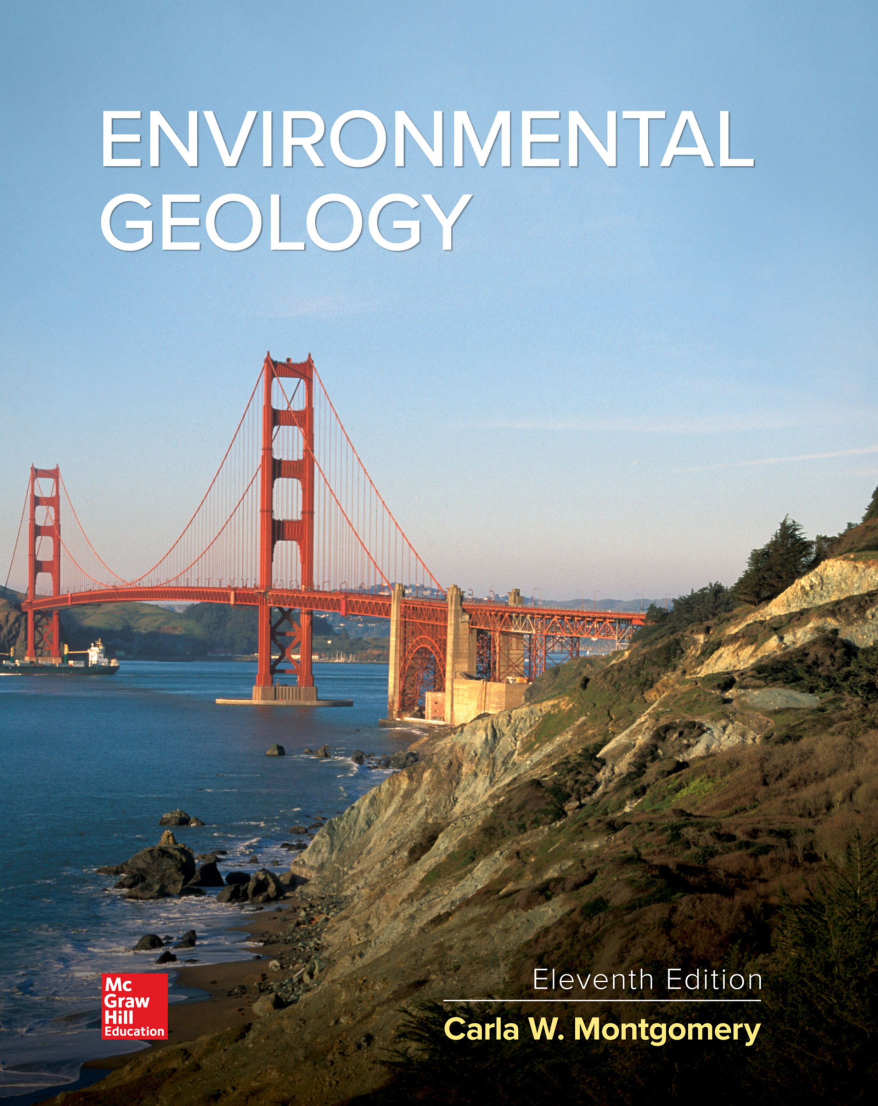
ENVIRONMENTAL GEOLOGY



Eleventh Edition

Carla W. Montgomery

Mc Graw Hill Education

eleventh edition

Environmental Geology

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Professor Emerita
Northern Illinois University

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Education

ENVIRONMENTAL GEOLOGY, ELEVENTH EDITION

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In Dedication

Environmental Geology is affectionately dedicated to the memory of Ed Jaffe, whose confidence in an unknown author made the first edition possible.

—CWM—

Preface

About the Course

Environmental Geology Is Geology Applied to Living

The *environment* is the sum of all the features and conditions surrounding an organism that may influence it. An individual's physical environment encompasses rocks and soil, air and water, such factors as light and temperature, and other organisms. One's social environment might include a network of family and friends, a particular political system, and a set of social customs that affect one's behavior.

Geology is the study of the earth. Because the earth provides the basic physical environment in which we live, all of geology might in one sense be regarded as environmental geology. However, the term *environmental geology* is usually restricted to refer particularly to geology as it relates directly to human activities, and that is the focus of this book. Environmental geology is geology applied to living. We will examine how geologic processes and hazards influence human activities (and sometimes the reverse), the geologic aspects of pollution and waste-disposal problems, and several other topics.

Why Study Environmental Geology?

One reason for studying environmental geology might simply be curiosity about the way the earth works, about the *how* and *why* of natural phenomena. Another reason is that we are increasingly faced with environmental problems to be solved and decisions to be made, and in many cases, an understanding of one or more geologic processes is essential to making informed choices or finding appropriate solutions.

Of course, many environmental problems cannot be fully assessed and solved using geologic data alone. The problems vary widely in size and in complexity. In a specific instance, data from other branches of science (such as biology, chemistry, or ecology), as well as economics, politics, social priorities, and so on may have to be taken into account. Because a variety of considerations may influence the choice of a solution, there is frequently disagreement about which solution is "best." Our personal choices will often depend strongly on our beliefs about which considerations are most important.

About the Book

An introductory text cannot explore all aspects of environmental concerns. Here, the emphasis is on the physical constraints imposed on human activities by the geologic processes that have shaped and are still shaping our natural environment. In a real sense, these are the most basic, inescapable constraints; we cannot, for instance, use a resource that is not there, or build a secure home or a safe dam on land that is fundamentally unstable. Geology, then, is a logical place to start in developing an understanding of many environmental issues. The principal aim of this book is to present the reader with a broad overview of environmental geology. Because geology does not exist in a vacuum, however, the text introduces related considerations from outside geology to clarify other ramifications of the subjects discussed. Likewise, the present does not exist in isolation from the past and future; occasionally, the text looks at both how the earth developed into its present condition and where matters seem to be moving for the future. It is hoped that this knowledge will provide the reader with a useful foundation for discussing and evaluating specific environmental issues, as well as for developing ideas about how the problems should be solved.

Features Designed for the Student

This text is intended for an introductory-level college course. It does not assume any prior exposure to geology or college-level mathematics or science courses. The metric system is used throughout, except where other units are conventional within a discipline. (For the convenience of students not yet "fluent" in metric units, a conversion table is included in Appendix C, and in some cases, metric equivalents in English units are included within the text.)

Each chapter opens with an introduction that sets the stage for the material to follow. In the course of the chapter, important terms and concepts are identified by boldface type, and these terms are collected as "Key Terms and Concepts" at the end of the chapter for quick review. The Glossary includes both these boldface terms and the additional, italicized terms that many chapters contain. Each chapter includes one or more case studies. Some involve a situation, problem, or application that might be encountered in everyday life. Others offer additional case histories or examples relevant to chapter contents. Every chapter concludes with review exercises, which allow students to test their comprehension and apply their knowledge. The "Exploring Further" section of each chapter includes a number of activities in which students can engage, some involving online data, and some, quantitative analysis. For example, they may be directed to examine real-time stream-gaging or landslide-monitoring data, or information on current or recent earthquake activity; they can manipulate historic climate data from NASA to examine trends by region or time period; they may calculate how big a wind farm or photovoltaic array would be required to replace a conventional power plant; they can even learn how to reduce sulfate pollution by buying SO_2 allowances.

Any text of this kind must necessarily be a snapshot in time: The earth keeps evolving and presenting us with new geologic challenges; our understanding of our world advances; our responses to our environment change. And of course, there is vastly more relevant material that might be included than will fit in one volume. To address both of these issues, at least in part, two kinds of online resources have been developed for each chapter. One is "NetNotes," a modest collection of Internet sites that provide additional information and/or images relevant to the chapter content, or may serve as sources of newer data as they become available. The NetNotes should prove useful to both students and instructors. An effort has been made to concentrate on sites with material at an appropriate level for the book's intended audience and also on sites likely to be relatively stable in the very fluid world of the Internet (government agencies, educational institutions, or professional-association sites). The other resource is "Suggested Readings/References," some of which can also be accessed online. These are a mix of background material and articles that feature additional ideas or examples pertinent to the chapter.

New and Updated Content

Environmental geology is, by its very nature, a dynamic field in which new issues continue to arise and old ones to evolve. Every chapter has been updated with regard to data, examples, and figures.

Illustrations Geology is a visual subject, and photographs, satellite imagery, diagrams, and graphs all enhance students' learning. Accordingly, this edition includes more than one hundred new or improved photographs/images and nearly sixty new figures, and revisions have been made to dozens more.

Content additions and revisions to specific chapters include:

Chapter 1 Population data and projections have been updated.

Chapter 2 Case Study 2 updated to reflect the current status of the Libby vermiculite site cleanup.

Chapter 3 Case Study 3 expanded to highlight some remaining questions about the details of plate tectonics.

Chapter 4 New major earthquakes have been added. The phenomenon of slow-slip earthquakes is introduced. Treatment of induced seismicity, especially as related to fracking, is expanded, as is discussion of the hazard represented by the Cascadia subduction zone. Earthquake hazard maps are updated. Results of appeals in the trials connected with the l'Aquila, Italy, earthquake are noted.

Chapter 5 Fractional crystallization as a means of modifying magma composition is added. New information on Yellowstone caldera presented. The deadly 2018 pyroclastic flows at Volcán de Fuego are described. Case Study 5.1 now includes the Kilauea activity that threatened Pahoa in 2014, and the more-extensive and varied activity of 2018.

Chapter 6 Information on more-recent flood events added. Discussions of flash floods, and of the role of hurricanes in inland flooding, expanded. New material on flood warnings.

Chapter 7 Updated with expanded coverage of Hurricane/Superstorm Sandy, including a connection between the damage and climate change, and addition of material on Hurricanes Harvey, Irma, and Maria. Storm tide added to discussion of storm surge.

Chapter 8 Images and discussion of the recent Big Sur, Oso, and Bingham Canyon slides added; coverage of the Attabad slide and Yosemite rockfalls expanded; the Montecito slide added as an illustration of the role of wildfires in increasing slide hazards.

Chapter 9 New data on the dwindling of alpine glaciers presented. Vulnerability of areas around the globe to desertification is illustrated.

Chapter 10 New/updated information on Arctic sea-ice cover, global temperatures, atmospheric CO_2 levels, effects of permafrost melting, heat storage in the oceans. New material on recent trends in temperature and precipitation in the contiguous United States and on the latest Australian heat wave. New section on geoengineering.

Chapter 11 U.S. water-use and groundwater-storage figures updated; new data on soil moisture added. Updates on recent subsidence in the San Joaquin valley and on the state of the Aral Sea. New Case Study 11 focuses on the Colorado River and includes information on the drought-enhanced depletion of Lake Mead.

Chapter 12 Updated data on U.S. soil erosion by wind and water and expanded discussion of changes over the past several decades. Patterns of soil composition across the contiguous 48 states presented.

Chapter 13 All tables of U.S. and world mineral reserves, resources, production, and consumption updated. Expanded coverage of U.S. import dependence, overall and in connection with materials in mobile devices. Case Study 13.1 updates the role of China in world REE supply and the status of the U.S. Mountain Pass mine.

Chapter 14 All data on U.S. and world reserves, and U.S. production and consumption, of fossil fuels updated. Expanded discussion of hydraulic fracturing, including its impact on gas reserves; expanded treatment of the Deepwater Horizon accident. Current status of the debate on oil leasing in the Arctic National Wildlife Reserve noted.

Chapter 15 World energy production by source and consumption projections updated. Current status of the Fukushima cleanup and the effects of the accident on global use of nuclear fission power discussed, with updated figures on power reactors worldwide. Current

U.S. use of renewable energy presented, noting the expanding use of wind power and the effects of western drought on hydropower availability.

Chapter 16 Updates on U.S. and selected other countries' waste-disposal strategies, including recycling; status of radioactive-waste disposal worldwide. New data on numbers of National Priorities List Superfund sites in the United States and on sites with cleanup completed.

Chapter 17 Chapter partially reorganized for better flow. New information on industrial sources of water-pollutant discharge and on water pollution detections in groundwater from municipal wells nationwide. Expanded/updated coverage of mercury in fish and shellfish, and fish consumption advisories in U.S. lakes and streams.

Chapter 18 Updates on U.S. emissions by type and source, with separate treatment of fine particulates, and information on the global effects of fine particulates on health. New data on U.S. air quality and trends, and pH, sulfate, and nitrate in precipitation. Improved presentation of global ozone distribution by season; current status of the Antarctic ozone hole, recent ozone depletion over the Arctic. Case Study 18 includes expanded coverage of radon as an indoor air-pollution hazard, and regional variations in that hazard.

Chapter 19 The Paris Agreement, including key provisions and the status of U.S. involvement, added, together with related data on changes in global CO_2 emissions since 2000, and China's rapidly rising share. Expanded discussion of Arctic land claims for potential resource development. Updated data on ozone-depleting substances and the Montreal Protocol, and Environmental Impact Statement filings. New information on the financial pressures on the federal flood-insurance program in light of recent severe storms. Status of the Keystone XL pipeline project updated in Case Study 19.

Chapter 20 New/updated information on U.S. land cover/use and changes since 1982; U.S. population-density map updated to reflect the latest census. New Case Study 20.2, on the Oroville Dam spillway incident of 2017.

The online "NetNotes" have been checked, all URLs confirmed, corrected, or deleted as appropriate, and new entries have been added for every chapter. The "Suggested Readings/References" have likewise been updated, with some older materials removed and new items added in each chapter.

Organization

The book starts with some background information: a brief outline of earth's development to the present, and a look at one major reason why environmental problems today are so pressing—the large and rapidly growing human population. This is followed by a short discussion of the basic materials of geology—rocks and minerals—and some of their physical properties, which introduces a number of basic terms and concepts that are used in later chapters.

The next several chapters treat individual processes in detail. Those examined in the second section are relatively large-scale processes, which can involve motions and forces in the earth hundreds of kilometers below the surface, and may lead to dramatic, often catastrophic events like earthquakes and volcanic eruptions. Other processes—such as the flow of rivers and glaciers or the blowing of the wind—occur only near the earth's surface, altering the landscape and occasionally causing their own special problems. These are the focus of the third section. In some cases, geologic processes can be modified, deliberately or accidentally; in others, human activities must be adjusted to natural realities. The section on surface processes concludes with a chapter on climate, which connects or affects a number of the surface processes described earlier.

A subject of increasing current concern is the availability of resources. A series of five chapters deals with water resources, soil, minerals, and energy; the rates at which they are being consumed; probable amounts remaining; and projections of future availability and use. Climate change may be affecting the availability and distribution of water resources. In the case of energy resources, we consider both those sources extensively used in the past and new sources that may or may not successfully replace them in the future.

Increasing population and increasing resource consumption lead to an increasing volume of waste to be disposed of; thoughtless or inappropriate waste disposal, in turn, commonly creates increasing pollution. The three chapters of the fifth section examine the interrelated problems of air and water pollution and the strategies available for the disposal of various kinds of wastes.

The final two chapters deal with a more diverse assortment of subjects. Environmental problems spawn laws intended to solve them; chapter 19 looks briefly at a sampling of laws, policies, and international agreements related to geologic matters discussed earlier in the book, and some of the problems with such laws and accords. Chapter 20 examines geologic constraints on construction schemes and the broader issue of trying to determine the optimum use(s) for particular parcels of land—matters that become more pressing as population growth pushes more people to live in marginal places.

Relative to the length of time we have been on earth, humans have had a disproportionate impact on this planet. Appendix A explores the concept of geologic time and its measurement and looks at the rates of geologic and other processes by way of putting human activities in temporal perspective. Appendix B provides short reference keys to aid in rock and mineral identification, and Appendix C includes units of measurement and conversion factors.

Of course, the complex interrelationships among geologic processes and features mean that any subdivision into chapter-sized pieces is somewhat arbitrary, and different instructors may prefer different sequences or groupings (streams and groundwater together, for example). An effort has been made to design chapters so that they can be resequenced in such ways without great difficulty.

Acknowledgments

A great many people have contributed to the development of one edition or another of this book. Portions of the manuscript of the first edition were read by Colin Booth, Lynn A. Brant, Arthur H. Brownlow, Ira A. Furlong, David Huntley, John F. Looney Jr., Robert A. Matthews, and George H. Shaw, and the entire book was reviewed by Richard A. Marston and Donald J. Thompson. The second edition was enhanced through suggestions from Robert B. Furlong, Jeffrey J. Gryta, David Gust, Robert D. Hall, Stephen B. Harper, William N. Mode, Martin Reiter, and Laura L. Sanders; the third, with the assistance of Susan M. Cashman, Robert B. Furlong, Frank Hanna, William N. Mode, Paul Nelson, Laura L. Sanders, and Michael A. Velbel; the fourth, through the input of reviewers Herbert Adams, Randall Scott Babcock, Pascal de Caprariis, James Cotter, Dru Germanoski, Thomas E. Hendrix, Gordon Love, Steven Lund, Michael McKinney, Barbara Ruff, Paul Schroeder, Ali Tabidian, Clifford Thurber, and John Vitek. The fifth edition was improved thanks to reviews by Kevin Cole, Gilbert N. Hanson, John F. Hildenbrand, Ann E. Homes, Alvin S. Konigsberg, Barbara L. Ruff, Vernon P. Scott, Jim Stimson, Michael Whitsett, and Doreen Zaback; the sixth, by reviews from Ray Beiersdorfer, Ellin Beltz, William B. N. Berry, Paul Bierman, W. B. Clapham Jr., Ralph K. Davis, Brian E. Lock, Gregory Hancock, Syed E. Hasan, Scott W. Keyes, Jason W. Kelsey, John F. Looney Jr., Christine Massey, Steve Mattox, William N. Mode, William A. Newman, Clair R. Ossian, David L. Ozsvath, Alfred H. Pekarek, Paul H. Reitan, and Don Rimstidt; and the seventh, by reviewers Thomas J. Algaeo, Ernest H. Carlson, Douglas Crowe, Richard A. Flory, Hari P. Garbharran, Daniel Horns, Ernst H. Kastning, Abraham Lerman, Mark Lord, Lee Ann Munk, June A. Oberdorfer, Assad I. Panah, James S. Reichard, Frederick J. Rich, Jennifer Rivers Coombs, Richard Sleezer, and Michael S. Smith. The eighth edition benefited from suggestions by Richard Aurisano, Thomas B. Boving, Ernest H. Carlson, Elizabeth Catlos, Dennis DeMets, Hailiang Dong, Alexander Gates, Chad Heinzel, Edward Kohut, Richard McGehee, Marguerite Moloney, Lee Slater, and Dan Vaughn, and additional comments by Nathan Yee; the ninth, from reviews by Christine Aide, James Bartholomew, Thomas Boving, Jim Constantopoulos, Mark Groszos, Duke Ophori, Bianca Pedersen, John Rockaway, Kevin Svitana, and Clifford H. Thurber, and input from Mauri Pelto; and the tenth, thanks to reviewers Michael Caudill, Katherine Grote, Lee Slater, Alexis Templeton, Adil Wadia, and Lee Widmer. This eleventh edition, in turn, has been enhanced by thoughtful suggestions and comments from reviewers Alan I. Benimoff, College of Staten Island/CUNY; Richard E. Cowart, Coastal Bend College; James Constantopoulos, Eastern New Mexico University; Marc Defant, University of South Florida; David Roy Dockstader, Jefferson Community and Technical College; Samuel Earman, Millersville University; Kenneth G. Galli, Noah Garrison, University of California; Boston College; Anne Marie Larson Hall, Emory University; Ann Harris, Eastern Kentucky University–Manchester Campus; Alan Hurt, College of the Desert; Amanda M. Hunt, University of Cincinnati Clermont College; Randy S. Kertes, Rider University; Molly D. Minnick, John Wood Community College; Carla S. Murray, Carl Sandburg College; Troy Sampere, McNeese State University; Kevin Svitana, Otterbein University; Alexis Templeton, University of Colorado Boulder; Shannon Wells, Old Dominion University; and Brian Zimmer, Appalachian State University; plus additional feedback from Jack Bloom, Salt Lake Community College, and Peter Nassar, George Washington University.

The input of all of the foregoing individuals, and of many other users who have informally offered additional advice, has substantially improved the text, and their help is most gratefully acknowledged. If, as one reviewer commented, the text "just keeps getting better," a large share of the credit certainly belongs to the reviewers and users. (I only wish that space had permitted me to incorporate all of the excellent ideas that have been offered over the years!) Any remaining shortcomings are, of course, my own responsibility.

M. Dalecheck, C. Edwards, I. Hopkins, and J. McGregor at the USGS Photo Library in Denver provided invaluable assistance with the photo research over the years. The encouragement of a number of my colleagues—particularly Colin Booth, Ron C. Flemal, Donald M. Davidson Jr., R. Kaufmann, and Eugene C. Perry Jr.—was a special help during the development of the first edition. The ongoing support and interest of fellow author, deanly colleague, and ecologist Jerrold H. Zar has been immensely helpful. Thanks are most certainly also due to the thousands of environmental geology students I have taught, many of whom in the early years suggested that I write a text, and whose classes collectively provided a testing ground for many aspects of the presentations herein.

My family has been supportive of this undertaking from the inception of the first edition. A very special vote of appreciation goes to my husband, Warren—ever-patient sounding board, occasional photographer and field assistant—in whose life this book has so often loomed so large.

Last, but assuredly not least, I express my deep gratitude to the entire McGraw-Hill book team and their predecessors for their enthusiasm, professionalism, and just plain hard work, without which successful completion of each subsequent edition of this book would have been impossible.

Carla W. Montgomery

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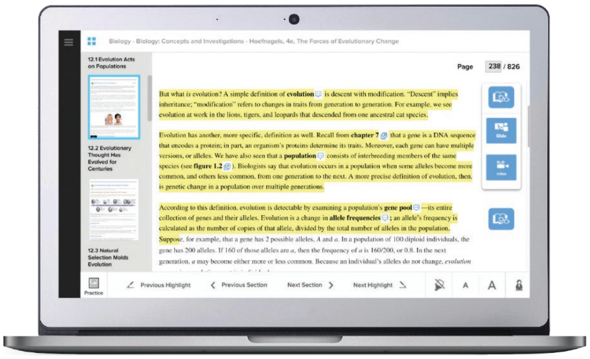

But what *is* evolution? A simple definition of **evolution** is descent with modification. "Descent" implies inheritance; "modification" refers to changes in traits from generation to generation. For example, we see evolution at work in the lions, tigers, and leopards that descended from one ancestral cat species.

Evolution has another, more specific, definition as well. Recall from **chapter 7** that a gene is a DNA sequence that encodes a protein; in part, an organism's proteins determine its traits. Moreover, each gene can have multiple versions, or alleles. We have also seen that a **population** consists of interbreeding members of the same species (see **figure 1.2**). Biologists say that evolution occurs in a population when some alleles become more common, and others less common, from one generation to the next. A more precise definition of evolution, then, is genetic change in a population over multiple generations.

According to this definition, evolution is detectable by examining a population's **gene pool**—its entire collection of genes and their alleles. Evolution is a change in **allele frequencies**; an allele's frequency is calculated as the number of copies of that allele, divided by the total number of alleles in the population. Suppose, for example, that a gene has 2 possible alleles, *A* and *a*. In a population of 100 diploid individuals, the gene has 200 alleles. If 160 of those alleles are *a*, then the frequency of *a* is 160/200, or 0.8. In the next generation, *a* may become either more or less common. Because an individual's alleles do not change, *evolution*

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>
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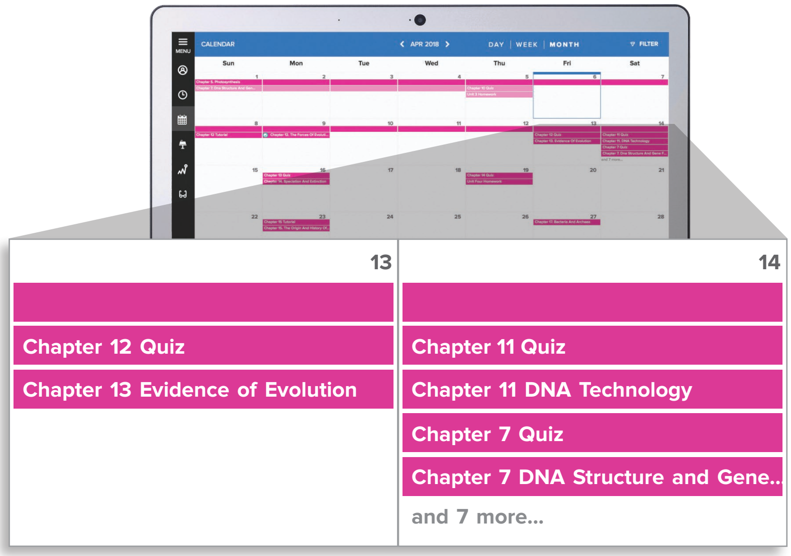

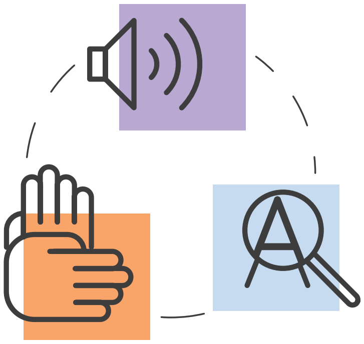

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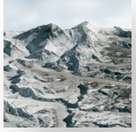

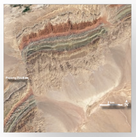

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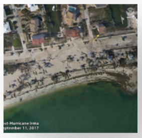

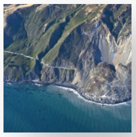

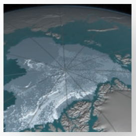

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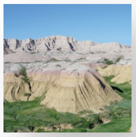

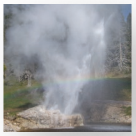

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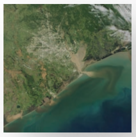

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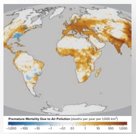

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SECTION I | FOUNDATIONS

CHAPTER 1

Planet and Population: An Overview

About five billion years ago, out of a swirling mass of gas and dust, evolved a system of varied planets hurtling around a nuclear-powered star—our solar system. One of these planets, and one only, gave rise to complex life-forms. Over time, a tremendous diversity of life-forms and ecological systems developed, while the planet, too, evolved and changed, its interior churning, its landmasses shifting, its surface constantly being reshaped. Within the last several million years, the diversity of life on earth has included humans, increasingly competing for space and survival on the planet's surface. With the control over one's surroundings made possible by the combination of intelligence and manual dexterity, humans have found most of the land on the planet inhabitable; they have learned to use not only plant and animal resources, but minerals, fuels, and other geologic materials; in some respects, humans have even learned to modify natural processes that inconvenience or threaten them. As we have learned how to study our planet in systematic ways, we have developed an ever-increasing understanding of the complex nature of the processes shaping, and the problems posed by, our geological environment. **Environmental geology** explores the many and varied interactions between humans and that geologic environment.

As the human population grows, these interactions expand. It becomes increasingly difficult for us to survive on the resources and land remaining, to avoid those hazards that cannot be controlled, and to refrain from making irreversible and undesirable changes in environmental systems. The urgency of perfecting our understanding, not only of natural processes but

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Geology provides the ground we live on, the soil in which our crops are grown, many of the mineral and energy resources on which we depend, and even striking scenery. Over a thousand years ago, the Ancestral Puebloans found shelter and building materials amid the cliffs in what is now Mesa Verde National Park.

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also of our impact on the planet, is becoming more and more apparent worldwide, and has motivated increased international cooperation and dialogue on environmental issues. In 1992, more than 170 nations came together in Rio de Janeiro for the United Nations Conference on Environment and Development, to address such issues as global climate change, sustainable development, and environmental protection. The resultant UN Framework Convention on Climate Change marked the start of a series of meetings and agreements on environmental issues that continues to this day; the most recent such agreement, adopted in Paris in 2016, involves commitment to limit carbon emissions and global warming. These and other environmental accords will be explored further in chapters 17 and 19. For now, we can note that even when nations agree on what the problematic issues are (and this is not always the case!), agreement on solutions is commonly more difficult to achieve, and implementation of those solutions frequently both complex and slow. Meanwhile, global population continues to grow.

1.1 Earth in Space and Time

The Early Solar System

In recent decades, scientists have been able to construct an ever-clearer picture of the origins of the solar system and, before that, of the universe itself. Most astronomers now accept some sort of "Big Bang" as the origin of today's universe. Just before it occurred, all matter and energy would have been compressed into an enormously dense, hot volume a few millimeters (much less than an inch) across. Then everything was flung violently apart across an ever-larger volume of space. The time of the Big Bang can be estimated in several ways. Perhaps the most direct is the back-calculation of the universe's expansion to its apparent beginning. Other methods depend on astrophysical models of creation of the elements or the rate of evolution of different types of stars. Most age estimates overlap in the range of 12 to 14 billion years.

Stars formed from the debris of the Big Bang, as locally high concentrations of mass were collected together by gravity, and some became large and dense enough that energy-releasing atomic reactions were set off deep within them. Stars are not permanent objects. They are constantly losing energy and mass as they burn their nuclear fuel. The mass of material that initially formed the star determines how rapidly the star burns; some stars burned out billions of years ago, while others are probably forming now from the original matter of the universe mixed with the debris of older stars.

Our sun and its system of circling planets, including the earth, are believed to have formed from a rotating cloud of gas and dust (small bits of rock and metal), some of the gas debris from older stars (**figure 1.1**). Most of the mass of the cloud coalesced to form the sun, which became a star and began to "shine," or release light energy, when its interior became so dense and hot from the crushing effects of its own gravity that nuclear reactions were triggered inside it. Meanwhile, dust condensed from the gases remaining in the flattened cloud disk rotating around the young sun. The dust clumped into planets, the formation of which was essentially complete over 4½ billion years ago.

The Planets

The compositions of the planets formed depended largely on how near they were to the hot sun. The planets formed nearest to the sun contained mainly metallic iron and a few minerals with very high melting temperatures, with little water or gas. Somewhat farther out, where temperatures were lower, the

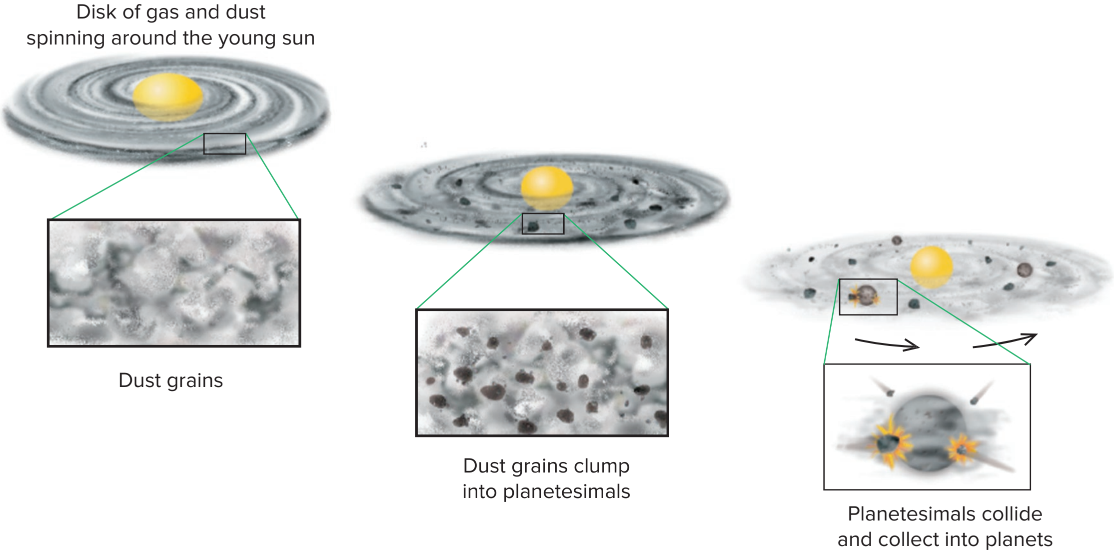


Figure 1.1

Our solar system formed as dust condensed from the gaseous nebula, then clumped together to make planets.

Table 1.1 Some Basic Data on the Planets

Planet	Mean Distance from Sun (millions of km)	Mean Temperature (°C)	Equatorial Diameter, Relative to Earth	Density* (g/cu. cm)	
Mercury	58	167	0.38	5.4	Predominantly rocky/metal planets
Venus	108	464	0.95	5.2	
Earth	150	15	1.00	5.5	
Mars	228	−65	0.53	3.9	
Jupiter	778	−110	11.19	1.3	Gaseous planets
Saturn	1427	−140	9.41	0.7	
Uranus	2870	−195	4.06	1.3	
Neptune	4479	−200	3.88	1.6	

Source: Data from NASA.

*No other planets have been extensively sampled to determine their compositions directly, though we have some data on their surfaces. Their approximate bulk compositions are inferred from the assumed starting composition of the solar nebula and the planets' densities. For example, the higher densities of the inner planets reflect a significant iron content and relatively little gas.

developing planets incorporated much larger amounts of lower-temperature minerals, including some that contain water locked within their crystal structures. (This later made it possible for the earth to have liquid water at its surface.) Still farther from the sun, temperatures were so low that nearly all of the materials in the original gas cloud condensed—even materials like methane and ammonia, which are gases at normal earth surface temperatures and pressures.

The result was a series of planets with a variety of compositions, most quite different from that of Earth. This is confirmed by observations and measurements of the planets. For example, the planetary densities listed in **table 1.1** are consistent with a higher metal and rock content in the four planets closest to the sun and a much larger proportion of ice and gas in the planets farther from the sun (see also **figure 1.2**). These differences should be kept in mind when it is proposed that other planets could be mined for needed minerals. Both the basic chemistry of these other bodies and the kinds of ore-forming or other resource-forming processes that might occur on them would differ considerably from those on Earth, and may not have led to products we would find useful. (This is leaving aside any questions of the economics or technical practicability of such mining activities!) In addition, our principal current energy sources required living organisms to form, and so far, no such life-forms have been found on other planets or moons. Venus—close to Earth in space, similar in size and density—shows marked differences: Its dense, cloudy atmosphere is thick with carbon dioxide, producing planetary surface temperatures hot enough to melt lead through runaway greenhouse-effect heating (see chapter 10). Mars would likewise be inhospitable: It is very cold, and we could not breathe its atmosphere. Though its surface features indicate the presence of liquid water in its past, there is none now, and only small amounts of water ice have been found. There is not so much as a blade of grass for vegetation; the brief flurry of excitement over possible evidence of life on Mars referred only to fossil microorganisms, and more-intensive investigations suggested that the tiny structures in question likely are inorganic, though the search for Martian microbes continues.

Earth, Then and Now

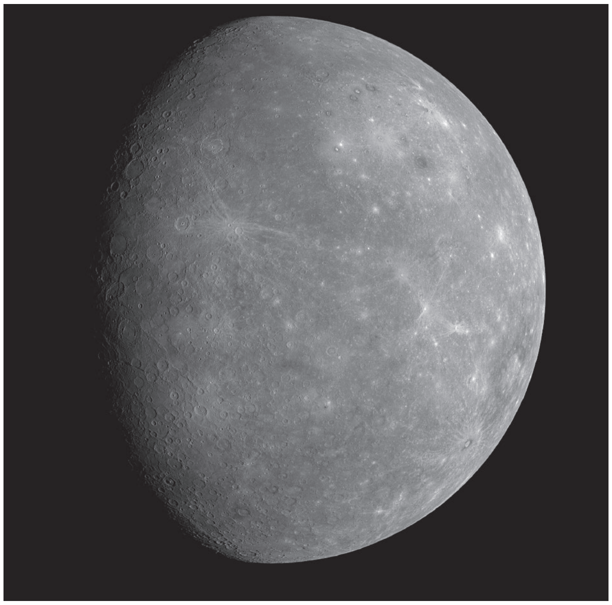
The earth has changed continuously since its formation, undergoing some particularly profound changes in its early history. The early earth was very different from what it is today, lacking the modern oceans and atmosphere and having a much different surface from its present one, probably more closely resembling the barren, cratered surface of the moon. Like other planets, Earth was formed by accretion, as gravity collected together the solid bits that had condensed from the solar nebula. Some water may have been contributed by gravitational capture of icy comets, though recent analyses of modern comets do not suggest that this was a major water source. The planet was heated by the impact of the colliding dust particles and meteorites as they came together to form the earth, and by the energy release from decay of the small amounts of several naturally radioactive elements that the earth contains. These heat sources combined to raise the earth's internal temperature enough that parts of it, perhaps eventually most of it, melted, although it was probably never molten all at once. Dense materials, like metallic iron, would have tended to sink toward the middle of the earth. As cooling progressed, lighter, low-density minerals crystallized and floated out toward the surface. The eventual result was an earth differentiated into several major compositional zones: the central **core,** the surrounding **mantle,** and a thin **crust** at the surface (see **figure 1.3**). The process was complete well before 4 billion years ago.

Although only the crust and a few bits of uppermost mantle that are carried up into the crust by volcanic activity can be sampled and analyzed directly, we nevertheless have a good deal of information on the composition of the earth's interior. First, scientists can estimate from analyses of stars the starting composition of the cloud from which the solar system formed. Geologists can also infer aspects of the earth's bulk composition from analyses of certain meteorites believed to have formed at the same time

Figure 1.2

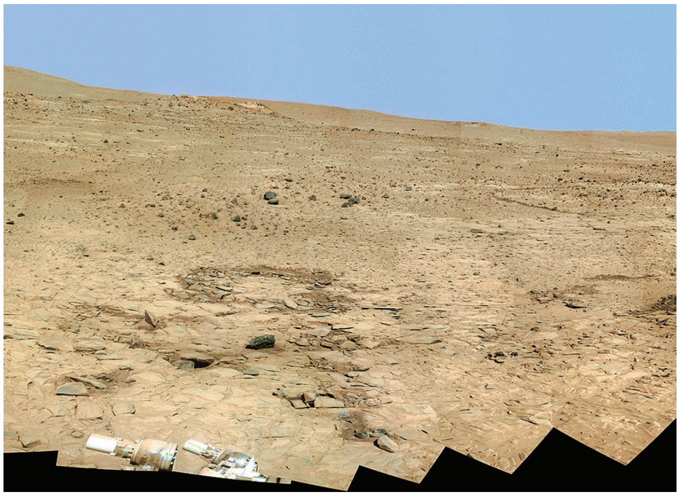
The planets of the solar system vary markedly in both composition and physical properties. For example, Mercury (A), as shown in this image from a 2008 *Messenger* spacecraft flyby, is rocky, iron-rich, dry, and pockmarked with craters. Mars (B) shares many surface features with Earth (volcanoes, canyons, dunes, slumps, stream channels, and more), but the surface is now dry and barren; (C) a 2008 panorama by the Mars rover *Spirit*. Jupiter (D) is a huge gas ball, with no solid surface at all, and dozens of moons of ice and rock that circle it to mimic the solar system in miniature. Note also the very different sizes of the planets (E). The Jovian planets—named for Jupiter—are gas giants; the terrestrial planets are more rocky, like Earth.

Sources: (A) NASA image courtesy Science Operations Center at Johns Hopkins University Applied Physics Laboratory; (B) NASA; (C) Image courtesy NASA/JPL/Cornell; (D) NSSDC Goddard Space Flight Center; (E) NASA.



A

B



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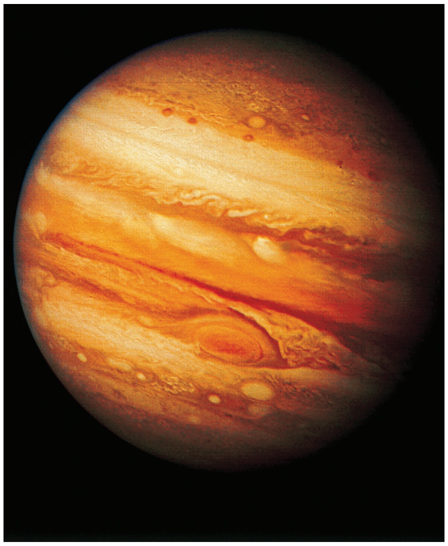

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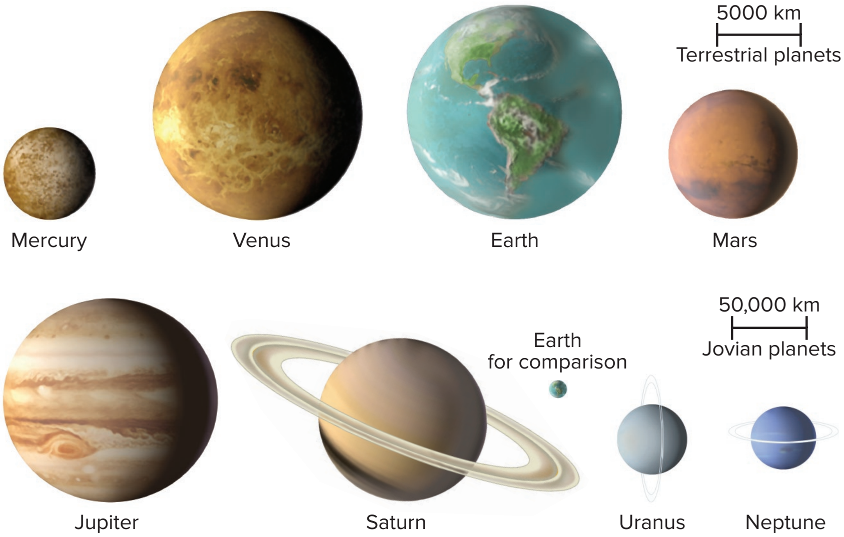

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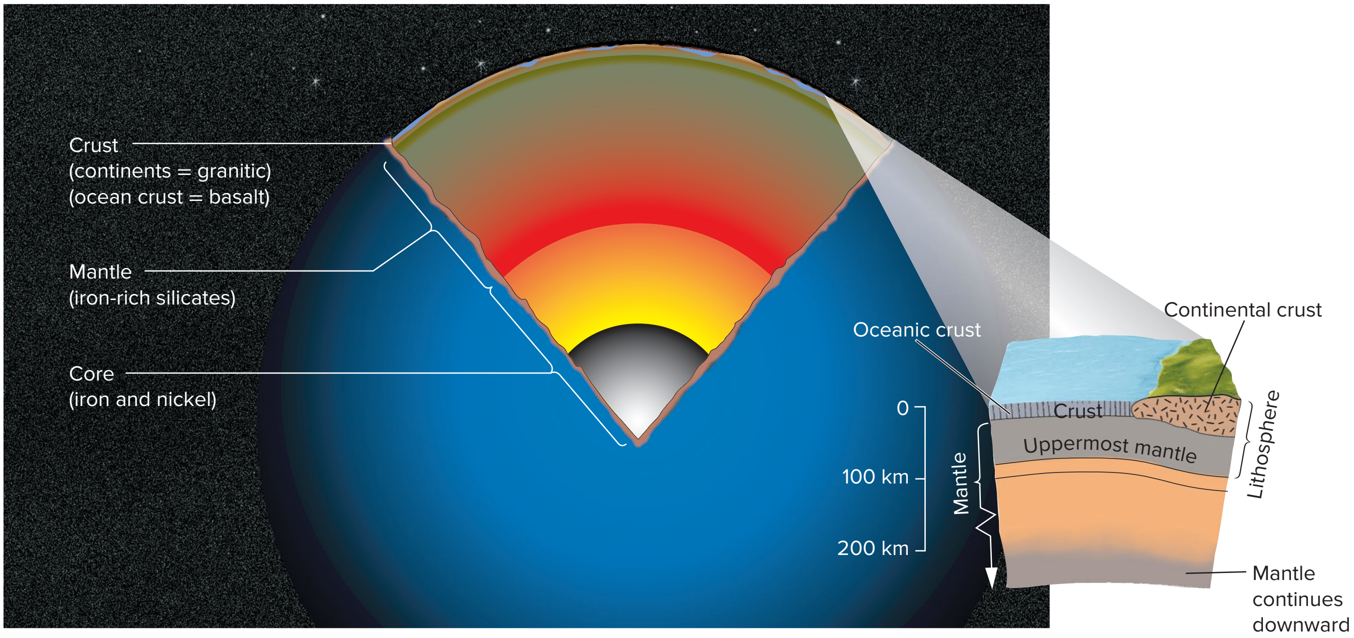

Figure 1.3

A chemically differentiated Earth. The core consists mostly of iron; the outer part is molten. The mantle, the largest zone, is made up primarily of ferromagnesian silicates (see chapter 2) and, at great depths, of oxides of iron, magnesium, and silicon. The crust (not drawn to scale, but exaggerated vertically in order to be visible at this scale) forms a thin skin around the earth. Oceanic crust, which forms the sea floor, has a composition somewhat like that of the mantle, but is richer in silicon. Continental crust is both thicker and less dense. It rises above the oceans and contains more light minerals rich in calcium, sodium, potassium, and aluminum. The "plates" of plate tectonics (the lithosphere) comprise the crust and uppermost mantle. (100 km ≈ 60 miles)

as, and under conditions similar to, the earth. Geophysical data demonstrate that the earth's interior is zoned and also provide information on the densities of the different layers within the earth, which further limits their possible compositions. These and other kinds of data indicate that the earth's core is made up mostly of iron, with some nickel and a few minor elements; the outer core is molten, the inner core solid. The mantle consists mainly of iron, magnesium, silicon, and oxygen combined in varying proportions in several different minerals. The earth's crust is much more varied in composition and very different chemically from the average composition of the earth (see **table 1.2**). As is evident from this table, many of the metals we have come to prize as resources are relatively uncommon elements in the crust. Crust and uppermost mantle together form a somewhat brittle shell around the earth.

The heating and subsequent differentiation of the early earth led to another important result: formation of the atmosphere and oceans. Many minerals that had contained water or gases in their crystals released them during the heating and melting, and as the earth's surface cooled, the water could condense to form the oceans. Without this abundant surface water, which in the solar system is unique to Earth, most life as we know it could not exist. The oceans filled basins, while the continents, buoyant because of their lower-density rocks and minerals, stood above the sea surface. At first, the continents were barren of life.

The earth's early atmosphere was quite different from the modern one, aside from the effects of modern pollution. The first atmosphere had little or no free oxygen in it. It probably consisted dominantly of nitrogen and carbon dioxide (the gas most commonly released from volcanoes, aside from water) with minor amounts of such gases as methane, ammonia, and various sulfur gases. Humans could not have survived in this early atmosphere. Oxygen-breathing life of any kind could not exist before the single-celled blue-green algae appeared in large

Table 1.2 **Most Common Chemical Elements in the Earth**

WHOLE EARTH		CRUST	
Element	**Weight Percent**	**Element**	**Weight Percent**
Iron	32.4	Oxygen	46.6
Oxygen	29.9	Silicon	27.7
Silicon	15.5	Aluminum	8.1
Magnesium	14.5	Iron	5.0
Sulfur	2.1	Calcium	3.6
Nickel	2.0	Sodium	2.8
Calcium	1.6	Potassium	2.6
Aluminum	1.3	Magnesium	2.1
(All others, total)	.7	(All others, total)	1.5

(Compositions cited are averages of several independent estimates.)

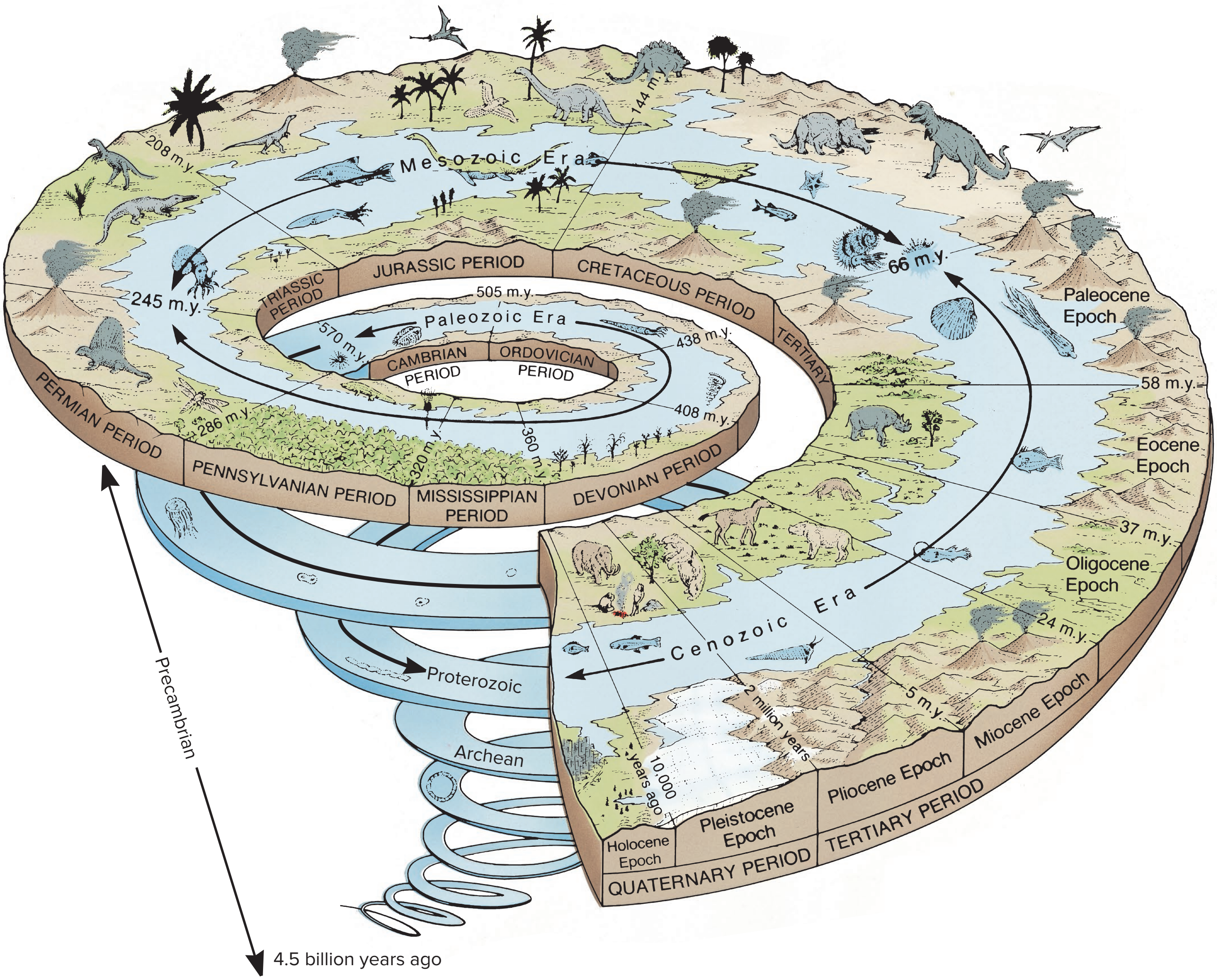

Figure 1.4

The "geologic spiral": Important plant and animal groups appear where they first occurred in significant numbers. If earth's whole history were equated to a 24-hour day, modern thinking humans *(Homo sapiens)* would have arrived on the scene just about six seconds ago. For another way to look at these data, see table A.1 in appendix A.

Source: Modified after U.S. Geological Survey publication Geologic Time.

numbers to modify the atmosphere. Their remains are found in rocks as much as several billion years old. They manufacture food by photosynthesis, using sunlight for energy, consuming carbon dioxide, and releasing oxygen as a by-product. In time, enough oxygen accumulated that the atmosphere could support oxygen-breathing organisms.

Life on Earth

The rock record shows when different plant and animal groups appeared. Some are represented schematically in **figure 1.4**. The earliest creatures left very few remains because they had no hard skeletons, teeth, shells, or other hard parts that could be preserved in rocks. The first multicelled oxygen-breathing creatures probably developed about 1 billion years ago, after oxygen in the atmosphere was well established. By about 550 million years ago, marine animals with shells had become widespread.

The development of organisms with hard parts—shells, bones, teeth, and so on—greatly increased the number of preserved animal remains in the rock record; consequently, biological developments since that time are far better understood. Dry land was still barren of large plants or animals half a billion years ago. In rocks about 500 million years old is the first evidence of animals with backbones—the fish—and soon thereafter, early land plants developed, before 400 million years ago. Insects appeared approximately 300 million years ago. Later, reptiles and amphibians moved onto the continents. The dinosaurs appeared about 200 million years ago and the first mammals at nearly the same time. Warm-blooded animals took to the air with the development of birds about 150 million years ago, and by 100 million years ago, both birds and mammals were well established.

Such information has current applications. Certain energy sources have been formed from plant or animal remains. Knowing the times at which particular groups of organisms appeared and flourished is helpful in assessing the probable amounts of these energy sources available and in concentrating the search for these fuels on rocks of appropriate ages.

On a timescale of billions of years, human beings have just arrived. The most primitive human-type remains are no more than 4 to 5 million years old, and modern, rational humans *(Homo sapiens)* developed only about half a million years ago. Half a million years may sound like a long time, and it is if compared to a single human lifetime. In a geologic sense, though, it is a very short time. If we equate the whole of earth's history to a 24-hour day, then shelled organisms appeared only about 3 hours ago; fish, about 2 hours and 40 minutes ago; land plants, 2 hours ago; birds, about 45 minutes ago—and *Homo sapiens* has been around for just the last 6 *seconds*. Nevertheless, we humans have had an enormous impact on the earth, at least at its surface, an impact far out of proportion to the length of time we have occupied it. Our impact is likely to continue to increase rapidly as the population does likewise.

1.2 Geology, Past and Present

Two centuries ago, geology was mainly a descriptive science involving careful observation of natural processes and their products. The subject has become both more quantitative and more interdisciplinary through time. Modern geoscientists draw on the principles of chemistry to interpret the compositions of geologic materials, apply the laws of physics to explain these materials' physical properties and behavior, use the biological sciences to develop an understanding of ancient life-forms, and rely on engineering principles to design safe structures in the presence of geologic hazards. The emphasis on the "why," rather than just the "what," has also increased.

The Geologic Perspective

Geologic observations now are combined with laboratory experiments, careful measurements, and calculations to develop theories of how natural processes operate. Geology is especially challenging because of the disparity between the scientist's laboratory and nature's. In the research laboratory, conditions of temperature and pressure, as well as the flow of chemicals into or out of the system under study, can be carefully controlled. One then knows just what has gone into creating the product of the experiment. In nature, the geoscientist is often confronted only with the results of the "experiment" and must deduce the starting materials and processes involved.

Another complicating factor is time. The laboratory scientist must work on a timescale of hours, months, years, or, at most, decades. Natural geologic processes may take a million or a billion years to achieve a particular result, by stages too slow even to be detected in a human lifetime (**table 1.3**). This understanding may be one of the most significant contributions of early geoscientists: the recognition of the vast length of geologic history, sometimes described as "deep time." The qualitative and quantitative tools for sorting out geologic events and putting dates on them are outlined in appendix A. For now, it is useful to bear in mind that the immensity of geologic time can make it difficult to arrive at a full understanding of how geologic processes operated in the past from observations made on a human timescale. It dictates caution, too, as we try to project, from a few years' data on global changes associated with human activities, all of the long-range impacts we may be causing.

Also, the laboratory scientist may conduct a series of experiments on the same materials, but the experiments can be stopped and those materials examined after each stage. Over the vast spans of geologic time, a given mass of earth material may have been transformed a half-dozen times or more, under different conditions each time. The history of the rock that ultimately results may be very difficult to decipher from the end product alone.

Table 1.3 **Some Representative Geologic-Process Rates**

Process	Occurs Over a Time Span of About This Magnitude
Rising and falling of tides	1 day
"Drift" of a continent by 2–3 centimeters (about 1 inch)	1 year
Accumulation of energy between large earthquakes on a major fault zone	10–100 years
Rebound (rising) by 1 meter of a continent depressed by ice sheets during the Ice Age	100 years
Flow of heat through 1 meter of rock	1000 years
Deposition of 1 centimeter of fine sediment on the deep-sea floor	1000–10,000 years
Ice sheet advance and retreat during an ice age	10,000–100,000 years
Life span of a small volcano	100,000 years
Life span of a large volcanic center	1–10 million years
Creation of an ocean basin such as the Atlantic	100 million years
Duration of a major mountain-building episode	100 million years
History of life on earth	Over 3 billion years

Geology and the Scientific Method

The **scientific method** is a means of discovering basic scientific principles. One begins with a set of observations and/or a body of data, based on measurements of natural phenomena or on experiments. One or more *hypotheses* are formulated to explain the observations or data. A **hypothesis** can take many forms, ranging from a general conceptual framework or model describing the functioning of a natural system, to a very precise mathematical formula relating several kinds of numerical data. What all hypotheses have in common is that they must all be susceptible to testing and, particularly, to *falsification.* The idea is not simply to look for evidence to support a hypothesis, but to examine relevant evidence with the understanding that it may show the hypothesis to be wrong.

In the classical conception of the scientific method, one uses a hypothesis to make a set of predictions. Then one devises and conducts experiments to test each hypothesis, to determine whether experimental results agree with predictions based on the hypothesis. If they do, the hypothesis gains credibility. If not, if the results are unexpected, the hypothesis must be modified to account for the new data as well as the old or, perhaps, discarded altogether. Several cycles of modifying and retesting hypotheses may be required before a hypothesis that is consistent with all the observations and experiments that one can conceive is achieved. A hypothesis that is repeatedly supported by new experiments advances in time to the status of a **theory,** a generally accepted explanation for a set of data or observations.

Much confusion can arise from the fact that in casual conversation, people often use the term *theory* for what might better be called a hypothesis, or even just an educated guess. ("So, what's your theory?" one character in a TV mystery show may ask another, even when they've barely looked at the first evidence.) Thus, people may assume that a scientist describing a theory is simply telling a plausible story to explain some data. A scientific theory, however, is a very well-tested model with a very substantial and convincing body of evidence that supports it. A hypothesis may be advanced by just one individual; a theory has survived the challenge of extensive testing to merit acceptance by many, often most, experts in a field. The Big Bang theory is not just a creative idea. It accounts for the decades-old observation that all the objects we can observe in the universe seem to be moving apart. If it is correct, the universe's origin was very hot; scientists have detected the cosmic microwave background radiation consistent with this. And astrophysicists' calculations predict that the predominant elements that the Big Bang would produce would be hydrogen and helium—which indeed overwhelmingly dominate the observed composition of our universe.

The classical scientific method is not strictly applicable to many geologic phenomena because of the difficulty of experimenting with natural systems, given the time and scale considerations noted earlier. For example, one may be able to conduct experiments on a single rock, but not to construct a whole volcano in the laboratory, nor to replicate a large meteorite impact (like that of **figure 1.5**) to study its effects. In such cases, hypotheses are often tested entirely through further observations or theoretical calculations and modified as necessary until they accommodate all the relevant observations (or are discarded when they cannot be reconciled with new data). This broader conception of the scientific method is well illustrated by the development of the theory of plate tectonics, discussed in chapter 3. "Continental drift" was once seen as a wildly implausible idea, advanced by an eccentric few, but in the latter half of the twentieth century, many kinds of evidence were found to be explained consistently and well by movement of plates—including continents—over earth's surface. Still, the details of plate tectonics continue to be refined by further studies. Even a well-established theory may ultimately be proved incorrect. (Plate tectonics in fact supplanted a very different theory about how mountain ranges form.) In the case of geology, complete rejection of an older theory has most often been caused by the development of new analytical or observational techniques, which make available wholly new kinds of data that were unknown at the time the original theory was formulated.

Figure 1.5

Meteor Crater, Arizona.

Source: U.S. Geological Survey/Photograph by David J. Roddy, USGS Branch of Astrogeology.

The Motivation to Find Answers

In spite of the difficulties inherent in trying to explain geologic phenomena, the search for explanations goes on, spurred not only by the basic quest for knowledge, but also by the practical problems posed by geologic hazards, the need for resources, and concerns about possible global-scale human impacts, such as ozone destruction and global warming.

The hazards may create the most dramatic scenes and headlines, the most abrupt consequences: The 1989 Loma Prieta (California) earthquake caused more than $5 billion in damage; the 1995 Kobe (Japan) earthquake (**figure 1.6**), similar in size to Loma Prieta, caused over 5200 deaths and about $100 billion in property damage; the 2004 Sumatran earthquake claimed nearly 300,000 lives; the 2011 quake offshore from

Figure 1.6

Overturned section of Hanshin Expressway, eastern Kobe, Japan, after 1995 earthquake. This freeway, elevated to save space, was built in the 1960s to then-current seismic design standards.

Source: Photograph by Christopher Rojahn, Applied Technology Council.

Honshu, Japan, killed over 15,000 people and caused an estimated $300 billion in damages. The 18 May 1980 eruption of Mount St. Helens (**figure 1.7**) took even the scientists monitoring the volcano by surprise, and the 1991 eruption of Mount Pinatubo in the Philippines not only devastated local residents but caught the attention of the world through a marked decline in 1992 summer temperatures. Efforts are underway to provide early warnings of such hazards as earthquakes, volcanic eruptions, and landslides so as to save lives, if not property. Likewise, improved understanding of stream dynamics and more prudent land use can together reduce the damages from flooding (**figure 1.8**), which amount in the United States to over $1 billion a year and the loss of dozens of lives annually. Landslides and other slope and ground failures (**figure 1.9**) take a similar toll in property damage, which could be reduced by more attention to slope stability and improved engineering practices. It is not only the more dramatic hazards that are costly: On average, the cost of structural damage from unstable soils each year approximately equals the combined costs of landslides, earthquakes, and flood damages in this country.

Figure 1.7

Ash pours from Mount St. Helens, May 1980.

Source: U.S. Geological Survey/Photograph by Peter Lipman.

Figure 1.8

A major river like the Mississippi floods when a large part of the area that it drains is waterlogged by more rain or snowmelt than can be carried away in the channel. Such floods—like that in summer 1993, shown here drenching Jefferson City, Missouri—can be correspondingly long-lasting. Over millennia, the stream builds a floodplain into which the excess water naturally flows; we build there at our own risk.

Source: Photograph by Mike Wright, courtesy Missouri Department of Transportation.

It is worth noting that as scientists become better able to predict such events as earthquakes and volcanic eruptions, new challenges arise: How certain should they be before a prediction is issued? How best to educate the public—and public officials—about the science behind the predictions and its limitations, so that they can prepare/respond appropriately? What if a prediction is wrong? Such issues will be examined in later chapters.

Our demand for resources of all kinds continues to grow and so do the consequences of resource use. In the United States, average per-capita water use is 1500 gallons per day; in many places, groundwater supplies upon which we have come to rely heavily are being measurably depleted. Worldwide, water-resource disputes between nations are increasing in number.