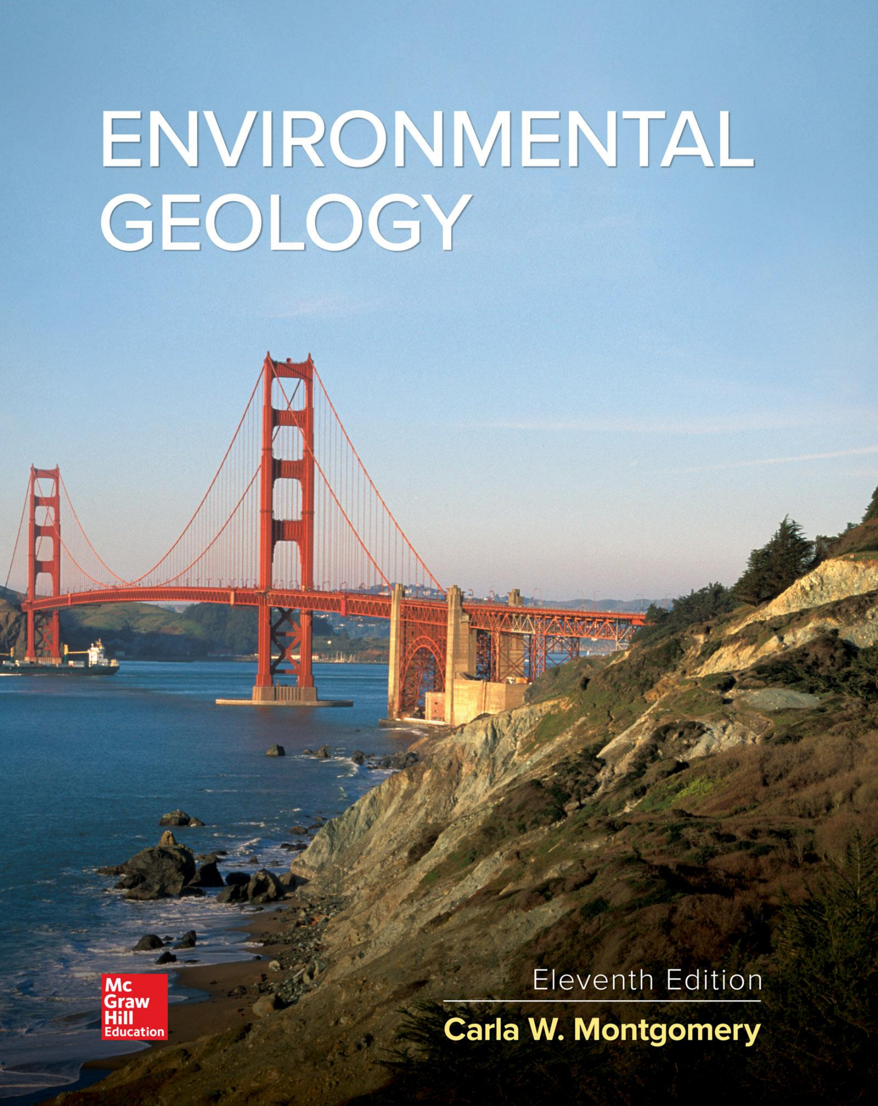


ENVIRONMENTAL GEOLOGY

Eleventh Edition

Carla W. Montgomery

Mc Graw Hill Education

eleventh edition

Environmental Geology

Carla W. Montgomery
Professor Emerita
Northern Illinois University

McGraw Hill Education

ENVIRONMENTAL GEOLOGY, ELEVENTH EDITION

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LWI 21 20 19

ISBN 978-0-07-802295-1 (bound edition)
MHID 0-07-802295-9 (bound edition)
ISBN 978-1-260-47114-4 (loose-leaf edition)
MHID 1-260-47114-4 (loose-leaf edition)

Portfolio Manager: *Michael Ivanov, PhD*
Product Developer: *Krystal Faust*
Marketing Manager: *Kelly Brown*
Content Project Managers: *Ann Courtney/Rachael Hillebrand*
Buyer: *Laura Fuller*
Design: *Egzon Shaqiri*
Content Licensing Specialist: *Shawntel Schmitt*
Cover Image: ©*John A. Karachewski*
Compositor: *MPS Limited*

All credits appearing on page are considered to be an extension of the copyright page.

Library of Congress Cataloging-in-Publication Data

Montgomery, Carla W., 1951- author.
  Environmental geology / Carla W. Montgomery (professor emerita,
  Northern Illinois University).
  Eleventh edition. | New York, NY : McGraw-Hill Education, [2020] |
  Includes index.
  LCCN 2018041730 | ISBN 9780078022951 (student edition : alk. paper)
  LCSH: Environmental geology.
  LCC QE38 .M66 2020 | DDC 550--dc23
  LC record available at https://lccn.loc.gov/2018041730

mheducation.com/highered

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

Mc Graw Hill Education **connect**®

Students—study more efficiently, retain more and achieve better outcomes. Instructors—focus on what you love—teaching.

SUCCESSFUL SEMESTERS INCLUDE CONNECT

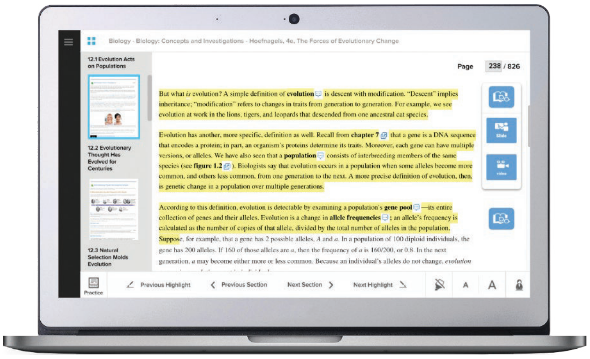
FOR INSTRUCTORS

You're in the driver's seat.

Want to build your own course? No problem. Prefer to use our turnkey, prebuilt course? Easy. Want to make changes throughout the semester? Sure. And you'll save time with Connect's auto-grading too.

65%

Less Time Grading



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*

They'll thank you for it.

Adaptive study resources like SmartBook® help your students be better prepared in less time. You can transform your class time from dull definitions to dynamic debates. Hear from your peers about the benefits of Connect at **www.mheducation.com/highered/connect**

Make it simple, make it affordable.

Connect makes it easy with seamless integration using any of the major Learning Management Systems—Blackboard®, Canvas, and D2L, among others—to let you organize your course in one convenient location. Give your students access to digital materials at a discount with our inclusive access program. Ask your McGraw-Hill representative for more information.


©Hill Street Studios/Tobin Rogers/Blend Images LLC

Solutions for your challenges.

A product isn't a solution. Real solutions are affordable, reliable, and come with training and ongoing support when you need it and how you want it. Our Customer Experience Group can also help you troubleshoot tech problems—although Connect's 99% uptime means you might not need to call them. See for yourself at **status.mheducation.com**

For Students

©Shutterstock/wavebreakmedia

Effective, efficient studying.

Connect helps you be more productive with your study time and get better grades using tools like SmartBook, which highlights key concepts and creates a personalized study plan. Connect sets you up for success, so you walk into class with confidence and walk out with better grades.

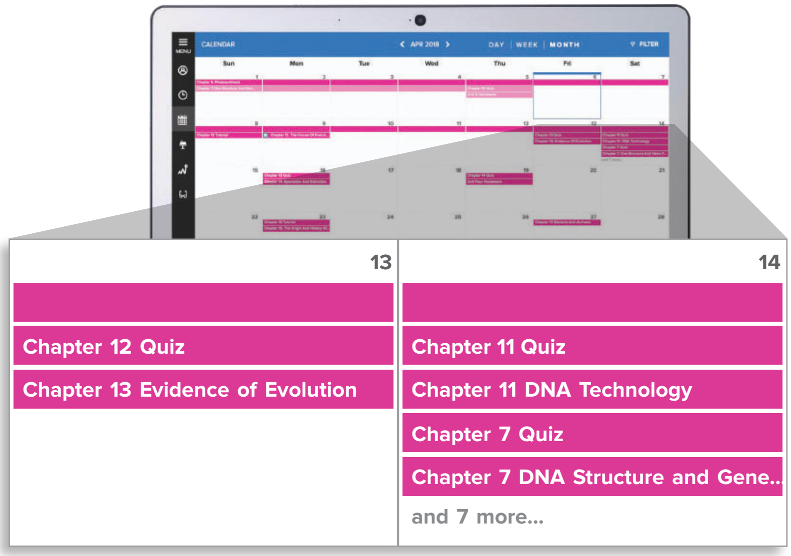
> “I really liked this app—it made it easy to study when you don't have your textbook in front of you.”
>
> - Jordan Cunningham,
> Eastern Washington University

Study anytime, anywhere.

Download the free ReadAnywhere app and access your online eBook when it’s convenient, even if you’re offline. And since the app automatically syncs with your eBook in Connect, all of your notes are available every time you open it. Find out more at **www.mheducation.com/readanywhere**

No surprises.

The Connect Calendar and Reports tools keep you on track with the work you need to get done and your assignment scores. Life gets busy; Connect tools help you keep learning through it all.



13

Chapter 12 Quiz

Chapter 13 Evidence of Evolution

14

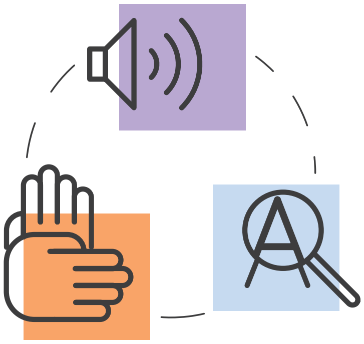
Chapter 11 Quiz

Chapter 11 DNA Technology

Chapter 7 Quiz

Chapter 7 DNA Structure and Gene...

and 7 more...



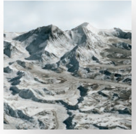
Learning for everyone.

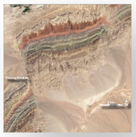
McGraw-Hill works directly with Accessibility Services Departments and faculty to meet the learning needs of all students. Please contact your Accessibility Services office and ask them to email accessibility@mheducation.com, or visit **www.mheducation.com/about/accessibility.html** for more information.

Contents

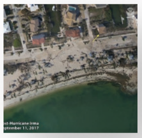
SECTION I **FOUNDATIONS**

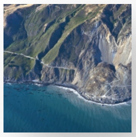
SECTION II **INTERNAL PROCESSES**

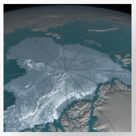




SECTION III **SURFACE PROCESSES**







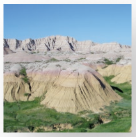
CHAPTER 10

Climate—Past, Present, and Future 219

SECTION IV **RESOURCES**

CHAPTER 11

Groundwater and Water Resources 238



CHAPTER 12

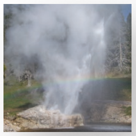
Weathering, Erosion, and Soil Resources 267

CHAPTER 13

Mineral and Rock Resources 290

CHAPTER 14

Energy Resources—Fossil Fuels 319



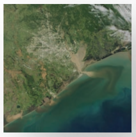
CHAPTER 15

Energy Resources—Alternative Sources 347

SECTION V **WASTE DISPOSAL, POLLUTION, AND HEALTH**

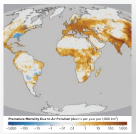
CHAPTER 16

Waste Disposal 378



CHAPTER 17

Water Pollution 411



CHAPTER 18

Air Pollution 443

SECTION VI **OTHER RELATED TOPICS**

CHAPTER 19 Environmental Law and Policy 469

CHAPTER 20 Land-Use Planning and Engineering Geology 495

Appendix A

Appendix B

Appendix C

Chapter-opening photo credits: Chapters 1, 2, 5, 9, 11, 12, 15, 19: ©Carla Montgomery; Chapter 3: Image by Joshua Stevens, courtesy NASA; Chapter 4: Image by Robert Simmon and Jesse Allen, courtesy NASA; Chapter 6: Image by Robert Simmon and Jesse Allen, courtesy NASA; Chapter 7: U.S. Geological Survey Coastal and Marine Geology Program/Photograph by NOAA; Chapter 8: U.S. Geological Survey/Photograph by Bob Van Wagenen; Chapter 10: Image by Cindy Starr, NASA Scientific Visualization Studio; Chapter 13: Earth Science and Remote Sensing Unit, Johnson Space Center, courtesy NASA; Chapter 14: NASA Earth Observatory image by Robert Simmon; Chapter 16: NASA Earth Observatory image by Joshua Stevens, using Landsat data provided by the U.S. Geological Survey; Chapter 17: NASA Earth Observatory image by Jesse Allen, using data from the Land, Atmosphere Near real-time Capability for EOS (LANCE); Chapter 18: NASA Earth Observatory image by Robert Simmon, using data provided by Jason West; Chapter 20: ISS Crew Earth Observations Facility and the Earth Science and Remote Sensing Unit, Johnson Space Center, courtesy NASA.

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

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.

©*Carla Montgomery.*

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

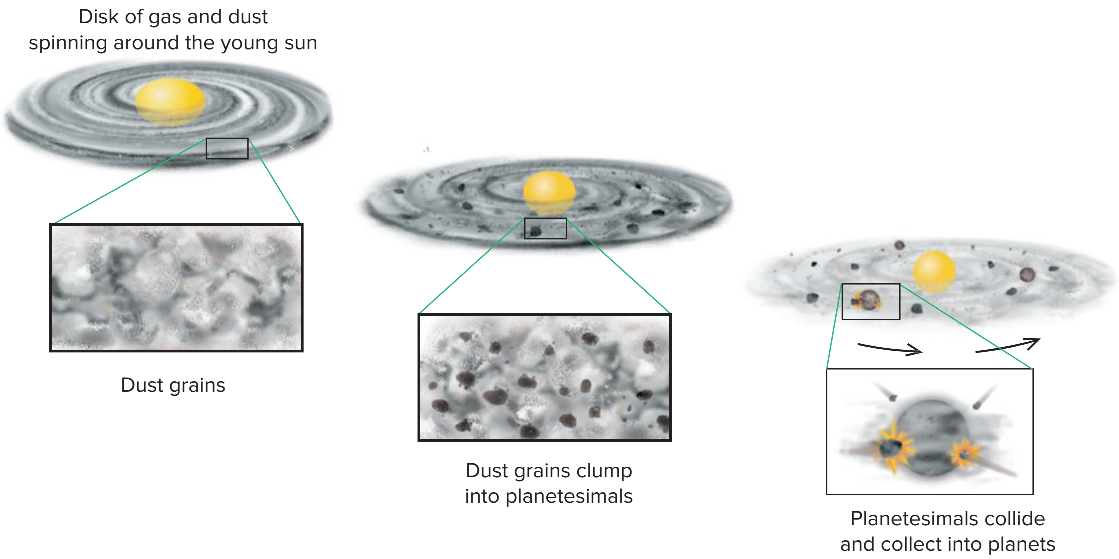


Figure 1.1

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

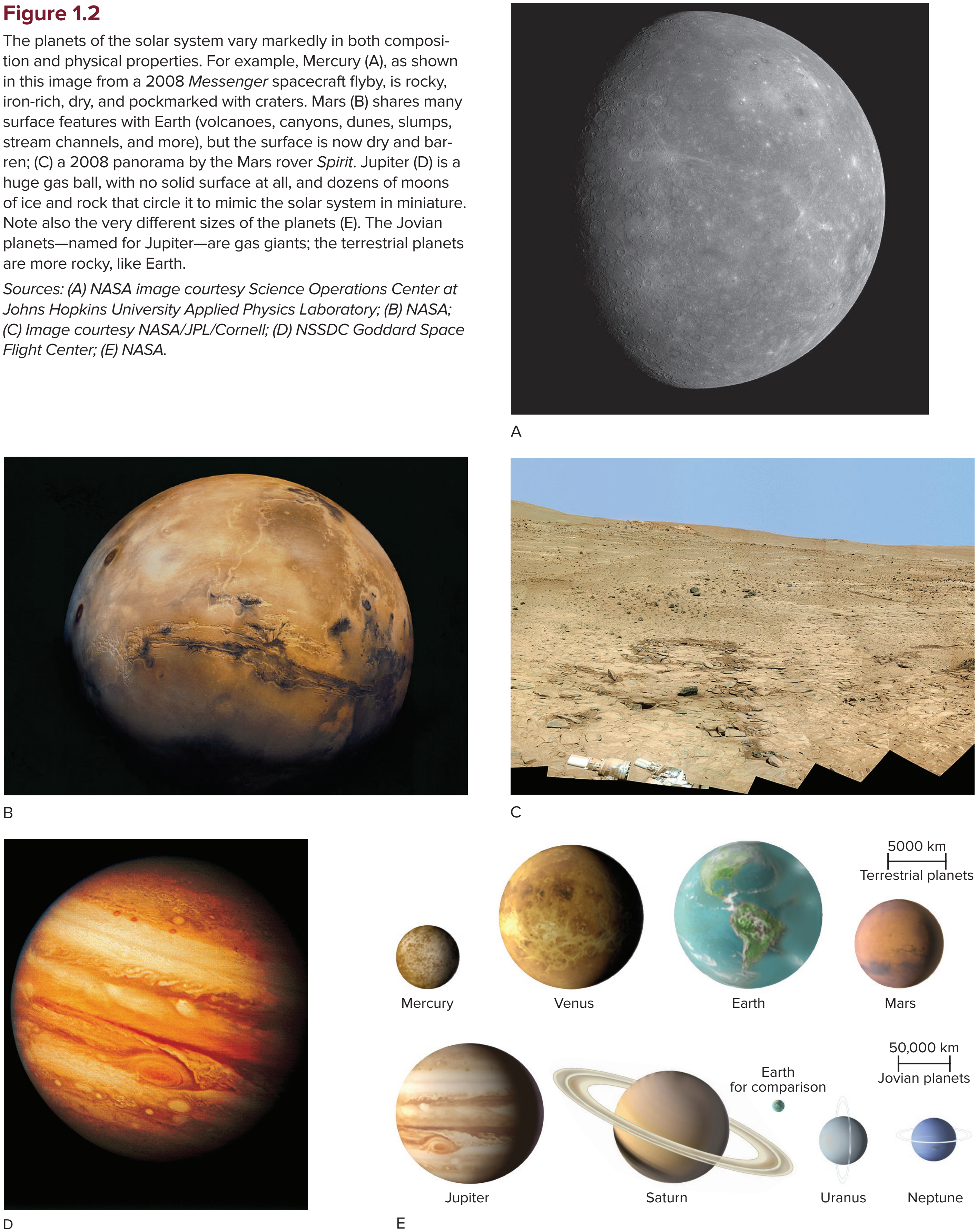
The earth has changed continuously since its formation, undergoing some particularly profound changes in its early history. The early earth was very different from what it is today, lacking the modern oceans and atmosphere and having a much different surface from its present one, probably more closely 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.



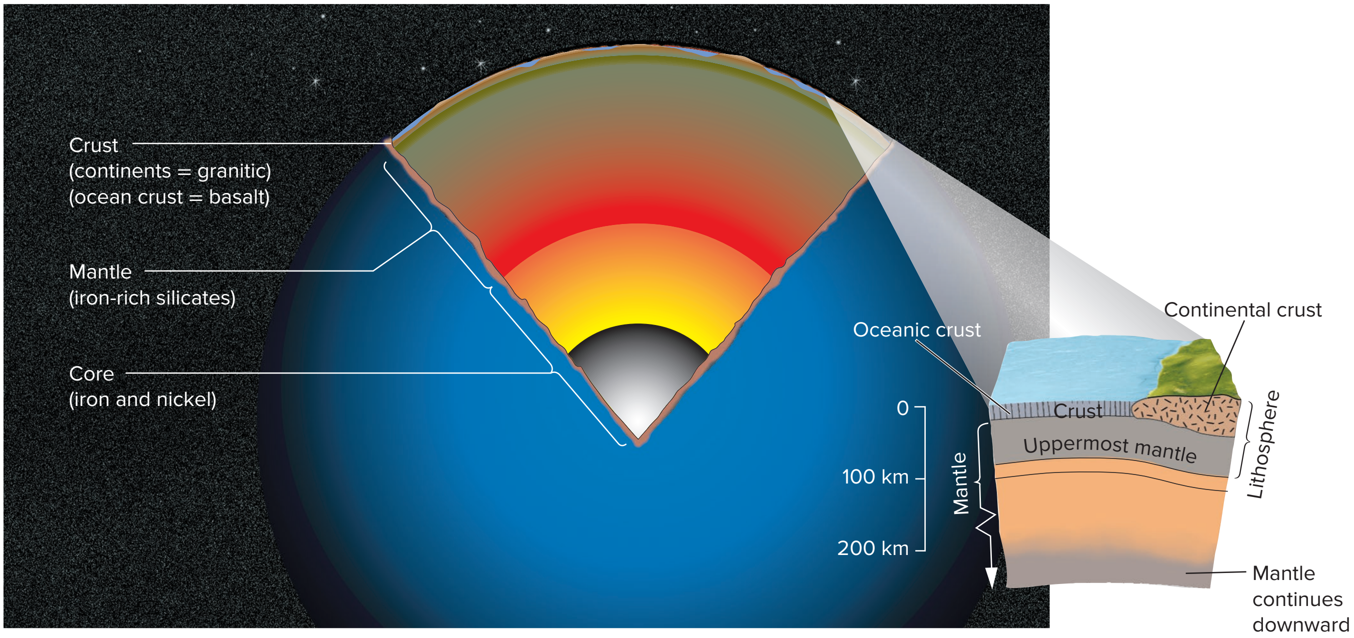


Figure 1.3

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.

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.)

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

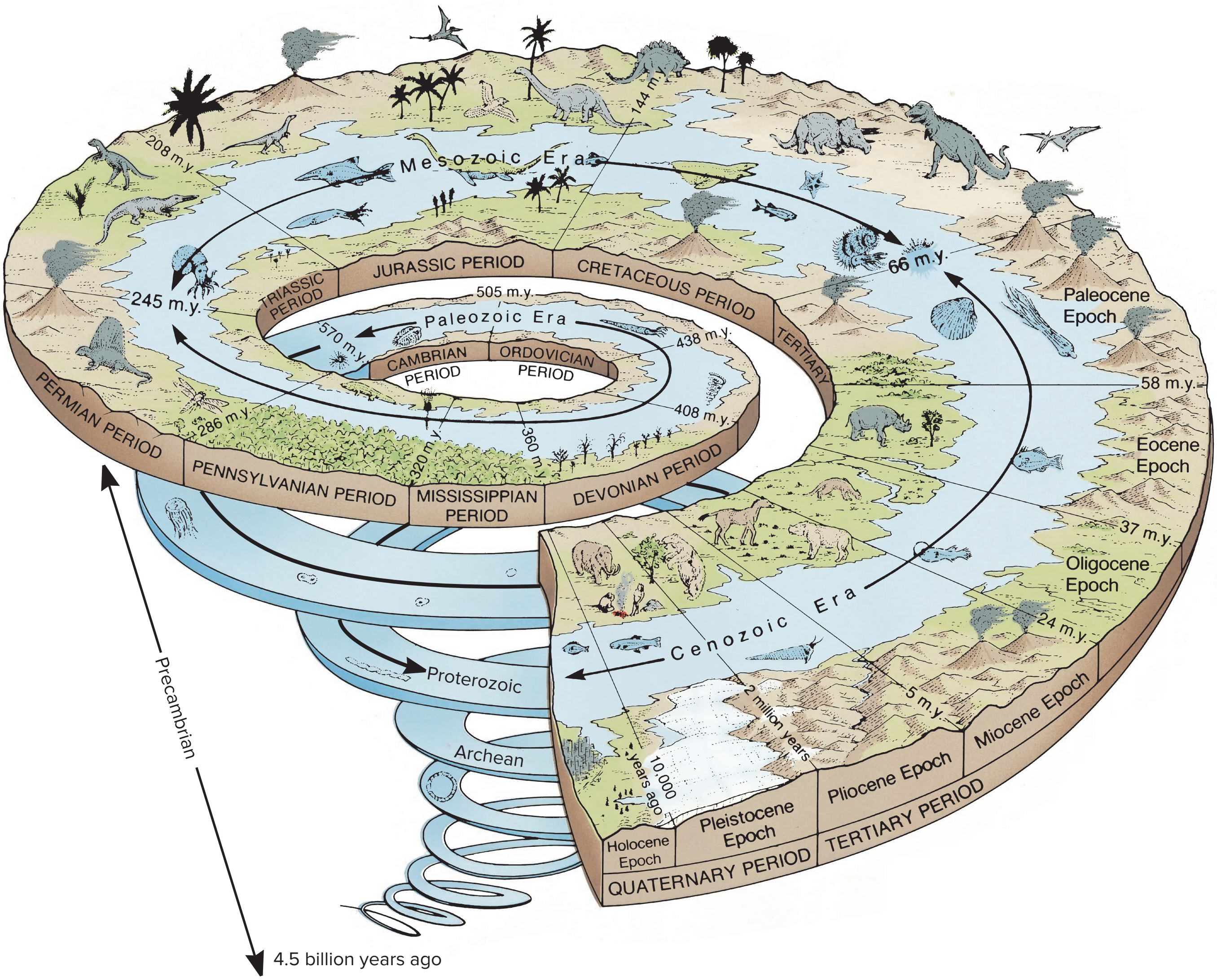


Figure 1.4

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.

Figure 1.9

Damage from the 2005 Laguna Beach, California, landslide.

Source: U.S. Geological Survey EROS Data Center Image Gallery/Photograph by Pam Irvine, California Geological Survey.

Figure 1.10

The Grasberg Mine in Irian Jaya, Indonesia, is one of the world's largest gold- and copper-mining operations. The surface pit is nearly 4 km (2½ miles) across; note the sharp contrast with surrounding topography. Slopes oversteepened by mining have produced deadly landslides, and local residents worry about copper and acid contamination in runoff water.

Source: Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center.

As we mine more extensively for mineral resources, we face the problem of how to minimize associated damage to the mined lands (**figure 1.10**). The grounding of the *Exxon Valdez* in 1989, dumping 11 million gallons of oil into Prince William Sound, Alaska, and the massive spill from the 2010 explosion of the *Deepwater Horizon* drilling platform in the Gulf of Mexico were reminders of the negative consequences of petroleum exploration, just as the 1991 war in Kuwait, and the later invasion of Iraq, were reminders of U.S. dependence on imported oil.

As we consume more resources, we create more waste. In the United States, total waste generation is estimated at close to 300 million tons per year—or more than a ton per person. Careless waste disposal, in turn, leads to pollution. The Environmental Protection Agency continues to identify toxic-waste disposal sites in urgent need of cleanup; by 2000, over 1500 so-called priority sites had been identified. Cleanup costs per site have risen to over $30 million, and the projected total costs to remediate these sites alone is over $1 trillion. As fossil fuels are burned, carbon dioxide in the atmosphere rises, and modelers of global climate strive to understand what that may do to global temperatures, weather, and agriculture decades in the future.

These are just a few of the kinds of issues that geologists play a key role in addressing.

Wheels Within Wheels: Earth Cycles and Systems

The earth is a dynamic, constantly changing planet—its crust shifting to build mountains; lava spewing out of its warm interior; ice and water and windblown sand and gravity reshaping its surface, over and over. Some changes proceed in one direction only: For example, the earth has been cooling progressively since its formation, though considerable heat remains in its interior. Many of the processes, however, are cyclic in nature.

Consider, for example, such basic materials as water or rocks. Streams drain into oceans and would soon run dry if not replenished; but water evaporates from oceans, to make the rain and snow that feed the streams to keep them flowing. This describes just a part of the *hydrologic* (water) *cycle,* explored more fully in chapters 6 and 11. Rocks, despite their appearance of permanence in the short term of a human life, participate in the *rock cycle* (chapters 2 and 3). The kinds of evolutionary paths rocks may follow through this cycle are many, but consider this illustration: A volcano's lava (**figure 1.11**) hardens into rock; the rock is weathered into sand and dissolved chemicals; the debris, deposited in an ocean basin, is solidified into a new rock of quite different type; and some of that new rock may be carried into the mantle via plate tectonics, to be melted into a new lava. The time frame over which this process occurs is generally much longer than that over which water cycles through atmosphere and

Figure 1.11

Bit by bit, lava flows like this one on Kilauea have built the Hawaiian Islands.

©Carla Montgomery.

oceans, but the principle is similar. The Appalachian or Rocky Mountains as we see them today are not as they formed, tens or hundreds of millions of years ago; they are much eroded from their original height by water and ice, and, in turn, contain rocks formed in water-filled basins and deserts from material eroded from more-ancient mountains before them (**figure 1.12**).

Chemicals, too, cycle through the environment. The carbon dioxide that we exhale into the atmosphere is taken up by plants through photosynthesis, and when we eat those plants for food energy, we release CO_2 again. The same exhaled CO_2 may also dissolve in rainwater to make carbonic acid that dissolves continental rock; the weathering products may wash into the ocean, where dissolved carbonate then contributes to the formation of carbonate shells and carbonate rocks in the ocean basins; those rocks may later be exposed and weathered by rain, releasing CO_2 back into the atmosphere or dissolved carbonate into streams that carry it back to the ocean. The cycling of chemicals and materials in the environment may be complex, as we will see in later chapters.

Furthermore, these processes and cycles are often interrelated, and seemingly local actions can have distant consequences. We dam a river to create a reservoir as a source of irrigation water and hydroelectric power, inadvertently trapping stream-borne sediment at the same time; downstream, patterns of erosion and deposition in the stream channel change, and at the coast, where the stream pours into the ocean, coastal erosion of beaches increases because a part of their sediment supply, from the stream, has been cut off. The volcano that erupts the lava to make the volcanic rock also releases water vapor into the atmosphere, and sulfur-rich gases and dust that influence the amount of sunlight reaching earth's surface to heat it, which, in turn, can alter the extent of evaporation and resultant rainfall, which will affect the intensity of landscape erosion and weathering of rocks by water. . . . So although we divide the great variety and complexity of geologic processes and

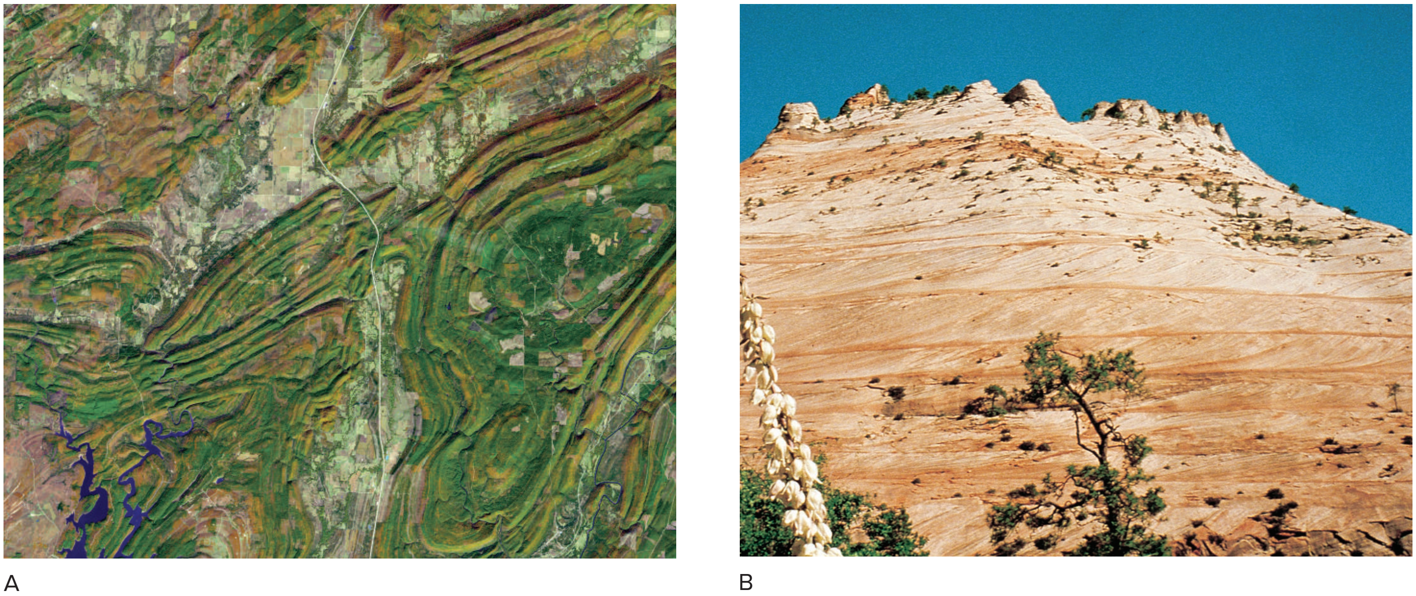


Figure 1.12

Rocks tell a story of constant change. (A) The folds of the Ouachita Mountains of Oklahoma formed deep in the crust when Africa and North America converged hundreds of millions of years ago; now they are eroding and crosscut by rivers. (B) The sandstones of Zion National Park preserve ancient windswept dunes, made of sand eroded from older rocks, deeply buried and solidified into new rock, then uplifted to erode again.

Sources: (A) NASA image created by Jesse Allen & Robert Simmon, using data provided courtesy of NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team; (B) ©Carla Montgomery.

phenomena into more manageable, chapter-sized units for purposes of discussion, it is important to keep such interrelationships in mind. And superimposed on, influenced by, and subject to all these natural processes are humans and human activities.

1.3 Nature and Rate of Population Growth

Animal populations, as well as primitive human populations, are generally quite limited both in the areas that they can occupy and in the extent to which they can grow. They must live near food and water sources. The climate must be one to which they can adapt. Predators, accidents, and disease take a toll. If the population grows too large, disease and competition for food are particularly likely to cut it back to sustainable levels.

The human population grew relatively slowly for hundreds of thousands of years. Not until the middle of the nineteenth century did the world population reach 1 billion. However, by then, a number of factors had combined to accelerate the rate of population increase. The second, third, and fourth billion were reached far more quickly; the world population is now over 7 billion and is expected to rise to nearly 10 billion by 2050 (**table 1.4**).

Humans are no longer constrained to live only where conditions are ideal. We can build habitable quarters even in extreme climates, using heaters or air conditioners to bring the temperature to a level we can tolerate. In addition, people need not live where food can be grown or harvested or where there is abundant fresh water: The food and water can be transported, instead, to where the people choose to live.

Growth Rates: Causes and Consequences

Population growth occurs when new individuals are added to the population faster than existing individuals are removed from it. On a global scale, the population increases when its birthrate exceeds its death rate. In assessing an individual nation's or region's rate of population change, immigration and emigration must also be taken into account. Improvements in nutrition and health care typically increase life expectancies, decrease mortality rates, and thus increase the rate of population growth. Increased use of birth-control or family-planning methods reduces birthrates and, therefore, also reduces the rate of population growth; in fact, a population can begin to decrease if birthrates are severely restricted.

The sharply rising rate of population growth over the past few centuries can be viewed another way. It took until about A.D. 1830 for the world's population to reach 1 billion. The population climbed to 2 billion in the next 130 years, and to 3 billion in just 30 more years, as ever more people contributed to the population growth and individuals lived longer. The last billion people have been added to the world's population in just a dozen years.

There are wide differences in growth rates among regions (**table 1.4**; **figure 1.13**). The reasons for this are many. Religious or social values may cause larger or smaller families to be regarded as desirable in particular regions or cultures. High levels of economic development are commonly associated with reduced rates of population growth; conversely, low levels of development are often associated with rapid population growth. The impact of improved education, which may accompany economic development, can vary: It may lead to better nutrition and prenatal and child care, and thus to increased growth rates, but it may also lead to increased or more effective practice of family-planning methods, thereby reducing growth rates.

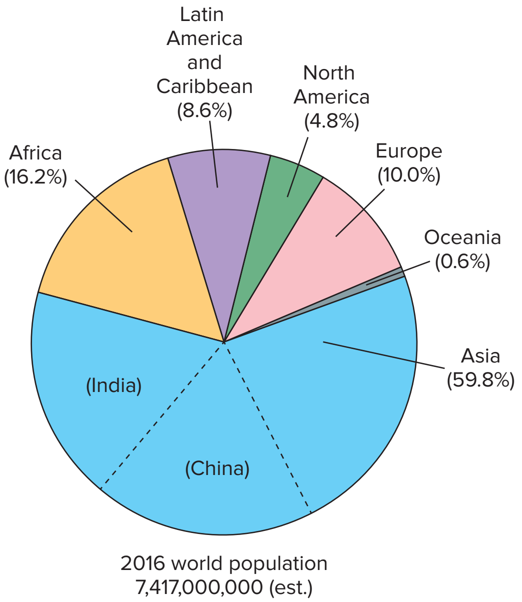
A few governments of nations with large and rapidly growing populations have considered encouraging or mandating family planning. India and the People's Republic of China have taken active measures, with varying results: China's population growth rate is just 0.2% per year; its population is expected to peak at just over 1.4 billion, then to decline by 2050. But India's remains a relatively high 1.0% per year; its population will shortly surpass that of China and is projected to be over 1.7 billion by 2050.

Table 1.4 **World and Regional Population Growth and Projections (in millions)**

Year	World	North America	Latin America and Caribbean	Africa	Europe	Asia	Oceania
1950	2520	172	167	221	547	1402	13
Mid-2016	7417	360	637	1203	740	4437	40
2050 (projected)	9868	445	775	2527	728	5327	66
Growth rate (%/year)	1.0	0.77	0.83	2.4	0	0.78	1.7
Doubling time (years)	70	91	84	29	*	90	41

*Not applicable; population expected to decline by 2050.

Source: Data for 1950 from *United Nations World Population Estimates and Projections;* all other data from *2016 World Population Data Sheet*, Population Reference Bureau, 2016. Population projections to 2050 involve longer-term estimates of future growth rates, which in most areas are expected to decrease from the present levels reported here.



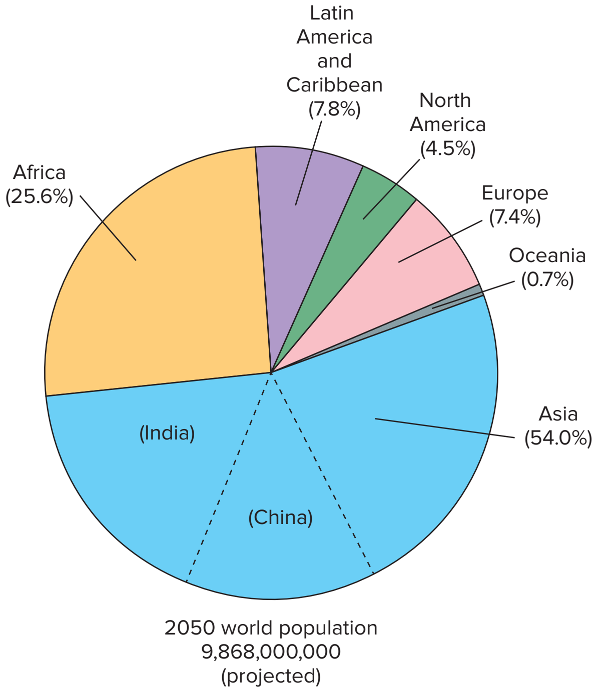


Figure 1.13

Population distribution by region in mid-2016 with projections to the year 2050. Size of circle reflects relative total population. The most dramatic changes in proportion are the relative growth of the population of Africa and decline of population in Europe. Data from table 1.4.

A relatively new factor that strongly affects population growth in some less-developed nations is AIDS. In more-developed countries, typically less than one-half of 1% of the population aged 15 to 49 is afflicted; the prevalence in some African nations is over 20%. In Swaziland, where AIDS/HIV prevalence in this age group is about 23% for men and 34% for women, life expectancy is down to 49 years (world average life expectancy is 72 years). How population in such countries will change over time depends greatly on how effectively the AIDS epidemic is controlled.

Even when the population growth rate is constant, the number of *individuals* added per unit of time increases over time. This is called **exponential growth,** a concept to which we will return when discussing resources in Section IV. The effect of exponential growth is similar to interest compounding. If one invests $100 at 10% per year and withdraws the interest each year, one earns $10/year, and after 10 years, one has collected $100 in interest. If one invests $100 at 10% per year, compounded annually, then, after one year, $10 interest is credited, for a new balance of $110. But if the interest is not withdrawn, then at the end of the second year, the interest is $11 (10% of $110), and the new balance is $121. By the end of the tenth year (assuming no withdrawals), the interest for the year is $23.58, but the interest *rate* has not increased. And the balance is $259.37 so, subtracting the original investment of $100, this means total interest of $159.37 rather than $100. Similarly with a population of 1 million growing at 5% per year: In the first year, 50,000 persons are added; in the tenth year, the population grows by 77,566 persons. The result is that a graph of population versus time steepens over time, even at a constant growth rate. If the growth rate itself also increases, the curve rises still more sharply.

For many mineral and fuel resources, consumption has been growing very rapidly, even more rapidly than the population. The effects of exponential increases in resource demand are like the effects of exponential population growth (**figure 1.14**). If demand increases by 2% per year, it will double not in 50 years, but in 35. A demand increase of 5% per year leads to a doubling in demand in 14 years and a tenfold increase in demand in 47 years! In other words, a prediction of how soon mineral or fuel supplies will be used up is very sensitive to the assumed rate of change in demand. Even if population is no longer growing exponentially, consumption of many resources is.

Growth Rate and Doubling Time

Another way to look at the rapidity of world population growth is to consider the expected **doubling time,** the length of time required for a population to double in size. Doubling time (D) in years may be estimated from growth rate (G), expressed in

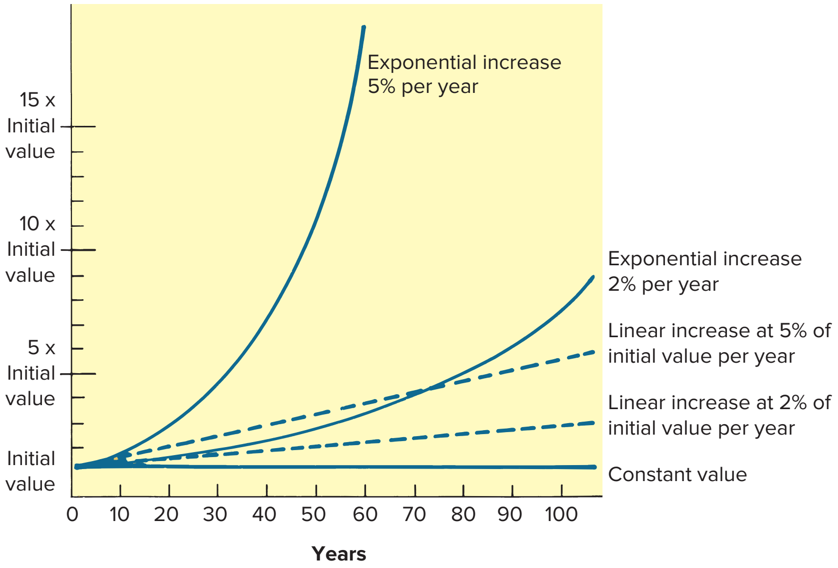


Figure 1.14

Graphical comparison of the effects of linear and exponential growth, whether on consumption of minerals, fuels, water, and other consumable commodities, or population. With linear growth, one adds a fixed percentage of the *initial* value each year (dashed lines). With exponential growth, the same percentage increase is computed each year, but year by year the value on which that percentage is calculated increases, so the annual increment keeps getting larger.

percent per year, using the simple relationship $D = 70/G$, which is derived from the equation for exponential growth (see "Exploring Further" question 2 at the chapter's end). The higher the growth rate, the shorter the doubling time of the population (see again **table 1.4**). By far the most rapidly growing segment of the population today is that of Africa. Its population, estimated at 1.20 billion in 2016, is growing at about 2.4% per year. The largest segment of the population, that of Asia, is increasing at 0.8% per year, and since the over 4 billion people there represent well over half of the world's total population, this leads to a relatively high global average growth rate. Europe's population has begun to decline slightly, but Europe contains only about 10% of the world's population.

The average worldwide population growth rate is about 1.0% per year, which corresponds to a doubling time of about 70 years. At that, the present population growth rate actually represents a substantial decline from nearly 2% per year in the mid-1960s, and that decline is expected to continue. However, a decreasing *growth rate* is not at all the same as a decreasing population. Depending upon projected fertility rates, estimates of world population in the year 2050 can vary by several billion. Using a medium fertility rate, the Population Reference Bureau projects a 2050 world population of almost 9.9 billion. **Figure 1.13** illustrates how those people will be distributed by region, considering differential growth rates from place to place.

Even breaking the world down into regions of continental scale masks a number of dramatic individual-country cases. Discussion of these, and of their political, economic, and cultural implications, is well beyond the scope of this chapter, but consider the following: While the population of Europe is nearly stable, in many parts of northern and eastern Europe, sharp declines are occurring. By 2050, the populations of Russia, Ukraine, and Bulgaria are expected to drop by 6, 21, and 18 percent, respectively. Conversely, parts of the Middle East are experiencing explosive population growth, with projected increases by 2050 of 68% in Israel, 58% in Saudi Arabia, 83% in the Palestinian Territory, and 101% in Iraq. The demographics differ widely between countries, too. Globally, 26% of the population is under 15, and only 8% above age 65. But in Japan, only 13% of the population is below age 15, with 27% age 65 or older; in Afghanistan, 44% of people are under 15 and only 2% age 65 or over. Thus, different nations face different challenges. Where rapid population growth meets scarcity of resources, problems arise.

1.4 Impacts of the Human Population

The problems posed by a rapidly growing world population have historically been discussed most often in the context of food: that is, how to produce sufficient food and distribute it effectively to prevent the starvation of millions in overcrowded countries or in countries with minimal agricultural development. This is a particularly visible and immediate problem, but it is also only one facet of the population challenge.

Farmland and Food Supply

Whether or not the earth can support 7 billion people, or 10 billion, or more, is uncertain. In part, it depends on the quality of life, the level of technological development, and other standards that societies wish to maintain. Yet even when considering the most basic factors, such as food, it is unclear just how many people the earth can sustain. Projections about the adequacy of food production, for example, require far more information than just the number of people to be fed and the amount of available land. The total arable land (land suitable for cultivation) in the world has been estimated at 3.5 billion acres, or about half an acre per person of the present population. The major limitation on this figure is availability of water, either as rainfall or through irrigation. Further considerations relating to the nature of the soil include the soil's fertility, water-holding capacity, and general suitability for farming. Soil character varies tremendously, and its productivity is similarly variable. Moreover, farmland can deteriorate through loss of nutrients and by wholesale erosion of topsoil, and this degradation must be considered when making production predictions.

There is also the question of what crops can or should be grown. Today, this is often a matter of preference or personal taste, particularly in farmland-rich (and energy- and water-rich) nations. The world's people are not now always being fed in the most resource-efficient ways. To produce one ton of corn requires about 250,000 gallons of water; a ton of wheat, 375,000 gallons; a ton of rice, 1,000,000 gallons; a ton of beef, 7,500,000 gallons. Some new high-yield crop varieties may require irrigation, whereas native varieties did not. The total irrigated acreage in the world has more than doubled in three decades. However, water resources are dwindling in many places; the water costs of food production must increasingly be taken into account.

Genetic engineering is now making important contributions to food production, as varieties are selectively developed for high yield, disease resistance, and other desirable qualities. These advances have led some to declare that fears of global food shortages are no longer warranted, even if the population grows by several billion more. However, at least two concerns remain: One, poor nations already struggling to feed their people may be least able to afford the higher-priced designer seed or specially developed animal strains to benefit from these advances. Second, as many small farms using many, genetically diverse strains of food crops are replaced by vast areas planted with a single, new variety, there is the potential for devastating losses if a new pest or disease to which that one strain is vulnerable enters the picture.

Food production as practiced in the United States is also a very energy-intensive business. The farming is heavily mechanized, and much of the resulting food is extensively processed, stored, and prepared in various ways requiring considerable energy. The products are elaborately packaged and often transported long distances to the consumer. Exporting the same production methods to poor, heavily populated countries short on energy and the capital to buy fuel, as well as food, may be neither possible nor practical. Even if possible, it would substantially increase the world's energy demands.

Population and Nonfood Resources

Food is at least a renewable resource. Within a human life span, many crops can be planted and harvested from the same land and many generations of food animals raised. By contrast, the supplies of many of the resources considered in later chapters—minerals, fuels, even land itself—are finite. There is only so much oil to burn, rich ore to exploit, and suitable land on which to live and grow food. When these resources are exhausted, alternatives will have to be found or people will have to do without.

The earth's supply of many such materials is severely limited, especially considering the rates at which these resources are presently being used. Many could be effectively exhausted within decades, yet most people in the world are consuming very little in the way of minerals or energy. Current consumption is strongly concentrated in a few highly industrialized societies. Per-capita consumption of most mineral and energy resources is higher in the United States than in any other nation. For the world population to maintain a standard of living comparable to that of the United States, mineral production would have to increase about fourfold, on the average. There are neither the recognized resources nor the production capability to maintain that level of consumption for long, and the problem becomes more acute as the population grows.

Some scholars believe that we are already on the verge of exceeding the earth's **carrying capacity,** its ability to sustain its population at a basic, healthy, moderately comfortable standard of living. Estimates of sustainable world population made over the last few decades range from under 7 billion—and remember, we are already past that—to over 100 billion persons. The wide range is attributable to considerable variations in model assumptions, including standard of living and achievable productivity of farmland. Certainly, given global resource availability and technology, even the present world population could not enjoy the kind of high-consumption lifestyle to which the average resident of the United States has become accustomed.

It is true that, up to a point, the increased demand for minerals, fuels, and other materials associated with an increase in population tends to raise prices and promote exploration for these materials. The short-term result can be an apparent increase in the resources' availability, as more exploration leads to discoveries of more oil fields, ore bodies, and so on. However, the quantity of each of these resources is finite. The larger and more rapidly growing the world population, and the faster its level of development and standard of living rise, the more rapidly limited resources are consumed, and the sooner those resources will be exhausted.

Land is clearly a basic resource. Seven, 10, or 100 billion people must be *put* somewhere. Already, the global average population density is about 55 persons per square kilometer of land surface (140 persons per square mile), and that is counting *all* the land surface, including jungles, deserts, and mountain ranges, leaving out only the Antarctic continent. The ratio of people to readily inhabitable land is plainly much higher. Land is also needed for agriculture, manufacturing, energy production, transportation, and a variety of other uses. Large numbers of people consuming vast quantities of materials generate vast quantities of wastes. Some of these wastes can be recovered and recycled, but others cannot. It is essential to find places to put the latter, and ways to isolate the harmful materials from contact with the growing population. This effort claims still more land and, often, resources. All of this is why land-use planning—making the most of every bit of land available—is becoming increasingly important. At present, it is too often true that the ever-growing population settles in areas that are demonstrably unsafe or in which the possible problems are imperfectly known (**figures 1.15** and **1.16**).

Figure 1.15

The landslide hazard to these structures sitting at the foot of steep slopes in Rio de Janeiro is obvious, but space for building here is limited.

©Will & Deni McIntyre/Getty Images.

Uneven Distribution of People and Resources

Even if global carrying capacity were ample in principle, that of an individual region may not be. None of the resources—livable land, arable land, energy, minerals, or water—is uniformly distributed over the earth. Neither is the population (see **figure 1.17**). In 2016, the population density in persons per square kilometer of arable land was 213 in the United States, 79 in Canada, 52 in Australia, and a staggering 983,000 in Singapore. Such data clearly have implications for a nation's ability to feed itself, whatever the availability of farmland globally may be.

Many of the most densely populated countries are resource-poor. In some cases, a few countries control the major share of one resource. Oil is a well-known example, but there are many others. Thus, economic and political complications enter into the question of resource adequacy. Just because one nation controls enough of some commodity to supply all the world's needs does not necessarily mean that the country will choose to share its resource wealth or to distribute it at modest cost to other nations. Some resources, like land, are simply not transportable and therefore cannot readily be shared. Some of the complexities of global resource distribution will be highlighted in subsequent chapters.

Figure 1.16

Even where safer land is abundant, people may choose to settle in hazardous—but scenic—places, such as barrier islands. Miami Beach, Florida.

©Getty Images/Tetra images.

Disruption of Natural Systems

Natural systems tend toward a balance or equilibrium among opposing factors or forces. When one factor changes, compensating changes occur in response. If the disruption of the system is relatively small and temporary, the system may, in time, return to its original condition, and evidence of the disturbance will disappear. For example, a coastal storm may wash away beach vegetation and destroy colonies of marine organisms living in a tidal flat, but when the storm has passed, new organisms will start to move back into the area, and new grasses will take root in the dunes. The violent eruption of a volcano like Mount Pinatubo may spew ash and gases high into the atmosphere, partially blocking sunlight and causing the earth to cool, but within a few years, the ash will have settled back to the ground, and normal temperatures will be restored. Dead leaves falling into a lake provide food for the microorganisms that within weeks or months will break the leaves down and eliminate them.

This is not to say that permanent changes never occur in natural systems. The size of a river channel reflects the maximum amount of water it normally carries. If long-term climatic or other conditions change so that the volume of water regularly reaching the stream increases, the larger quantity of water will,

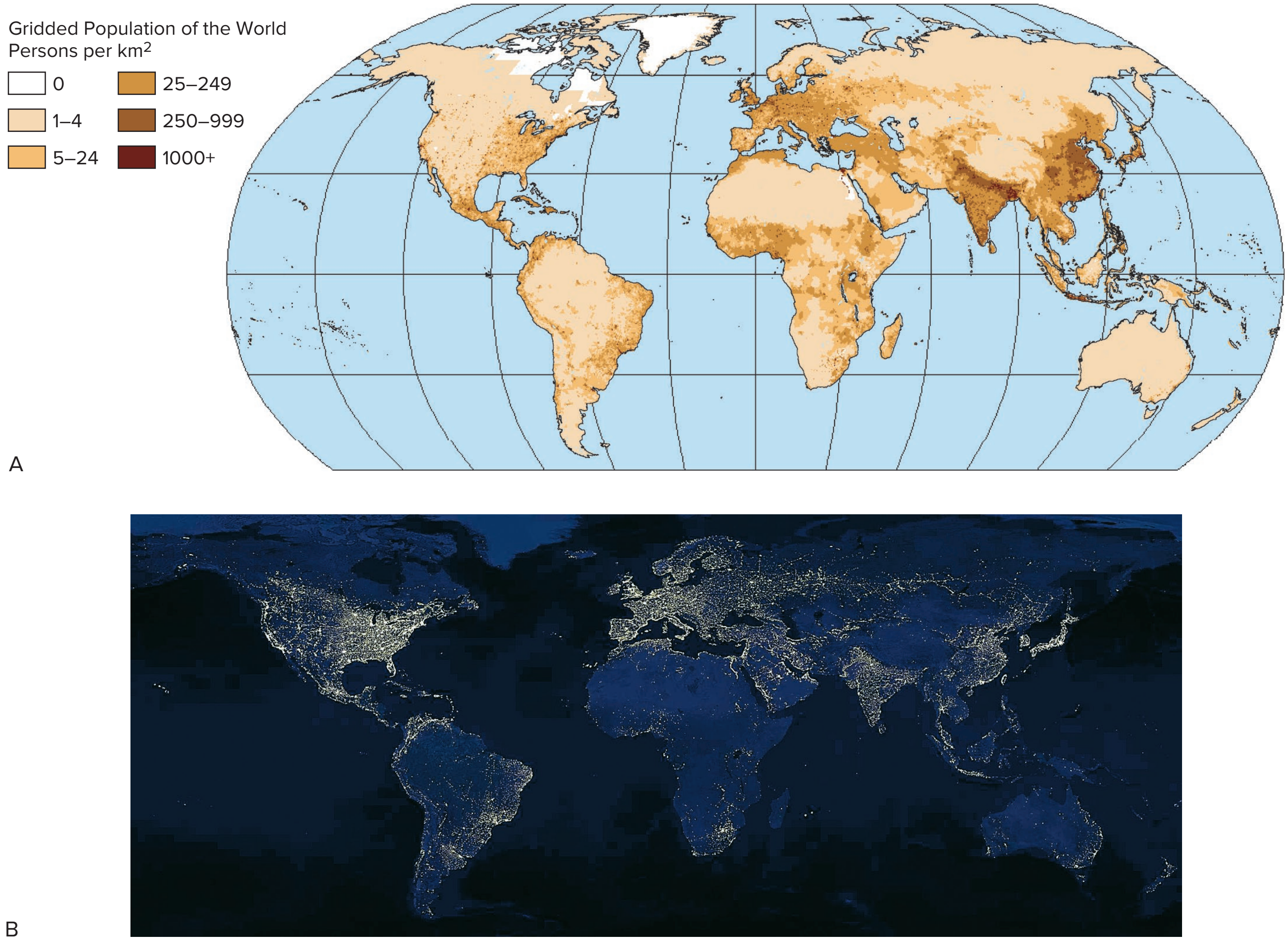


Figure 1.17

(A) Global population density, 2000; the darker the shading, the higher the population density. Comparison with the distribution of lights at night in 2002 (B) shows that overall population density on the one hand, and urbanization/development on the other, are often, but not always, closely correlated.

Sources: (A) Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical (CIAT), Gridded Population of the World (GPW), Version 3. Palisades, NY: CIESIN, Columbia University. Available at: http://sedac.ciesin.columbia.edu/gpw. (B) C. Mayhew & R. Simmon (NASA/GSFC), NOAA/NGDC, DMSP.

in time, carve out a correspondingly larger channel to accommodate it. The soil carried downhill by a landslide certainly does not begin moving back upslope after the landslide is over; the face of the land is irreversibly changed. Even so, a hillside forest uprooted and destroyed by the slide may, within decades, be replaced by new growth in the soil newly deposited at the bottom of the hill.

Human activities can cause or accelerate permanent changes in natural systems. The impact of humans on the global environment is broadly proportional to the size of the population, as well as to the level of technological development achieved. This can be illustrated especially easily in the context of pollution. The smoke from one campfire pollutes only the air in the immediate vicinity; by the time that smoke is dispersed through the atmosphere, its global impact is negligible. The collective smoke from a century and a half of increasingly industrialized society, on the other hand, has caused measurable increases in several atmospheric pollutants worldwide, and these pollutants continue to pour into the air from many sources. It was once assumed that the seemingly vast oceans would be an inexhaustible "sink" for any extra CO_2 that we might generate by burning fossil fuels, but decades of steadily climbing atmospheric CO_2 levels have proven that in this sense, at least, the oceans are not as large as we thought. Likewise, seven people carelessly dumping wastes into the ocean would not appreciably pollute that huge volume of water. The prospect of 7 *billion* people doing the same thing, however, is quite another matter. And every hour, now, world population increases by nearly *8500 people*.

Case Study 1

Earth's Moon

Scientists have long strived to explain the origin of Earth's large and prominent satellite. Through much of the twentieth century, several different models competed for acceptance; within the last few decades a new theory of lunar origin has been developed. While a complete discussion of the merits and shortcomings of these is beyond the scope of this book, they provide good examples of how objective evidence can provide support for, or indicate weaknesses in, hypotheses and theories.

Any acceptable theory of lunar origin has to explain a number of facts. The moon orbits the Earth in an unusual orientation (**figure 1**), neither circling around Earth's equator nor staying in the plane in which the planets' orbits around the sun lie (the ecliptic plane). Its density is much lower than that of Earth, meaning that it contains a much lower proportion of iron. Otherwise, it is broadly similar in composition to the earth's mantle. However, analysis of samples from the *Apollo* missions revealed that relative to Earth, the moon is depleted not only in most gases, but also in volatile (easily vaporized) metals such as lead and rubidium, indicating a hot history for lunar material.

The older "sister-planet" model proposed that the Earth and moon accreted close together during solar system formation, and that is how the moon comes to be orbiting Earth. But in that case, why is the moon not orbiting in the ecliptic plane, and why the significant chemical differences between the two bodies?

The "fission hypothesis" postulated that the moon was spun off from a rapidly rotating early earth after earth's core had been differentiated, so the moon formed mainly from earth's mantle. That would account for the moon's lower density and relatively lower iron content. But analyses of the lunar samples revealed the many additional chemical differences between the moon and earth's mantle. Furthermore, calculations show that a moon formed this way should be orbiting in the equatorial plane, and that far more angular momentum would be required to make it happen than is present in the earth-moon system.

A third suggestion was that the moon formed elsewhere in the solar system and then passed close enough to Earth to be "captured" into orbit by gravity. A major flaw in this idea involves the dynamics necessary for capture. The moon is a relatively large satellite for a body the size of Earth. For Earth's gravity to snare it, the rate at which the moon came by would have to be very, very slow. But Earth is hurtling around the sun at about 107,000 km/hr (66,700 mph), so the probability of the moon happening by at just the right distance and velocity for capture to occur is extremely low. Nor does capture account for a hot lunar origin.

So how to explain the moon? The generally accepted theory for the past two decades (sometimes informally described as the "Big Whack") involves collision between the Earth and a body about the size of Mars, whose orbit in the early solar system put it on course to

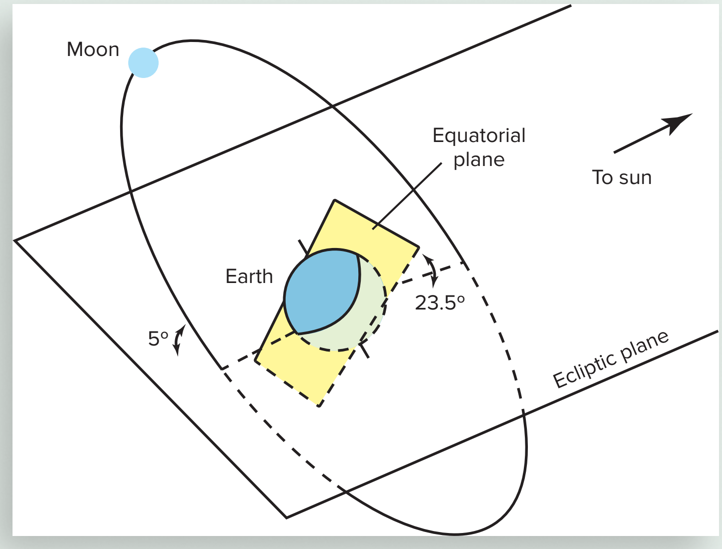


Figure 1

The moon's unusual orbit.

Summary

The solar system formed over 4½ billion years ago. The earth is unique among the planets in its chemical composition, abundant surface water, and oxygen-rich atmosphere. The earth passed through a major period of internal differentiation early in its history, which led to the formation of the atmosphere and the oceans. Earth's surface features have continued to change throughout the last 4^+ billion years, through a series of processes that are often cyclical in nature, and commonly interrelated. The oldest rocks in which remains of simple organisms are recognized are more than 3 billion years old. The intercept Earth. The tremendous energy of the collision would have destroyed the impactor and caused extensive heating and melting on Earth, ejecting quantities of vaporized minerals into space around Earth. If this impact occurred after core differentiation, that material would have come mainly from the mantles of Earth and the impactor. The orbiting material would have condensed and settled into a rotating disk of dust that later accreted to form the moon.

This theory, exotic as it sounds, does a better job of accounting for all the necessary facts. It provides for a (very) hot origin for the material that became the moon, explaining the loss of volatiles. With mantle material primarily involved, a resulting lunar composition similar to that of earth's mantle is reasonable, and contributions from the impactor would introduce some differences as well. An off-center hit by the impactor could easily produce a dust disk (and eventual lunar orbit) oriented at an angle to both the ecliptic plane and earth's equatorial plane. We know that the moon was extensively cratered early in its history, and accretion of debris from the collision could account for this. And computer models designed to test the mechanical feasibility of this theory have shown that indeed, it is physically plausible. So the "Big Whack" is likely to remain the prevailing theory of lunar origin—until and unless new evidence is found that does not fit.

Though humans have not been back to the moon for four decades, new information about it can still be generated. Since *Apollo*, computers have become much more powerful, and chemical-analysis techniques more sensitive and sophisticated. Reprocessing of *Apollo*-era seismic data has indicated that the moon has an iron-rich core like the Earth's, though proportionately much smaller. Reanalysis of lunar samples has provided more-detailed information on the moon's composition, including evidence for water in the lunar mantle. Such data will provide further tests of the "Big Whack" theory.

New chemical and mathematical analyses are also being applied to questions such as how much of the moon was derived from earth material and how much from the impactor, or whether, indeed, there were multiple impactors over an extended period of time.

Interest in returning humans to the moon, to study and even to live, has recently been growing. However, the environment is a daunting one (**figure 2**). The moon has essentially no atmosphere, to breathe or to trap heat to moderate surface temperatures, so in sunlight the surface soars to about 120°C (250°F) and during the lunar night plunges to about –175°C (–280°F). There is no vegetation or other life. In 2009, an ingenious experiment demonstrated that some water ice is buried in the lunar soil. A spent rocket was deliberately crashed into a shaded area within a crater; an accompanying spacecraft analyzed the resultant debris and identified ice and water vapor in it. However, how much ice is there, and how widespread, is unknown. To bring water to the moon for human use would cost an estimated $7000–$70,000 *per gallon.* Many other raw materials would certainly have to be shipped there. Furthermore (as the *Apollo* astronauts discovered), the moon presents another special challenge: a surface blanket of abrasive rock dust, the result of pounding by many meteorites over its history—dust that can abrade and foul equipment and, if breathed, injure lungs. So at least for now, any lunar colony is likely to be very small, and necessarily contained in a carefully controlled environment.

Figure 2

The lunar surface is not an environment in which humans could live outside protective structures, with high energy and resource costs. Geologist/astronaut Harrison Schmitt, lunar module commander of the Apollo 17 mission.

Source: NASA.

earliest plants were responsible for the development of free oxygen in the atmosphere, which, in turn, made it possible for oxygen-breathing animals to survive. Human-type remains are unknown in rocks over 4 to 5 million years of age. In a geologic sense, therefore, human beings are quite a new addition to the earth's cast of characters, but they have had a very large impact. Geology, in turn, can have an equally large impact on us.

The world population, now over 7 billion, might well be close to 10 billion by the year 2050. Even our present population cannot entirely be supported at the level customary in the more developed countries, given the limitations of land and resources. Extraterrestrial resources cannot realistically be expected to contribute substantially to a solution of this problem.

Key Terms and Concepts

carrying capacity
core
crust
doubling time
environmental geology
exponential growth
hypothesis
mantle
scientific method
theory

Test Your Learning

1. Describe the process by which the solar system is believed to have formed, and explain why it led to planets of different compositions, even though the planets formed simultaneously.
2. Compare the age of the earth with the length of time humans have inhabited the planet and come to influence their geologic environment.
3. Explain how the newly formed earth differed from the earth we know today.
4. Describe the kinds of information that are used to determine the internal composition of the earth.
5. Outline the processes by which the earth's atmosphere and oceans formed, and how the atmosphere has changed over earth's history.
6. Explain the differences among facts, scientific hypotheses, and scientific theories.
7. Many earth materials are transformed through processes that are cyclical in nature. Describe one example.
8. The size of the earth's human population directly affects the severity of many environmental problems. Illustrate this idea in the context of (a) resources and (b) pollution.
9. If earth's population has already exceeded the planet's carrying capacity, explain the implications for achieving a comfortable standard of living worldwide.
10. Know the world's present population, to the nearest billion. Explain how population growth rates over the last few centuries compare with those of earlier times, and why. Describe how global growth rates have changed over the last half-century.
11. Explain the concept of doubling time and how population doubling time has generally been changing through history. Know the approximate doubling time of the world's population at present.
12. Indicate what regions of the world currently have the fastest and slowest rates of population growth.
13. Describe any one of the older theories of lunar origin, and note at least one fact about the moon that it fails to explain.

Exploring Further

1. The urgency of population problems can be emphasized by calculating such "population absurdities" as the time at which there will be one person per square meter or per square foot of land or the time at which the weight of people will exceed the weight of the earth. Try calculating these "population absurdities" by using the world population projections from **table 1.4** and the following data concerning the earth:

   Mass 5976×10^{21} kg*

   Land surface area (approx.) 149,000,000 sq. km

   Average weight of human body (approx.) 75 kg

2. Derive the relation between doubling time and growth rate, starting from the exponential-growth relation

$$N = N_0 \, e^{(G/100)\cdot t}$$

   where N = the growing quantity (number of people, tons of iron ore consumed annually, dollars in a bank account, or whatever); N_0 is the initial quantity at the start of the time period of interest; G is growth rate expressed in percent per year, and "percent" means "parts per hundred"; and t is the time in years over which growth occurs. Keep in mind that doubling time, D, is the length of time required for N to double.

3. Select a single country or small set of related countries; examine recent and projected population growth rates in detail, including the factors contributing to the growth rates and trends in those rates. Compare with similar information for the United States or Canada. A useful starting point may be the latest World Population Data Sheet from the Population Reference Bureau (www.prb.org).

---

*This number is so large that it has been expressed in scientific notation, in terms of powers of 10. It is equal to 5976 with twenty-one zeroes after it. For comparison, the land surface area could also have been written as 149×10^6 sq. km, or $149{,}000 \times 10^3$ sq. km, and so on.

Dig Deeper: Connect, NetNotes, Readings

Test your recall, comprehension, and critical thinking skills on Connect, our digital homework platform, with homework, test, and quizzes created by your instructor.

Find out more! Go to **www.montgomeryenvironmentalgeology.com** for two kinds of resources from the author: **NetNotes** (websites to link you to news and information related to contents) and **Suggested Readings/References** (background on chapter material and additional issues/case studies).

CHAPTER 2

Rocks and Minerals—A First Look

It is difficult to talk for long about geology without discussing the rocks and minerals of which the earth is made. Considering that most common rocks and minerals are composed of a small subset of the chemical elements, they are remarkably diverse in color, texture, and other physical properties. Some minerals we prize as gemstones; others are hazardous to our health. The differences in the physical properties of rocks and soils determine their suitability for different purposes—extraction of water or of metals, construction, manufacturing, waste disposal, agriculture, and other uses. Also, each rock contains clues to the kinds of processes that formed it and to the geologic setting where it is likely to be found. The nature of a volcano's rocks may indicate what hazards it presents to us; our search for new ores or fuels is often guided by an understanding of the specialized geologic environments in which they occur.

For all of these reasons, it is helpful to understand something of the nature of geological materials. We will explore specific minerals and rocks in more detail in later chapters. For now, we will take a brief overview of the basics by way of background. Rocks are built of minerals, and minerals, of atoms. We start with a look at these smallest building blocks.

This colorful outcrop of sedimentary rocks at Capitol Reef National Park owes its bright hues to iron-bearing minerals, the different colors reflecting different conditions under which the sediments were deposited.

©Carla Montgomery.

2.1 Atoms, Elements, Isotopes, Ions, and Compounds

Atomic Structure

All natural and most synthetic substances on earth are made from the ninety naturally occurring chemical elements. An **atom** is the smallest particle into which an element can be divided while still retaining the chemical characteristics of that element (see **figure 2.1**). The **nucleus,** at the center of the atom, contains one or more particles with a positive electrical charge (**protons**) and usually some particles of similar mass that have no charge (**neutrons**). Circling the nucleus are the negatively charged **electrons.** Protons and neutrons are similar in mass, and together they account for most of the mass of an atom. The much lighter electrons are sometimes represented as a "cloud" around the nucleus, as in **figure 2.1**, and are sometimes shown as particles, as in **figure 2.3**. The −1 charge of one electron exactly balances the +1 charge of a single proton.

The number of protons in the nucleus determines what chemical element that atom is. Every atom of hydrogen contains one proton in its nucleus; every oxygen atom contains eight protons; every carbon atom, six; every iron atom, twenty-six; and so on. The characteristic number of protons is the **atomic number** of the element.

Elements and Isotopes

With the exception of the simplest hydrogen atoms, all nuclei contain neutrons, and the number of neutrons is similar to or somewhat greater than the number of protons. The number of neutrons in atoms of one element is not always the same. The sum of the number of protons and the number of neutrons in a nucleus is the atom's **atomic mass number.** Atoms of a given element with different atomic mass numbers—in other words, atoms with the same number of protons but different numbers of neutrons—are distinct **isotopes** of that element. Some elements have only a single isotope, while others may have ten or more. (The reasons for these phenomena involve principles of nuclear physics and the nature of the processes by which the elements are produced in the interiors of stars, and we will not go into them here!)

For most applications, we are concerned only with the elements involved, not with specific isotopes. When a particular isotope is to be designated, this is done by naming the element (which, by definition, specifies the atomic number, or number of protons) and the atomic mass number (protons plus neutrons). Carbon, for example, has three natural isotopes. By far the most abundant is carbon-12, the isotope with six neutrons in the nucleus in addition to the six protons common to all carbon atoms. The two rarer isotopes are carbon-13 (six protons plus seven neutrons) and carbon-14 (six protons plus eight neutrons). Chemically, all behave alike. The human body cannot, for instance, distinguish between sugar containing carbon-12 and sugar containing carbon-13.

Other differences between isotopes may, however, make a particular isotope useful for some special purpose. Some isotopes are *radioactive,* meaning that over time, their nuclei will decay (break down) into nuclei of other elements, releasing energy. Each such radioactive isotope will decay at its own specific rate, which allows us to use such isotopes to date geologic materials and events, as described in appendix A. A familiar example is carbon-14, used to date materials containing carbon, including archeological remains such as cloth, charcoal, and bones. Differences in the properties of two uranium isotopes are important in understanding nuclear power options: only one of the two common uranium isotopes is suitable for use as reactor fuel, and must be extracted and concentrated from natural uranium as it occurs in uranium ore. The fact that radioactive elements will inexorably decay—releasing energy—at their own fixed, constant rates is part of what makes radioactive-waste disposal such a challenging problem, because no chemical or physical treatment can make those waste isotopes nonradioactive and inert.

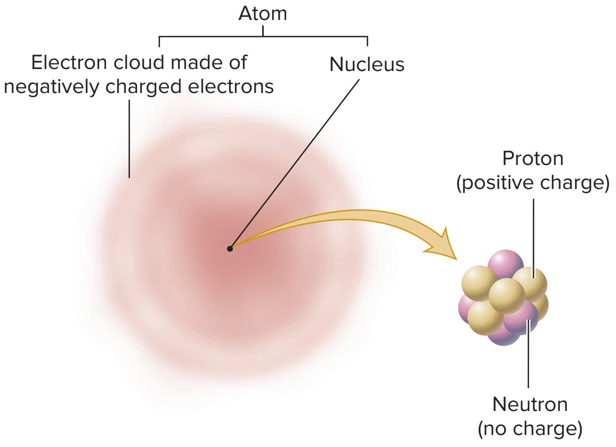
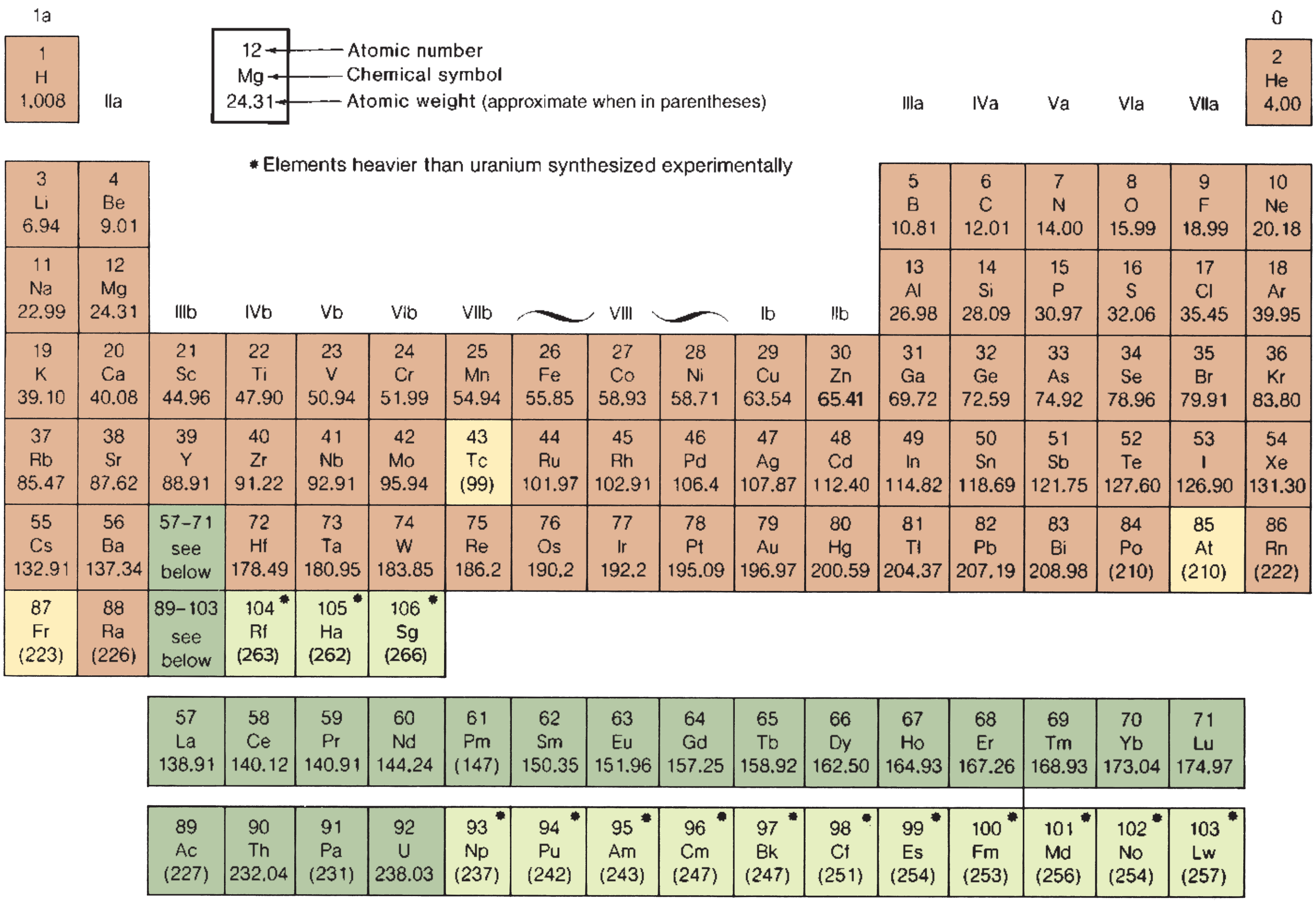


Figure 2.1

Schematic drawing of atomic structure (greatly enlarged and simplified). The nucleus is actually only about 1/1000th the overall size of the atom.

Ions

In an electrically neutral atom, the number of protons and the number of electrons are the same; the negative charge of one electron just equals the positive charge of one proton. Most atoms, however, can gain or lose some electrons. When this happens, the atom has a positive or negative electrical charge and is called an **ion.** If it loses electrons, it becomes positively charged, since the number of protons then exceeds the number of electrons. If the atom gains electrons, the ion has a negative electrical charge. Positively and negatively charged ions are called, respectively, **cations** and **anions.** Both solids and liquids are, overall, electrically neutral, with the total positive and negative charges of cations and anions balanced. Moreover, free ions do not exist in solids; cations and anions are bonded together. In a solution, however, individual ions may exist and move independently. Many minerals break down into ions as they dissolve in water. Individual ions may then be taken up by plants as nutrients or react with other materials. The concentration of hydrogen ions (pH) determines a solution's acidity.



12 — Atomic number
Mg — Chemical symbol
24.31 — Atomic weight (approximate when in parentheses)

* Elements heavier than uranium synthesized experimentally

1a	IIa	IIIb	IVb	Vb	VIb	VIIb	VIII			Ib	IIb	IIIa	IVa	Va	VIa	VIIa	0
1 H 1.008																	2 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.00	8 O 15.99	9 F 18.99	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 51.99	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.71	29 Cu 63.54	30 Zn 65.41	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.91	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (99)	44 Ru 101.97	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30
55 Cs 132.91	56 Ba 137.34	57-71 see below	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.98	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89-103 see below	104 * Rf (263)	105 * Ha (262)	106 * Sg (266)												
		57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (147)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97	
		89 Ac (227)	90 Th 232.04	91 Pa (231)	92 U 238.03	93 * Np (237)	94 * Pu (242)	95 * Am (243)	96 * Cm (247)	97 * Bk (247)	98 * Cf (251)	99 * Es (254)	100 * Fm (253)	101 * Md (256)	102 * No (254)	103 * Lw (257)	

Figure 2.2

The periodic table.

The Periodic Table

Some idea of the probable chemical behavior of elements can be gained from a knowledge of the **periodic table** (figure 2.2). The Russian scientist Dmitri Mendeleyev first observed that certain groups of elements showed similar chemical properties, which seemed to be related in a regular way to their atomic numbers. At the time (1869) that Mendeleyev published the first periodic table, in which elements were arranged so as to reflect these similarities of behavior, not all elements had even been discovered, so there were some gaps. The addition of elements identified later confirmed the basic concept. In fact, some of the missing elements were found more easily because their properties could to some extent be anticipated from their expected positions in the periodic table.

We now can relate the periodicity of chemical behavior to the electronic structures of the elements. Electrons around an atom occur in shells of different energies, each of which can hold a fixed maximum number of electrons. Those elements in the first column of the periodic table, known as the alkali metals, have one electron in the outermost shell of the neutral atom. Thus, they all tend to form cations of +1 charge by losing that odd electron. Outermost electron shells become increasingly full from left to right across a row. The next-to-last column, the halogens, are those elements lacking only one electron in the outermost shell, and they thus tend to gain one electron to form anions of charge −1. In the right-hand column are the inert gases, whose neutral atoms contain all fully filled electron shells.

The elements that occur naturally on earth have now been known for decades. Additional new elements must be created, not simply discovered, because these very heavy elements, with atomic numbers above 92 (uranium), are too unstable to have lasted from the early days of the solar system to the present. Some, like plutonium, are by-products of nuclear-reactor operation; others are created by nuclear physicists who, in the process, learn more about atomic structure and stability.

Compounds

A **compound** is a chemical combination of two or more chemical elements, bonded together in particular proportions, that has a distinct set of physical properties (often very different from those of any of the individual elements in it). In minerals, most bonds are *ionic* or *covalent,* or a mix of the two. In **ionic bonding,** the bond is based on the electrical attraction between oppositely charged ions. Bonds between atoms may also form if the atoms share electrons. This is **covalent bonding.** Table salt (sodium chloride) provides a common example of

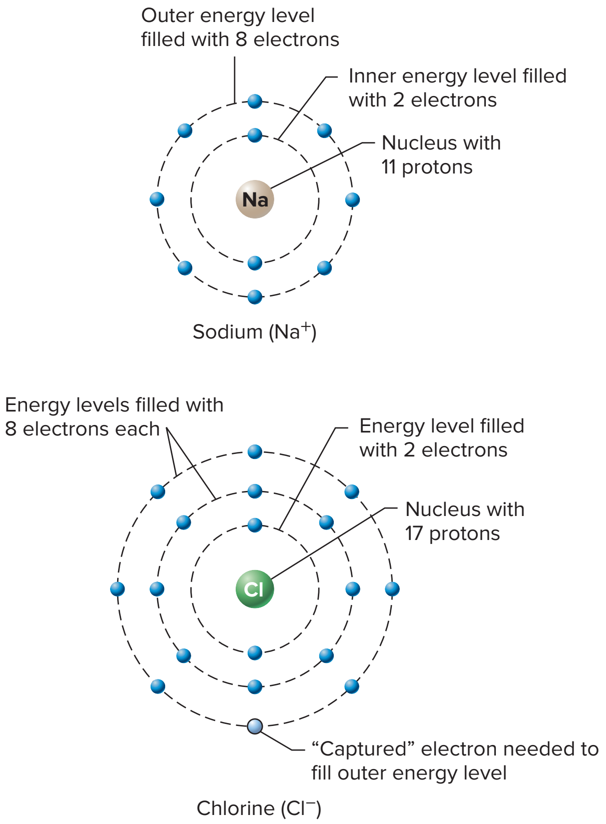


Figure 2.3

Sodium, with 11 protons and electrons, has two filled shells and one "leftover" electron in its outermost shell. Chlorine can accept that odd electron, filling its own outermost shell exactly. The resulting oppositely charged ions attract and bond.

ionic bonding (**figure 2.3**). Sodium, an alkali metal, loses its outermost electron to chlorine, a halogen. The two elements now have filled electron shells, but sodium is left with a +1 net charge, chlorine −1. The ions bond ionically to form sodium chloride. Sodium is a silver metal, and chlorine is a greenish gas that is poisonous in large doses. When equal numbers of sodium and chlorine atoms combine to make table salt, or sodium chloride, the resulting compound forms colorless crystals that do not resemble either of the component elements.

2.2 Minerals—General

Minerals Defined

A **mineral** is a naturally occurring, inorganic, solid element or compound with a definite chemical composition and a regular internal crystal structure. *Naturally occurring,* as distinguished from synthetic, means that minerals do not include the thousands of chemical substances invented by humans. *Inorganic,* in this context, means not produced solely by living organisms or by biological processes. That minerals must be *solid* means that the ice of a glacier is a mineral, but liquid water is not. Chemically, minerals may consist either of one element—like diamonds, which are pure carbon—or they may be compounds of two or more elements. Some mineral compositions are very complex, consisting of ten elements or more. Minerals have a definite chemical composition or a compositional range within which they fall. The presence of certain elements in certain proportions is one of the identifying characteristics of each mineral. Finally, minerals are crystalline, at least on the microscopic scale. **Crystalline** materials are solids in which the atoms or ions are arranged in regular, repeating patterns (**figure 2.4**). These patterns may not be apparent to the naked eye, but most solid compounds are crystalline, and their crystal structures can be recognized and studied using X rays and other techniques. Examples of noncrystalline solids include glass (discussed later in the chapter) and plastic.

Identifying Characteristics of Minerals

The two fundamental characteristics of a mineral that together distinguish it from all other minerals are its chemical composition and its crystal structure. No two minerals are identical in both respects, though they may be the same in one. For example, diamond and graphite (the "lead" in a lead pencil) are chemically the same—both are made up of pure carbon. Their physical properties, however, are vastly different because of the differences in their internal crystalline structures. In a diamond, each carbon atom is firmly bonded to every adjacent carbon atom in every direction by covalent bonds. In graphite, the carbon atoms are bonded strongly in two dimensions into sheets, but the sheets are only weakly held together in the third dimension. Diamond is clear, colorless, and very hard, and a jeweler can cut it into beautiful precious gemstones. Graphite is black, opaque, and soft, and its sheets of carbon atoms tend to slide apart as the weak bonds between them are broken.

A mineral's composition and crystal structure can usually be determined only by using sophisticated laboratory equipment. When a mineral has formed large crystals with well-developed shapes, a trained mineralogist may be able to infer some characteristics of its internal atomic arrangement because crystals' shapes are controlled by and related to this atomic structure, but most mineral samples do not show large symmetric crystal forms by which they can be recognized with the naked eye. Moreover, many minerals share similar external forms, and the same mineral may show different external forms, though it will always have the same internal structure (**figure 2.5**). No one can look at a mineral and know its chemical composition without first recognizing what mineral it is. Thus, when scientific instruments are not at hand, mineral identification must be based on a variety of other physical properties that in some way reflect the mineral's composition and structure. These other properties are often what make the mineral commercially valuable. However, they are rarely unique to one mineral and often are deceptive. A few examples of such properties follow.

Other Physical Properties of Minerals

Perhaps surprisingly, color is often not a reliable guide to mineral identification. While some minerals always appear the same color, many vary from specimen to specimen. Variation in color is usually due to the presence of small amounts of

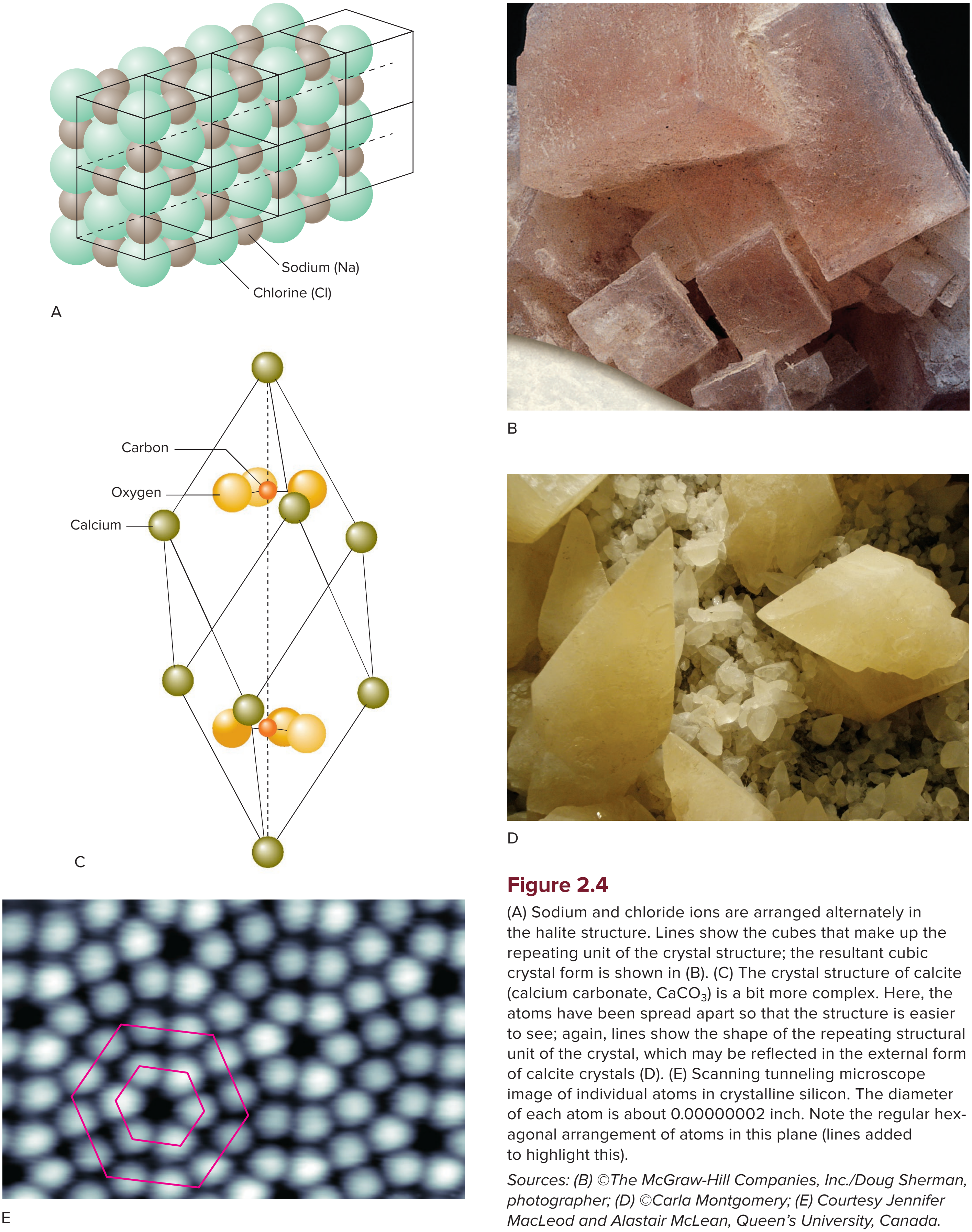


Figure 2.4

(A) Sodium and chloride ions are arranged alternately in the halite structure. Lines show the cubes that make up the repeating unit of the crystal structure; the resultant cubic crystal form is shown in (B). (C) The crystal structure of calcite (calcium carbonate, $CaCO_3$) is a bit more complex. Here, the atoms have been spread apart so that the structure is easier to see; again, lines show the shape of the repeating structural unit of the crystal, which may be reflected in the external form of calcite crystals (D). (E) Scanning tunneling microscope image of individual atoms in crystalline silicon. The diameter of each atom is about 0.00000002 inch. Note the regular hexagonal arrangement of atoms in this plane (lines added to highlight this).

Sources: (B) ©The McGraw-Hill Companies, Inc./Doug Sherman, photographer; (D) ©Carla Montgomery; (E) Courtesy Jennifer MacLeod and Alastair McLean, Queen's University, Canada.

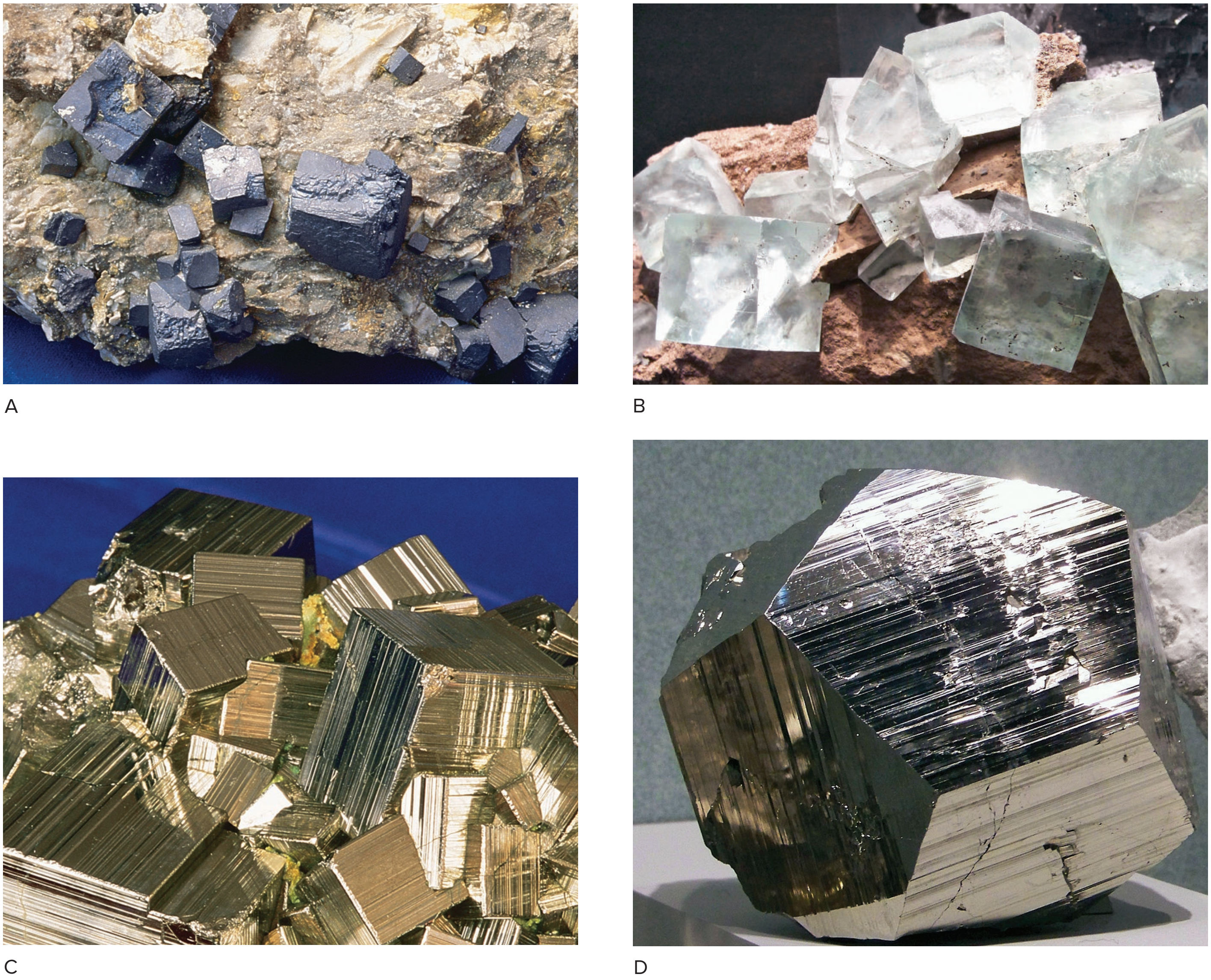


Figure 2.5

Many minerals may share the same external crystal form: (A) galena (PbS) and (B) fluorite (CaF_2) form cubes, as do halite (figure 2.4B) and pyrite (C). However, these minerals may show other forms; (D), for example, is a distinctive form of pyrite called a pyritohedron.

(A, C) ©Doug Sherman/Geofile; (B, D) ©Carla Montgomery.

chemical impurities in the mineral that have nothing to do with the mineral's basic characteristic composition, and such variation is especially common when the pure mineral is light-colored or colorless. The very common mineral quartz, for instance, is colorless in its pure form. However, quartz also occurs in other colors, among them rose pink, golden yellow, smoky brown, purple (amethyst), and milky white. Clearly, quartz cannot always be recognized by its color, or lack of it (**figure 2.6A**).

Another example is the mineral corundum, a simple compound of aluminum and oxygen. In pure form, it too is colorless, and quite hard (in fact, it is the second-hardest mineral known, after diamond), which makes it a good abrasive. It is often used for the grit on sandpaper. Yet a little color from trace impurities not only disguises corundum, it can transform this utilitarian material into highly prized gems: Traces of chromium produce the deep bluish-red gem we call ruby, while sapphire is just corundum tinted blue by iron and titanium. The color of a mineral can vary within a single crystal (**figure 2.6B**). Even when the color shown by a mineral sample is the true color of the pure mineral, it is probably not unique. There are approximately 4400 known minerals, so there are usually many of any one particular color. (Interestingly, *streak,* the color of the powdered mineral as revealed when the mineral is scraped across a piece of unglazed tile, may be quite different from the color of the bulk sample, and more consistent for a single mineral. However, a tile is not always handy, and some samples are too valuable to treat this way.)

Hardness, the ability to resist scratching, is another easily measured physical property that can help to identify a mineral,

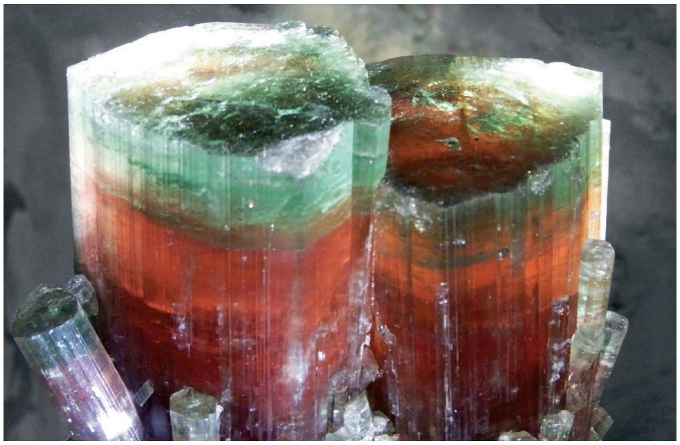


Figure 2.6

(A) The many colors of these quartz samples illustrate why color is a poor guide in mineral identification. See also figure 2.7B. (B) If chemical conditions change as a crystal grows, different parts may be different colors, as in this tourmaline.

(A, B) ©Carla Montgomery.

although it usually does not uniquely identify the mineral. Classically, hardness is measured on the Mohs hardness scale (**table 2.1**), in which ten common minerals are arranged in order of hardness. Unknown minerals are assigned a hardness on the basis of which minerals they can scratch and which minerals scratch them. A mineral that scratches gypsum and is scratched by calcite is assigned a hardness of 2½ (the hardness of an average fingernail). Because a diamond is the hardest natural substance known on earth, and corundum the second-hardest mineral, these minerals might be identifiable from their hardnesses. Among the thousands of "softer" (more readily scratched) minerals, however, there are many of any particular hardness, just as there are many of any particular color.

Not only is the external form of crystals related to their internal structure; so is **cleavage,** a distinctive way some minerals may break up when struck. Some simply crumble or shatter into irregular fragments (fracture). Others, however, break cleanly in certain preferred directions that correspond to planes of weak bonding in the crystal, producing planar cleavage faces. There may be only one direction in which a mineral shows good cleavage (as with mica, discussed later in the chapter), or there may be two or three directions of good cleavage. Cleavage surfaces are characteristically shiny (**figure 2.7**).

Table 2.1 **The Mohs Hardness Scale**

Mineral	Assigned Hardness
talc	1
gypsum	2
calcite	3
fluorite	4
apatite	5
orthoclase	6
quartz	7
topaz	8
corundum	9
diamond	10

For comparison, the approximate hardnesses of some common objects, measured on the same scale, are: fingernail, 2½; copper penny, 3; glass, 5 to 6; pocketknife blade, 5 to 6. These materials can be used to estimate an unknown mineral's hardness when samples of these reference minerals are not available.

A number of other physical properties may individually be common to many minerals. *Luster* describes the appearance of the surfaces—glassy, metallic, pearly, etc. Some minerals are noticeably denser than most; a few are magnetic. Usually it is only by considering a whole set of such nonunique properties as color, hardness, cleavage, density, and others together that a mineral can be identified without complex instruments. For instance, there are many colorless minerals; but if a sample of such a mineral has a hardness of only 3, cleaves into rhombohedral shapes, and fizzes when weak acid is dripped on it, it is probably calcite (the fizzing is due to release of carbon dioxide, CO_2, as the calcite reacts with the acid).

Unique or not, the physical properties arising from minerals' compositions and crystal structures are often what give minerals value from a human perspective—the slickness of talc (main ingredient of talcum powder), the malleability and conductivity of copper, the durability of diamond, and the rich colors of tourmaline gemstones are all examples. Some minerals have several useful properties: table salt (halite), a necessary nutrient, also imparts a taste we find pleasant, dissolves readily to flavor liquids but is soft enough not to damage our teeth if we munch on crystals of it sprinkled on solid food, and will serve as a food preservative in high concentrations, among other helpful qualities.

2.3 Types of Minerals

As was indicated earlier, minerals can be grouped or subdivided on the basis of their two fundamental characteristics—composition and crystal structure. Compositionally, classification is typically on the basis of ions or ion groups that a set of

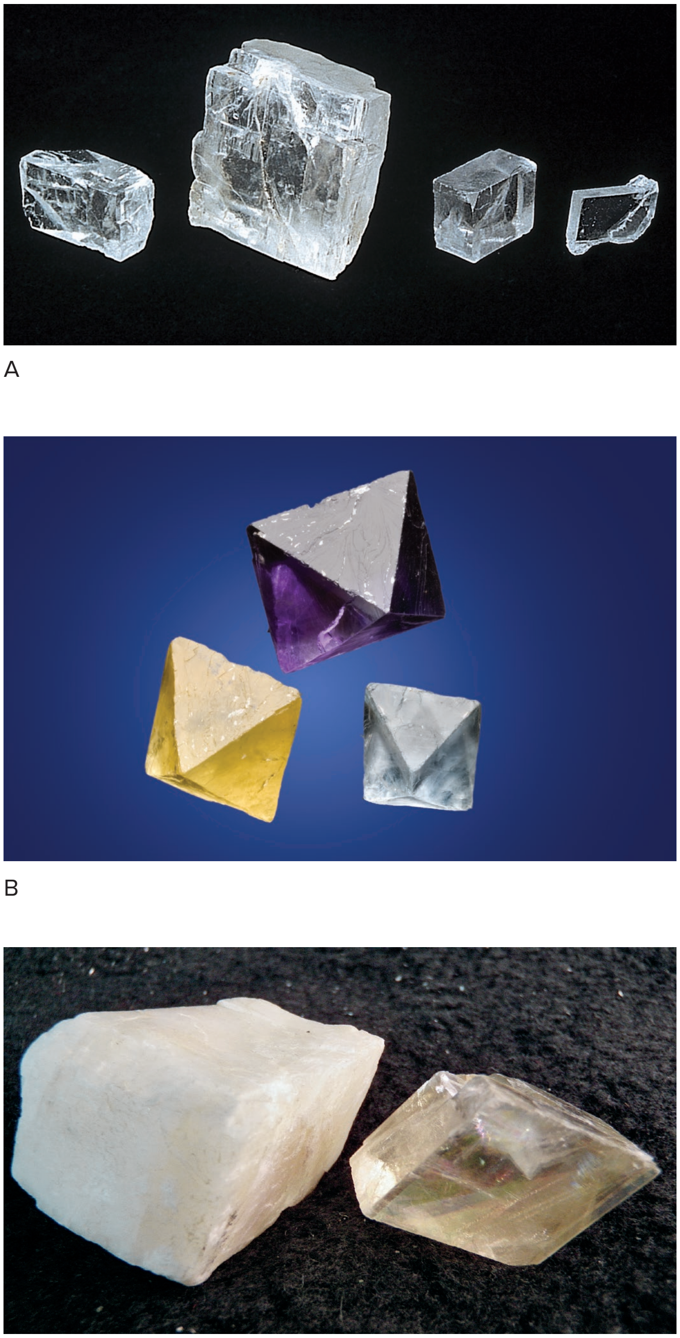


Figure 2.7

Another relationship between structures and physical properties is cleavage. Because of their internal crystalline structures, many minerals break apart preferentially in certain directions. (A) Halite has the cubic structure shown in figure 2.4A, and breaks into cubic or rectangular pieces, cleaving parallel to the crystal faces. (B) Fluorite also forms cubic crystals, but cleaves into octahedral fragments, breaking along different planes of its internal structure. (Note the variety of colors, too.) (C) Calcite cleaves into rhombohedra; compare with figure 2.4C.

(A) ©McGraw-Hill Education/Bob Coyle, photographer; (B) ©McGraw-Hill Education/Charles D. Winters, photographer; (C) ©Carla Montgomery.

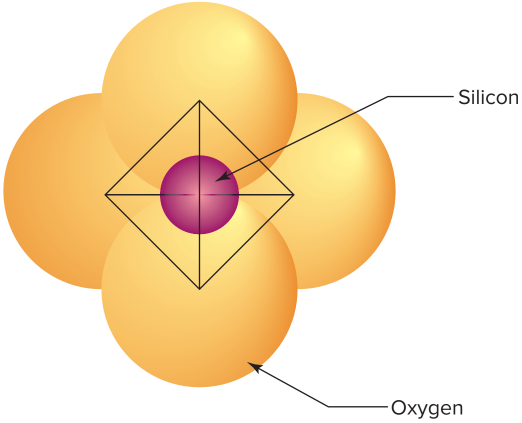


Figure 2.8

The basic silica tetrahedron, building block of all silicate minerals. (In figure 2.9, this group of atoms is represented only by the tetrahedron.)

minerals have in common. In this section, we will briefly review some of the basic mineral categories. A comprehensive survey of minerals is well beyond the scope of this book, and the interested reader should refer to standard mineralogy texts for more information. A summary of physical properties of selected minerals is found in appendix B.

Silicates

In chapter 1, we noted that the two most common elements in the earth's crust are oxygen and silicon. It comes as no surprise, therefore, that by far the largest compositional group of minerals is the **silicate** group, all of which are compounds containing silicon and oxygen, and most of which contain other elements as well. Because this group of minerals is so large, it is subdivided on the basis of crystal structure, by the ways in which the silicon and oxygen atoms are linked together. The basic building block of all silicates is a tetrahedral arrangement of four oxygen atoms (anions) around the much smaller silicon cation (**figure 2.8**). In different silicate minerals, these *silica tetrahedra* may be linked into chains, sheets, or three-dimensional frameworks by the sharing of oxygen atoms. Some of the physical properties of silicates and other minerals are closely related to their crystal structures (see **figure 2.9**). In general, we need not go into the structural classes of the silicates in detail. It is more useful to mention briefly a few of the more common, geologically important silicate minerals.

While not the most common, *quartz* is probably the best-known silicate. Compositionally, it is the simplest, containing only silicon and oxygen. It is a framework silicate, with silica tetrahedra linked in three dimensions, which helps make it relatively hard and weathering-resistant. Quartz is found in a variety of rocks and soils. Commercially, the most common use of pure quartz is in the manufacture of glass, which also consists mostly of silicon and oxygen. Quartz-rich sand and gravel are used in very large quantities in construction.

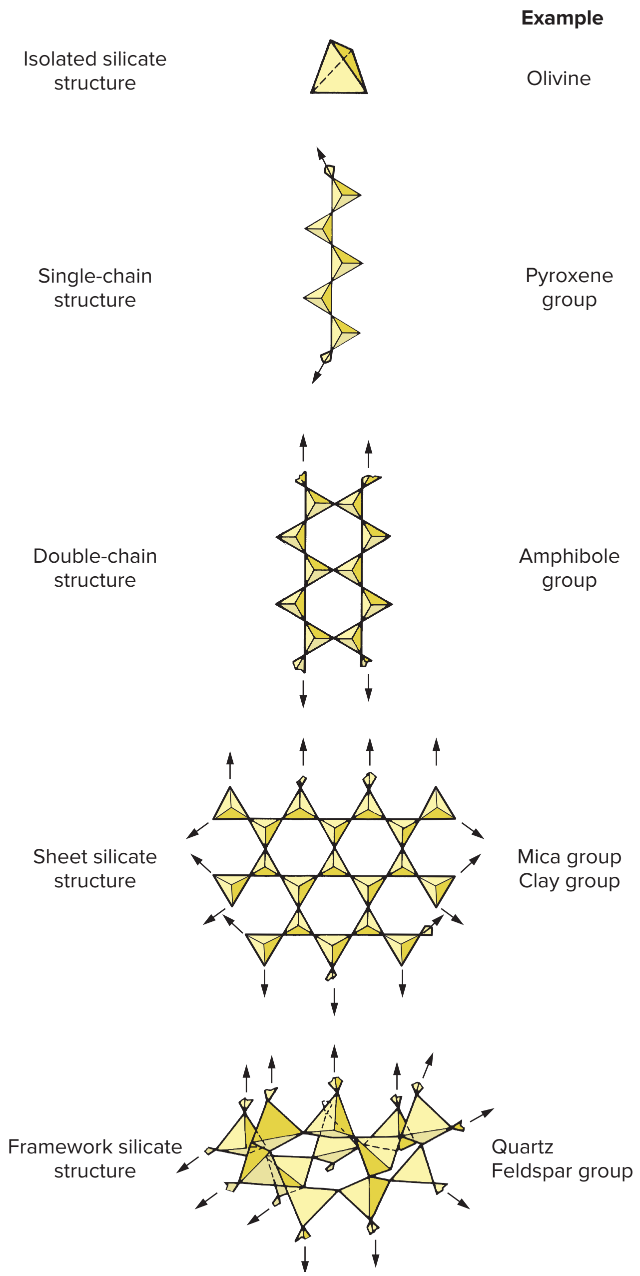


Figure 2.9

Silica tetrahedra link together by sharing oxygen atoms (where the corners of the tetrahedra meet) to form a variety of structures. (Olivine and the pyroxenes and amphiboles are among the ferromagnesian silicates, described in the text.) Other structural arrangements (such as stacked rings of tetrahedra) exist, but they are less common.

The most abundant group of minerals in the crust is a set of chemically similar minerals known collectively as the *feldspars.* They are composed of silicon, oxygen, aluminum, and either sodium, potassium, or calcium, or some combination of these three. Again, logically enough, these common minerals are made from elements abundant in the crust. They are used extensively in the manufacture of ceramics.

Iron and magnesium are also among the more common elements in the crust and are therefore found in many silicate minerals. **Ferromagnesian** is the general term used to describe those silicates—usually dark-colored (black, brown, or green)—that contain iron and/or magnesium, with or without additional elements.

Most ferromagnesian minerals weather relatively readily. Rocks containing a high proportion of ferromagnesian minerals, then, also tend to weather easily, which is an important consideration in construction. Individual ferromagnesian minerals may be important in particular contexts. *Olivine,* a simple ferromagnesian mineral, is a major constituent of earth's mantle; gem-quality olivines from mantle-derived volcanic rocks are the semiprecious gem *peridot.*

Like the feldspars, the *micas* are another group of several silicate minerals with similar physical properties, compositions, and crystal structures. Micas are sheet silicates, built on an atomic scale of stacked-up sheets of linked silicon and oxygen atoms. Because the bonds between sheets are relatively weak, the sheets can easily be broken apart (**figure 2.10C**).

Clays are another family within the sheet silicates; in clays, the sheets tend to slide past each other, a characteristic that contributes to the slippery feel of many clays and related minerals. Clays are somewhat unusual among the silicates in that their structures can absorb or lose water, depending on how wet conditions are. Absorbed water may increase the slippery tendencies of the clays. Also, some clays expand as they soak up water and shrink as they dry out. A soil rich in these "expansive clays" is a very unstable base for a building, as we will see in later chapters. On the other hand, clays also have important uses, especially in making ceramics and in building materials. Other clays are useful as lubricants in the muds used to cool the drill bits in oil-drilling rigs.

A sampling of the variety of silicates is shown in **figure 2.10**.

Nonsilicates

Just as the silicates, by definition, all contain silicon plus oxygen as part of their chemical compositions, each nonsilicate mineral group is defined by some chemical constituent or characteristic that all members of the group have in common. Most often, the common component is the same negatively charged ion or group of atoms. Discussion of some of the nonsilicate mineral groups with examples of common or familiar members of each follows. See also **table 2.2**.

The **carbonates** all contain carbon and oxygen combined in the proportions of one atom of carbon to three atoms of oxygen (written CO_3). The carbonate minerals all dissolve relatively easily, particularly in acids, and the oceans contain a great deal of dissolved carbonate. Geologically, the most important, most abundant carbonate mineral is calcite, which is calcium carbonate. Precipitation of calcium carbonate from seawater is a major process by which marine rocks are formed (see the discussion under "Sediments and Sedimentary Rocks" later in this chapter). Another common carbonate mineral is dolomite, which contains both calcium and magnesium in approximately equal proportions. Carbonates may contain many

Figure 2.10

A collection of silicates: (A) Crystals of olivine that have been tumbled for use as a semiprecious gem, peridot; (B) tremolite, a variety of amphibole; (C) mica, showing cleavage between sheets of tetrahedra; (D) potassium feldspar; and (E) quartz.

Sources: (A–C, E) ©Carla Montgomery; (D) U.S. Geological Survey Bureau of Mines.

other elements—iron, manganese, or lead, for example. The limestone and marble we use extensively for building and sculpture consist mainly of carbonates, generally calcite; calcite is also an important ingredient in cement.

The **sulfates** all contain sulfur and oxygen in the ratio of 1:4 (SO_4). A calcium sulfate—gypsum—is the most important, for it is both relatively abundant and commercially useful, particularly as the major constituent in plaster of paris. Sulfates of many other elements, including barium, lead, and strontium, are also found.

When sulfur is present without oxygen, the resultant minerals are called **sulfides.** A common and well-known sulfide mineral is the iron sulfide *pyrite.* Pyrite (**figures 2.5C, D**) has also been called "fool's gold" because its metallic golden color often deceived early gold miners and prospectors into thinking they had struck it rich. Pyrite is not a commercial source of iron because

Table 2.2 Some Nonsilicate Mineral Groups*

Group	Compositional Characteristic	Examples
carbonates	metal(s) plus carbonate (1 carbon + 3 oxygen ions, CO_3)	calcite (calcium carbonate, $CaCO_3$) dolomite (calcium-magnesium carbonate, $CaMg(CO_3)_2$)
sulfates	metal(s) plus sulfate (1 sulfur + 4 oxygen ions, SO_4)	gypsum (calcium sulfate, with water, $CaSO_4 \cdot 2H_2O$) barite (barium sulfate, $BaSO_4$)
sulfides	metal(s) plus sulfur, without oxygen	pyrite (iron disulfide, FeS_2) galena (lead sulfide, PbS) cinnabar (mercury sulfide, HgS)
oxides	metal(s) plus oxygen	magnetite (iron oxide, Fe_3O_4) hematite (ferric iron oxide, Fe_2O_3) corundum (aluminum oxide, Al_2O_3) spinel (magnesium-aluminum oxide, $MgAl_2O_4$)
hydroxides	metal(s) plus hydroxyl (1 oxygen + 1 hydrogen ion, OH)	gibbsite (aluminum hydroxide, $Al(OH)_3$; found in aluminum ore) brucite (magnesium hydroxide, $Mg(OH)_2$; one ore of magnesium)
halides	metal(s) plus halogen element (fluorine, chlorine, bromine, or iodine)	halite (sodium chloride, NaCl) fluorite (calcium fluoride, CaF_2)
native elements	mineral consists of a single chemical element	gold (Au), silver (Ag), copper (Cu), sulfur (S), graphite (carbon, C)

*Other groups exist, and some complex minerals contain components of several groups (carbonate and hydroxyl groups, for example).

there are richer ores of this metal. Nonetheless, sulfides comprise many economically important metallic ore minerals. An example that may be familiar is the lead sulfide mineral *galena,* which often forms in silver-colored cubes (**figure 2.5A**). The rich lead ore deposits near Galena, Illinois, gave the town its name. Sulfides of copper, zinc, and numerous other metals may also form valuable ore deposits (see chapter 13). Sulfides may also be problematic: When pyrite associated with coal is exposed by strip mining and weathered, the result is sulfuric acid in runoff water from the mine.

Minerals containing just one or more metals combined with oxygen, and lacking the other elements necessary to classify them as silicates, sulfates, carbonates, and so forth, are the **oxides.** Iron combines with oxygen in different proportions to form more than one oxide mineral. One of these, magnetite, is, as its name suggests, magnetic, which is relatively unusual among minerals. Magnetic rocks rich in magnetite were known as lodestone in ancient times and were used as navigational aids like today's more compact compasses. Another iron oxide, hematite, may sometimes be silvery black but often has a red color and gives a reddish tint to many soils. Iron oxides on Mars's surface are responsible for that planet's orange hue. Many other oxide minerals also exist, including corundum, the aluminum oxide mineral mentioned earlier.

Native elements, as shown in **table 2.2**, are even simpler chemically than the other nonsilicates. Native elements are minerals that consist of a single chemical element, and the minerals' names are usually the same as the corresponding elements. Not all elements can be found, even rarely, as native elements. However, some of our most highly prized materials, such as gold, silver, and platinum, often occur as native elements. Diamond and graphite are both examples of native carbon. Sulfur may occur as a native element, either with or without associated sulfide minerals. Some of the richest copper ores contain native copper. Other metals that may occur as native elements include tin, iron, and antimony.

Interestingly, several of the factors that make the Earth unique in the solar system also increase its mineralogic diversity. Earth is large enough still to retain sufficient internal heat to keep churning and reprocessing crust and mantle. Abundant surface water not only allows for hydrous minerals and supports life on Earth; organisms, in turn, modify the chemistry of atmosphere and oceans, which creates additional mineral possibilities. Altogether, it is estimated that Mars is likely to have only about one-tenth as many different minerals as are found on the Earth, while other rocky planets and Earth's moon would have still fewer. Many of Earth's thousands of minerals are rare curiosities, but many others have become vital resources.

2.4 Rocks

A **rock** is a solid, cohesive aggregate of one or more minerals, or mineral materials (for example, volcanic glass, discussed later). This means that a rock consists of many individual mineral grains (crystals)—not necessarily all of the same mineral—or crystals plus glass, which are firmly held together in a solid mass. Because the many mineral grains of beach sand fall apart when handled, sand is not a rock, although, in time, sand grains may become cemented together to form a rock. The properties

Case Study 2

Asbestos—A Tangled Topic

Billions of dollars are spent each year on asbestos abatement—removing and/or isolating asbestos in the materials of schools and other buildings—much of it mandated by law. The laws are intended to protect public health. But are they well-considered?

Asbestos is not a single mineral. To a geologist, the term describes any of a number of ferromagnesian chain silicates when they occur in needlelike or fibrous crystal forms. To OSHA (Occupational Safety and Health Administration), "asbestos" means one of six very specific minerals—five of them amphiboles—and only when they occur in small, elongated crystals of specific dimensions. Above certain very low concentration limits in air, abatement is mandatory.

The relevant regulations, first formulated in 1972 and modified since, were enacted after it was realized that certain lung diseases occurred much more frequently in workers in the asbestos industry than in the population at large. Occupational exposure to asbestos had been associated with later increased incidence of mesothelioma (a type of lung cancer) and other respiratory diseases, including a scarring of the lungs called asbestosis. The risks sometimes extended to families of asbestos workers, exposed secondhand to fibers carried home on clothes, and to residents of communities where asbestos processing occurred.

However, the precise level of risk, and appropriate exposure limits, cannot be determined exactly. Most of the diseases caused by asbestos can be caused, or aggravated, by other agents and activities (notably smoking) too, and they generally develop long after exposure. Even for workers in the asbestos industry, the link between asbestos exposure and lung disease is far from direct. For setting exposure limits for the general public, it has been assumed that the risk from low, incidental exposure to asbestos can be extrapolated linearly from the identified serious effects of high occupational exposures, while there is actually no evidence that this yields an accurate estimate of the risks from low exposures. Some advocate what is called the "one-fiber theory" (really only a hypothesis!)—that if inhaling a lot of asbestos fibers is bad, inhaling even one does some harm. Yet we are all exposed to some airborne asbestos fibers from naturally occurring asbestos in the environment. In fact, measurements have indicated that an adult breathing typical outdoor air would inhale *nearly 4000 asbestos fibers a day.* The problem is very much like that of setting exposure limits for radiation, discussed in chapter 16, for we are all exposed daily to radiation from our environment, too.

Moreover, studies have clearly shown that different asbestos minerals present very different degrees of risk. In general, the risks from amphibole asbestos seem to be greatest. Mesothelioma is associated particularly with occupational exposure to the amphibole *crocidolite,* "blue asbestos," and asbestosis with another amphibole, *amosite,* "grey asbestos," mined almost exclusively in South Africa. On the other hand, the non-amphibole asbestos *chrysotile,* "white asbestos" (**figure 1**), which represents about 95% of the asbestos used in the United States, appears to be by far the least hazardous asbestos, and to pose *no* significant health threat from incidental exposure in the general public, even in buildings with damaged, exposed asbestos-containing materials. So, arguably, chrysotile could be exempted from the abatement regulations applied outside the asbestos industry proper, with a corresponding huge reduction in national abatement expenditures.

The case of Libby, Montana, is also interesting. Beginning in 1919, *vermiculite* (a ferromagnesian sheet silicate; **figure 2**), used in insulation and as a soil conditioner, was mined from a deposit near Libby. Unfortunately, it was found that the vermiculite in that deposit is associated with asbestos, including *tremolite* (**figure 2.10B**), one of the OSHA-regulated amphibole-asbestos varieties. Decades ago, workers appealed to the state board of health for safer working conditions, but little was done for years. Meanwhile, Libby vermiculite was used in attic insulation in local homes, and waste rock from the processing was tilled into local soil, so exposures went beyond mining operations. Over time, at least 1500 people in Libby—workers and town residents—became ill, and an estimated 400 have died, from lung diseases attributed to asbestos. The mine closed in 1990, EPA moved in in 1999, and cleanup of the town's buildings and soils has begun. Recent geologic studies have revealed several other pertinent facts: (1) Only about 6% of the asbestos in the Libby vermiculite deposit is tremolite. Most consists of chemically similar varieties of amphibole, which might also cause lung disease but which are *not* OSHA-regulated. (2) The soils of the town contain other

of rocks are important in determining their suitability for particular applications, such as for construction materials or for the base of a building foundation. Each rock also contains within it a record of at least a part of its history, in the nature of its minerals and in the way the mineral grains fit together. The three broad categories of rocks—*igneous, sedimentary,* and *metamorphic*—are distinguished by the processes of their formation. However, they are also linked, over time, by the *rock cycle.*

In chapter 1, we noted that the earth is a constantly changing body. Mountains come and go; seas advance and retreat over the faces of continents; surface processes and processes occurring deep in the crust or mantle are constantly altering the planet. One aspect of this continual change is that rocks, too, are always subject to change. We do not have a single sample of rock that has remained unchanged since the earth formed. Therefore, when we describe a rock as being of a particular type, or give it a specific rock name, it is important to realize that we are really describing the form it has most recently taken, the results of the most recent processes acting on it.

asbestos that is chemically and mineralogically distinct from the asbestos of the deposit. (3) The deposit weathers easily, and lies in hills upstream from Libby. So, not surprisingly, there is deposit-related asbestos in town soils that clearly predate any mining activity, meaning that residents could easily have been exposed to deposit-related asbestos that was unrelated to mining activity.

The evidence indicates that significant risk is associated with Libby amphibole species that are not OSHA-regulated. Perhaps they should be—and given the health effects observed in Libby, cleanup certainly seems desirable. On the other hand, given that little of the asbestos at Libby is actually one of the OSHA six, and considering the other facts noted, how much liability should the mining company bear for the cleanup? It has proved to be a long and costly process: So far it has consumed more than 15 years and $540 million. Cleanup of a property involves replacing contaminated soil with clean soil and removing accessible asbestos-bearing building materials for disposal. Over 7100 properties have been inspected, cleanup has been completed at 2275 of these found to require it, and EPA estimates that several hundred more properties in need of cleanup remain. It hopes to complete the work by 2020.

With asbestos abatement generally, should the regulations be modified to take better account of what we now know about the relative risks of different asbestos varieties? That might well be appropriate. (Unfortunately, some lawmakers have proposed going to the extreme of defining “asbestos” as “elongated mineral particles,” ignoring mineralogy altogether, a definition so broad as to include quartz, feldspar, and other common minerals that obviously pose no risk to the general population, which would divert abatement efforts, and funds, from the small number of minerals posing real dangers.) In general, how would you decide when the benefits of such a regulation justify the costs? This question will arise again in chapter 19.

Figure 1

Chrysotile asbestos, or “white asbestos,” accounts for about 95% of asbestos mined and used in the United States.

©McGraw-Hill Education/Bob Coyle, photographer.

Figure 2

Vermiculite. This sample has been processed for commercial use; it has been heated to expand the grains, “popping” them apart between silicate sheets.

©Carla Montgomery.

For example, as will be described in the following section, an *igneous rock* is one crystallized from molten material, formed at high temperatures. But virtually any rock can be melted, and in the process, its previous characteristics may be obliterated. So when the melt crystallizes, we have an igneous rock—but what was it before? A *sedimentary rock* is formed from sediment, debris of preexisting rocks deposited at low temperatures at the earth’s surface. But the sediment, in turn, is derived by weathering—physical and chemical breakdown of rocks—and a given deposit of sediment may include bits of many different rocks. (Look closely at beach sand or river gravel.) The essence of the concept of the **rock cycle,** explored more fully at the end of this chapter, is that rocks, far from being the permanent objects we may imagine them to be, are continually being changed by geological processes. Over the vast span of geologic time, billions of years, a given bit of material may have been subject to many, many changes and may have been part of many different rocks. The following sections examine in more detail the various types of rock-forming processes involved and some of the rocks they form.

Igneous Rocks

At high enough temperatures, rocks and minerals can melt. **Magma** is the name given to naturally occurring hot, molten rock material. Silicates are the most common minerals, so magmas are usually rich in silica. They also contain some dissolved water and gases and generally have some solid crystals suspended in the melt. An **igneous** rock is a rock formed by the solidification and crystallization of a cooling magma. (*Igneous* is derived from the Latin term *ignis,* meaning "fire.")

Because temperatures significantly higher than those of the earth's surface are required to melt silicates, magmas form at some depth below the surface. The molten material may or may not reach the surface before it cools enough to crystallize and solidify. The depth at which a magma crystallizes will affect how rapidly it cools and the sizes of the mineral grains in the resultant rock.

If a magma remains well below the surface during cooling, it cools relatively slowly, insulated by overlying rock and soil. It may take hundreds of thousands of years or more to crystallize completely. Under these conditions, the crystals have ample time to form and to grow very large, and the rock eventually formed has mineral grains large enough to be seen individually with the naked eye. A rock formed in this way is a **plutonic** igneous rock. (The name is derived from Pluto, the Greek god of the lower world.) *Granite* is probably the most widely known example of a plutonic rock (**figure 2.11A**). Compositionally, a typical granite consists principally of quartz and feldspars, and it usually contains some ferromagnesian minerals or other silicates. The proportions and compositions of these constituent minerals may vary, but all granites show the coarse, interlocking crystals characteristic of a plutonic rock. Much of the mass of the continents consists of granite or of rock of granitic composition.

A magma that flows out on the earth's surface while still wholly or partly molten is called **lava.** Lava is a common product of volcanic eruptions, and the term **volcanic** is given to an igneous rock formed at or close to the earth's surface. Magmas that crystallize very near the surface cool more rapidly. There is less time during crystallization for large crystals to form from the magma, so volcanic rocks are typically fine-grained, with most crystals too small to be distinguished with the naked eye. In extreme cases, where cooling occurs very fast, even tiny crystals may not form before the magma solidifies, and its atoms are frozen in a disordered state. The resulting clear, noncrystalline solid is a natural **glass,** *obsidian* (**figure 2.11B**). The most common volcanic rock is *basalt,* a dark rock rich in ferromagnesian minerals and feldspar (**figure 2.11C**). The ocean floor consists largely of basalt. Occasionally, a melt begins to crystallize slowly at depth, growing some large crystals, and then is subjected to rapid cooling (following a volcanic eruption, for instance). This results in coarse crystals in a fine-grained groundmass, a *porphyry* (**figure 2.11D**).

Though there are fundamental similarities in the origins of magmas and volcanic rocks, there are practical differences, too. Differences in the chemical compositions of magmas lead to differences in their physical properties, with magmas richer in silica (SiO_2) tending to be more viscous. This, in turn, produces differences in the behavior of the volcanoes from which the magmas erupt, explaining why the Hawaiian volcano Kilauea erupts so quietly that tourists can almost walk up and touch the lava flows in safety, while Mount St. Helens and the Philippine volcano Pinatubo are prone to violent, sudden, and devastating explosions. Relationships among magma origins, magma types, and volcanoes' eruptive styles will be explored further in chapter 5.

Regardless of the details of their compositions or cooling histories, all igneous rocks have some textural characteristics in common. If they are crystalline, their crystals, large or small, are tightly interlocking or intergrown (unless they are formed from loose material such as volcanic ash). If glass is present, crystals tend to be embedded in or closely surrounded by the glass. The individual crystals tend to be angular in shape, not rounded. There is usually little pore space, little empty volume that could be occupied by such fluids as water. Structurally, most plutonic rocks are relatively strong unless they have been fractured, broken, or weathered.

Sediments and Sedimentary Rocks

At the lower end of the spectrum of rock-formation temperatures are the **sedimentary** rocks. **Sediments** are loose, unconsolidated accumulations of mineral or rock particles that have been transported by wind, water, or ice, or shifted under the influence of gravity, and redeposited. Beach sand is a kind of sediment; so is the mud on a river bottom. Soil is a mixture of mineral sediment and organic matter. Most sediments originate, directly or indirectly, through the weathering of preexisting rocks—either by physical breakup into finer and finer fragments, or by solution, followed by precipitation of crystals out of solution. The physical properties of sediments and soils bear on a broad range of environmental problems, from the stability of slopes and building foundations, to the selection of optimal waste-disposal sites, to how readily water drains away after a rainstorm and therefore how likely that rain is to produce a flood.

When sediments are compacted or cemented together into a solid, cohesive mass, they become sedimentary rocks. The set of processes by which sediments are transformed into rock is collectively described as **lithification** (from the Greek word *lithos,* meaning "stone"). The resulting rock is generally more compact and denser, as well as more cohesive, than the original sediment. Sedimentary rocks are formed at or near the earth's surface, at temperatures close to ordinary surface temperatures. They are subdivided into two groups—clastic and chemical.

Clastic sedimentary rocks (from the Greek word *klastos,* meaning "broken") are formed from the products of the mechanical breakup of other rocks. Natural processes continually attack rocks exposed at the surface. Rain and waves pound them, windblown dust scrapes them, frost and tree roots crack them—these and other processes are all part of the physical weathering of rocks. In consequence, rocks are broken up into smaller and smaller pieces and ultimately, perhaps, into individual mineral grains. The resultant rock and mineral fragments may be transported by wind, water, or ice, and accumulate as sediments in streams, lakes, oceans, deserts, or soils. Later geologic processes can cause these sediments to become lithified. Burial under the