eleventh edition

Environmental Geology

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In Dedication

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

–CWM–

Preface

About the Course

Environmental Geology Is Geology Applied to Living

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

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

Why Study Environmental Geology?

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

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

About the Book

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

Features Designed for the Student

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

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

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

New and Updated Content

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

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

Content additions and revisions to specific chapters include:

Chapter 1 Population data and projections have been updated.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Organization

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

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

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

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

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

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

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

Acknowledgments

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

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

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

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

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

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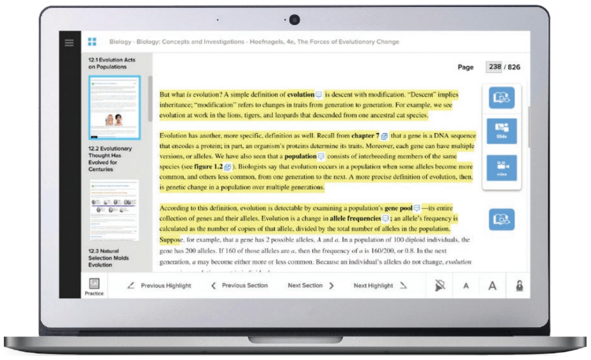

But what *is* evolution? A simple definition of **evolution** is descent with modification. "Descent" implies inheritance; "modification" refers to changes in traits from generation to generation. For example, we see evolution at work in the lions, tigers, and leopards that descended from one ancestral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

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

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

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>
> - Jordan Cunningham,
> Eastern Washington University

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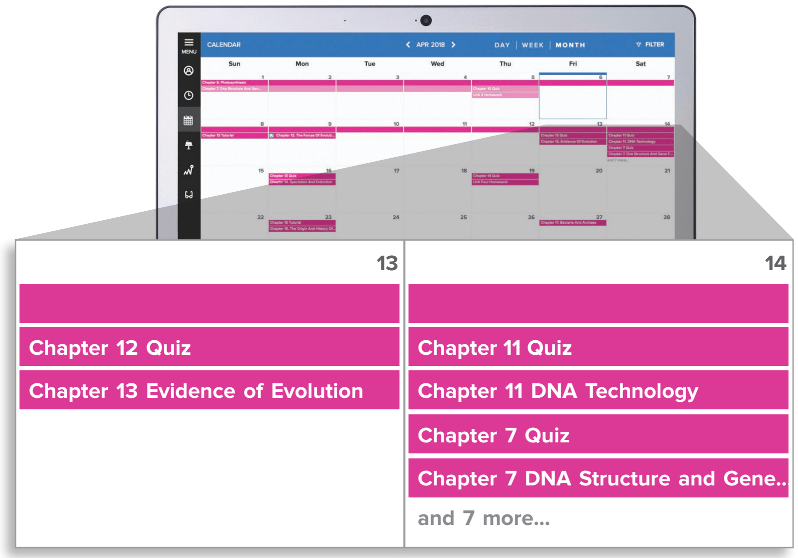

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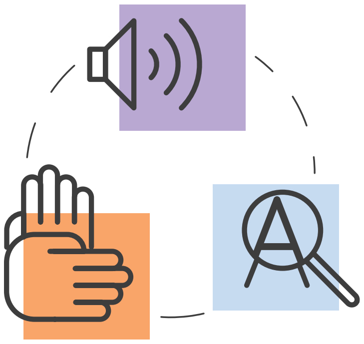

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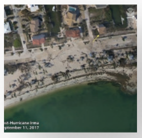

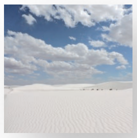

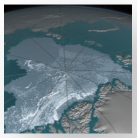

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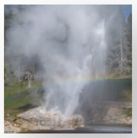

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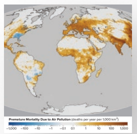

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CHAPTER 2

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.

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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.

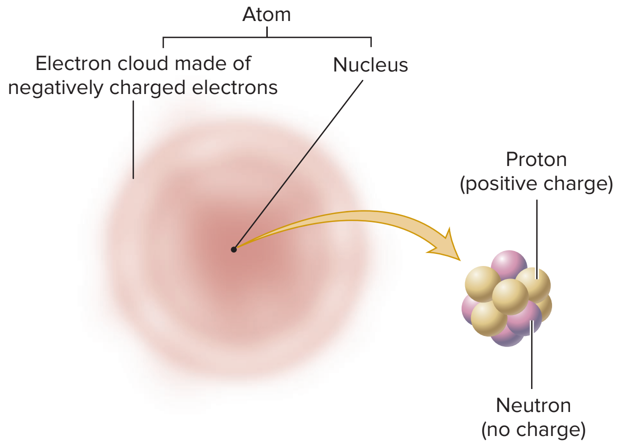
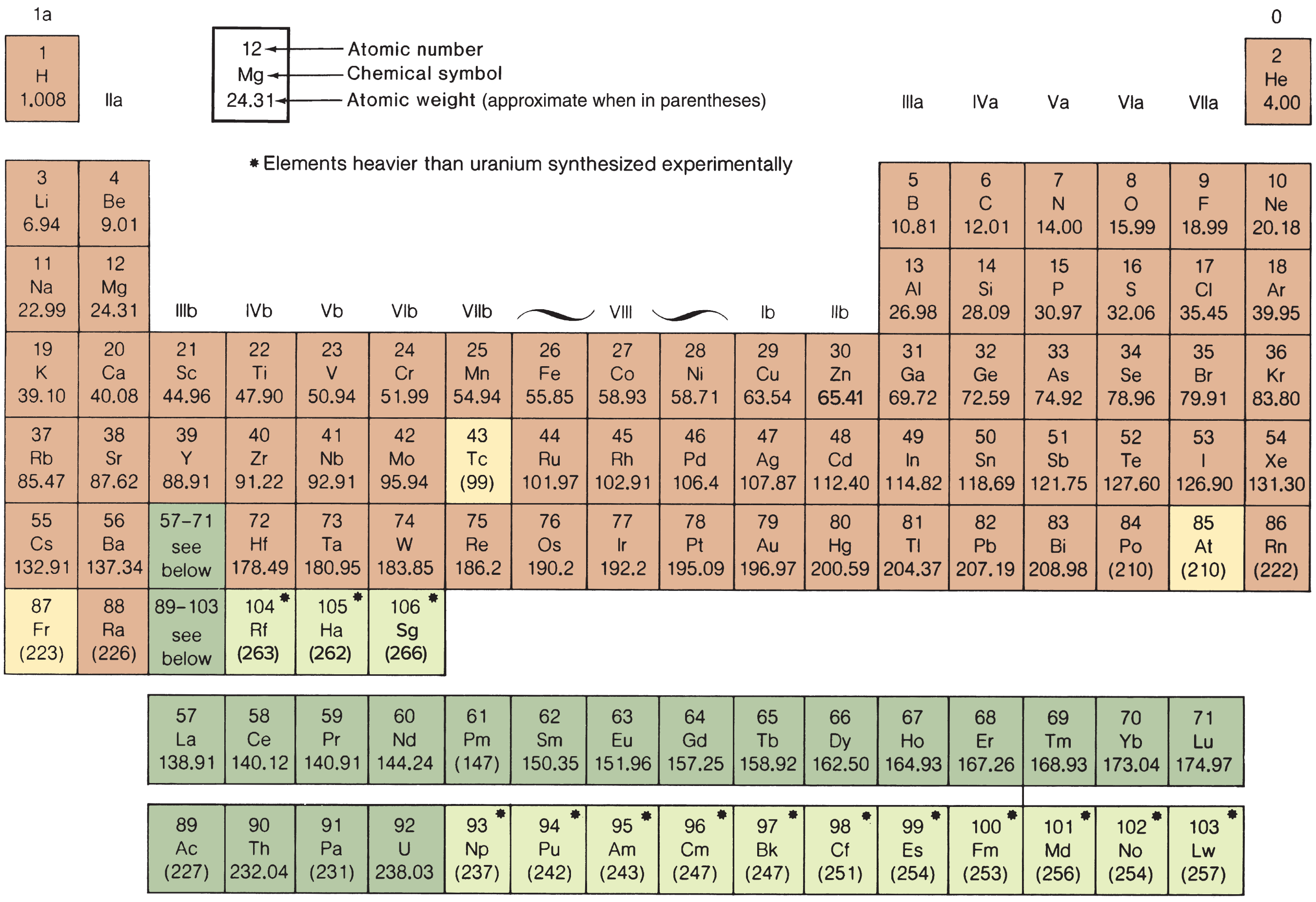


Figure 2.1

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.



1a	IIa	IIIb	IVb	Vb	VIb	VIIb	VIII	VIII	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)

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

* Elements heavier than uranium synthesized experimentally

Figure 2.2

The periodic table.

The Periodic Table

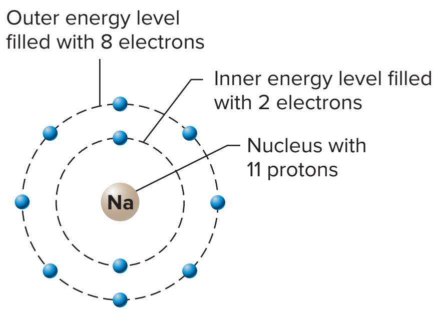
Some idea of the probable chemical behavior of elements can be gained from a knowledge of the **periodic table** (figure 2.2). The Russian scientist Dmitri Mendeleyev first observed that certain groups of elements showed similar chemical properties, which seemed to be related in a regular way to their 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.

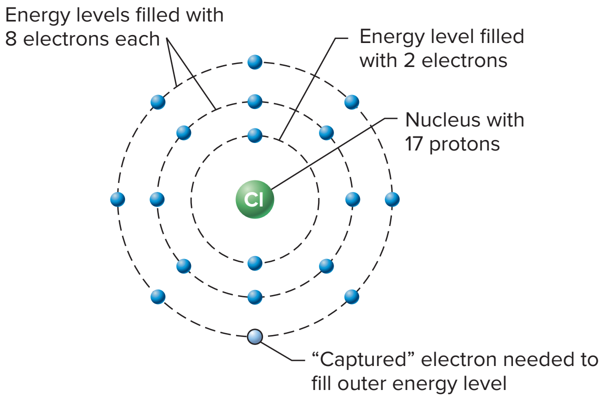
The elements that occur naturally on earth have now been known for decades. Additional new elements must be created, not simply discovered, because these very heavy elements, with atomic numbers above 92 (uranium), are too unstable to have lasted from the early days of the solar system to the present. 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



Sodium (Na^+)



Chlorine (Cl^-)

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

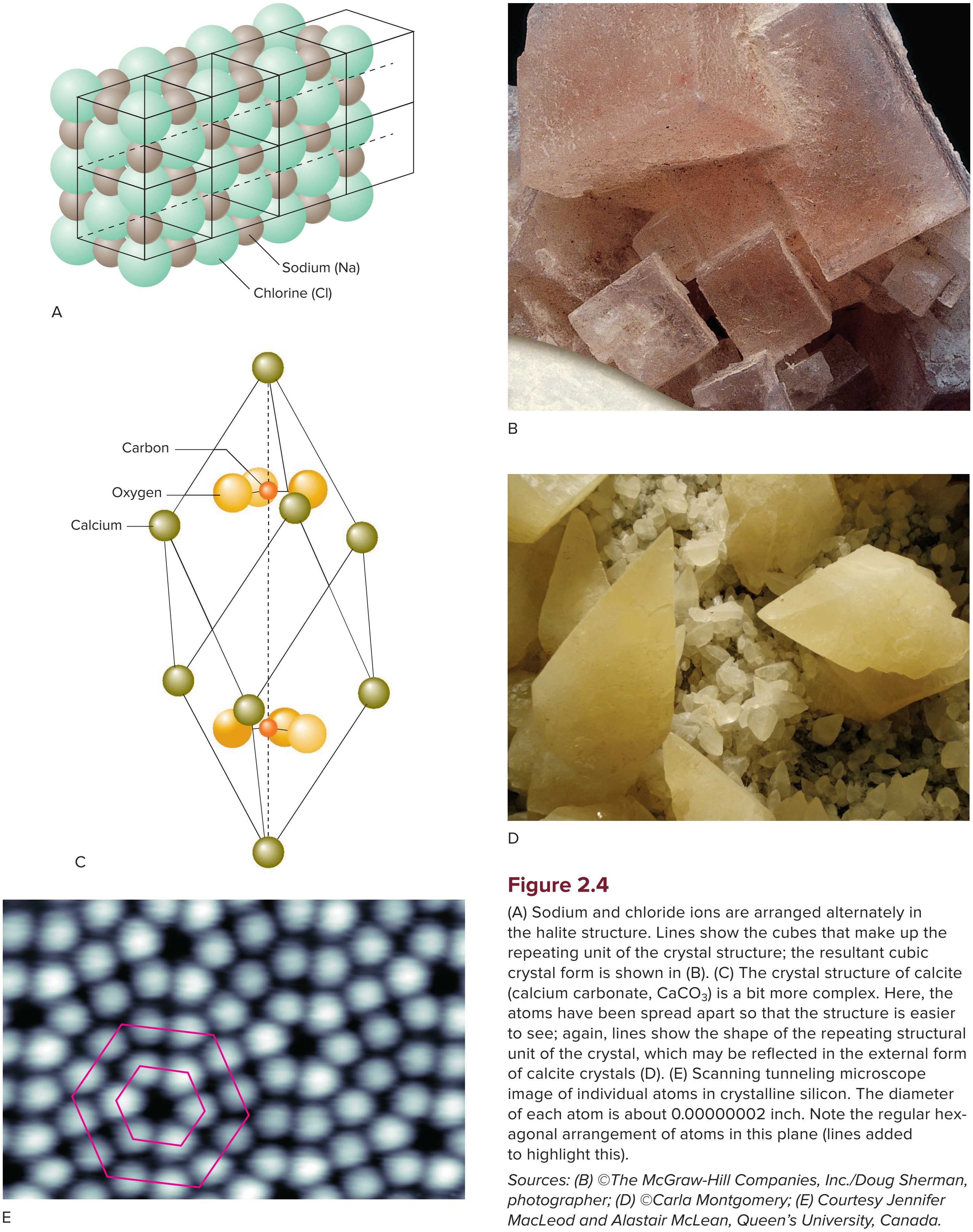


Figure 2.4

(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.

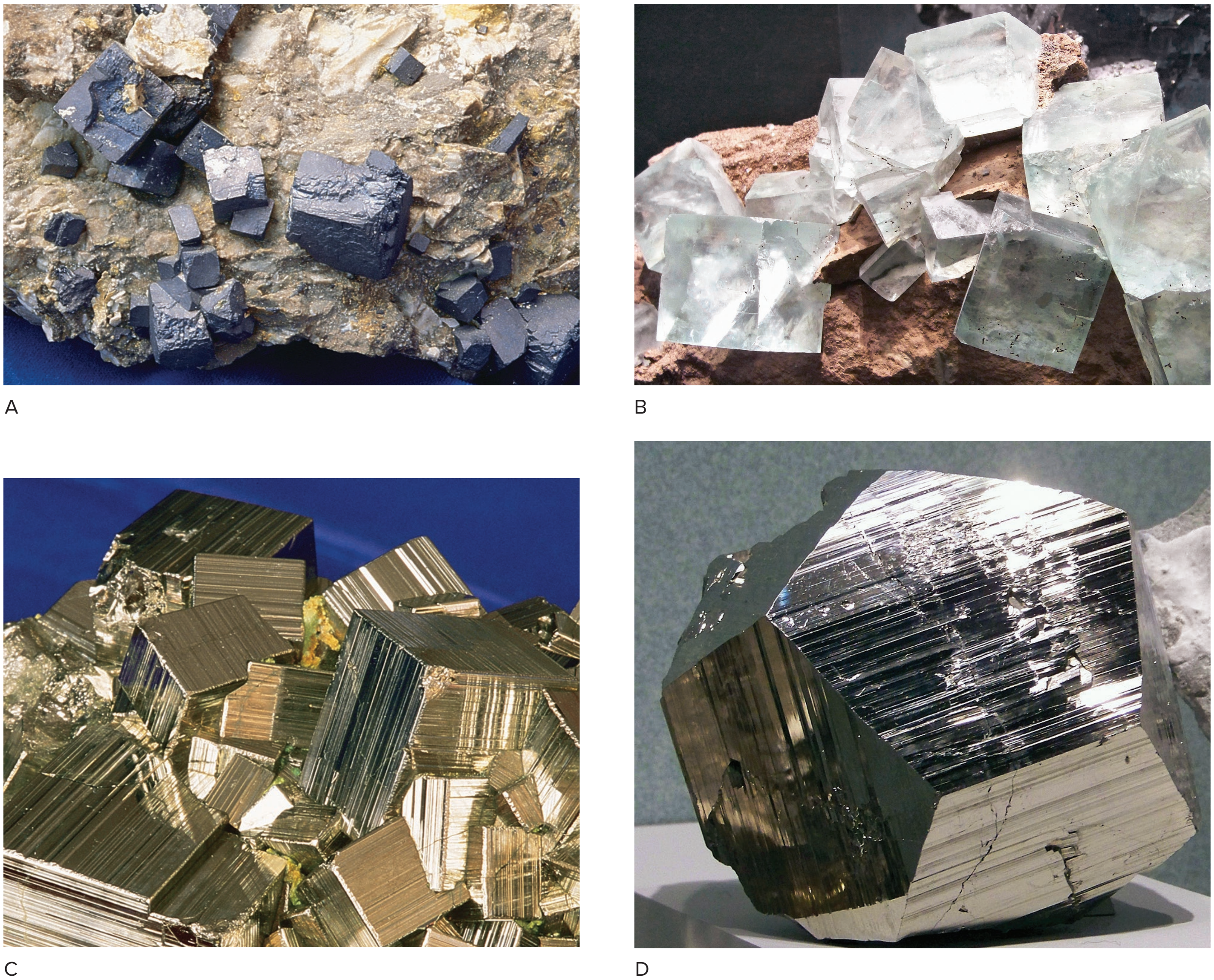


Figure 2.5

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,

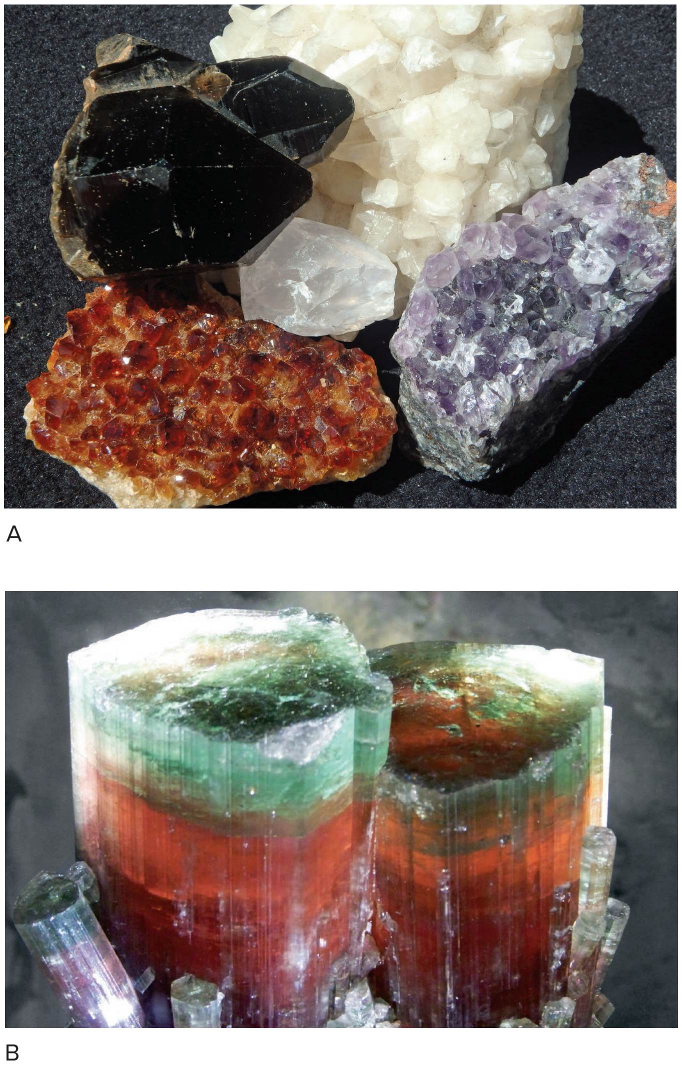


Figure 2.6

(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

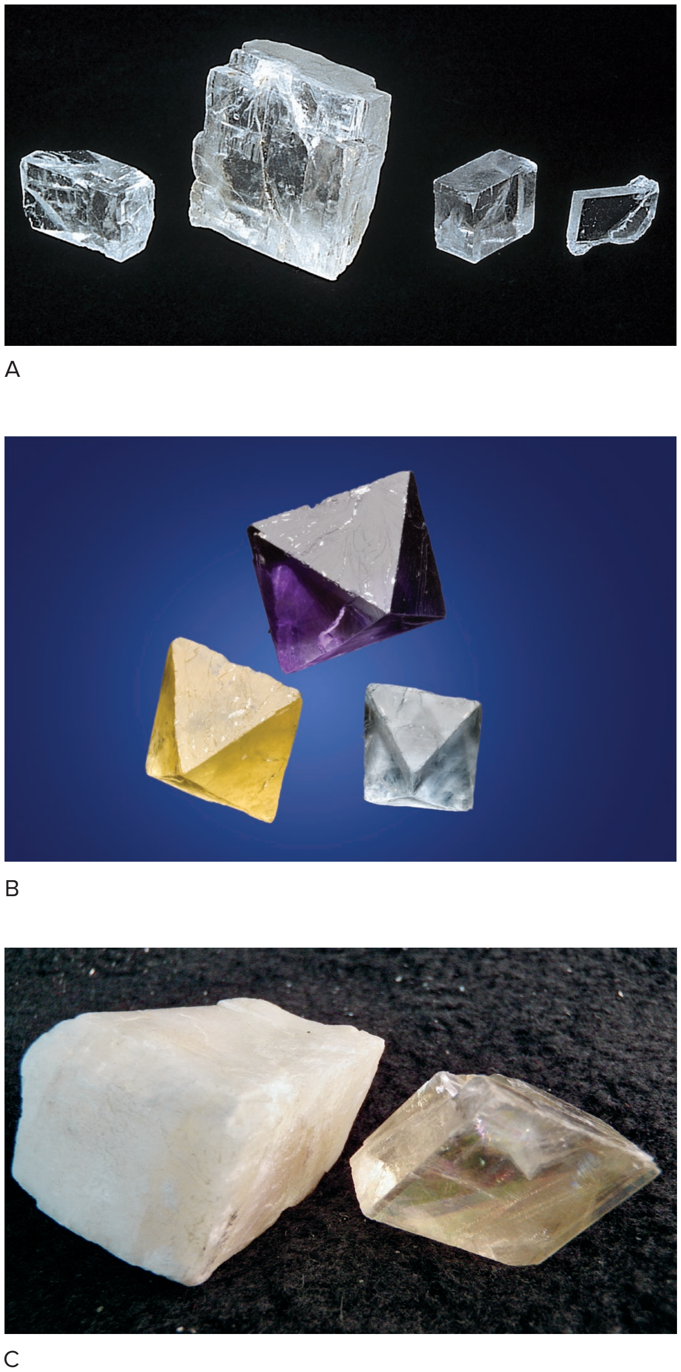


Figure 2.7

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.

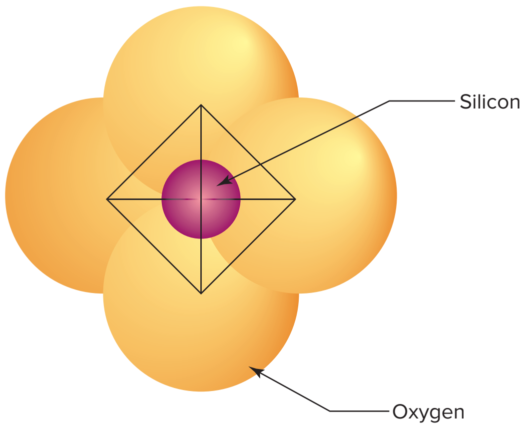


Figure 2.8

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.

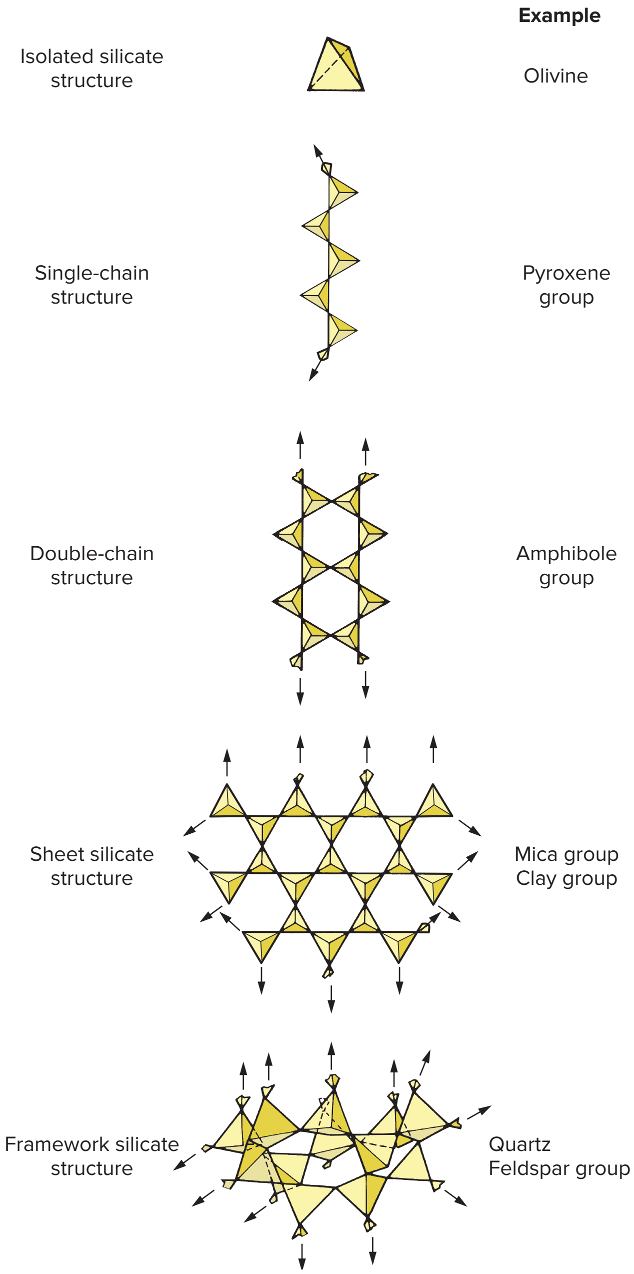


Figure 2.9

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.

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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.

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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

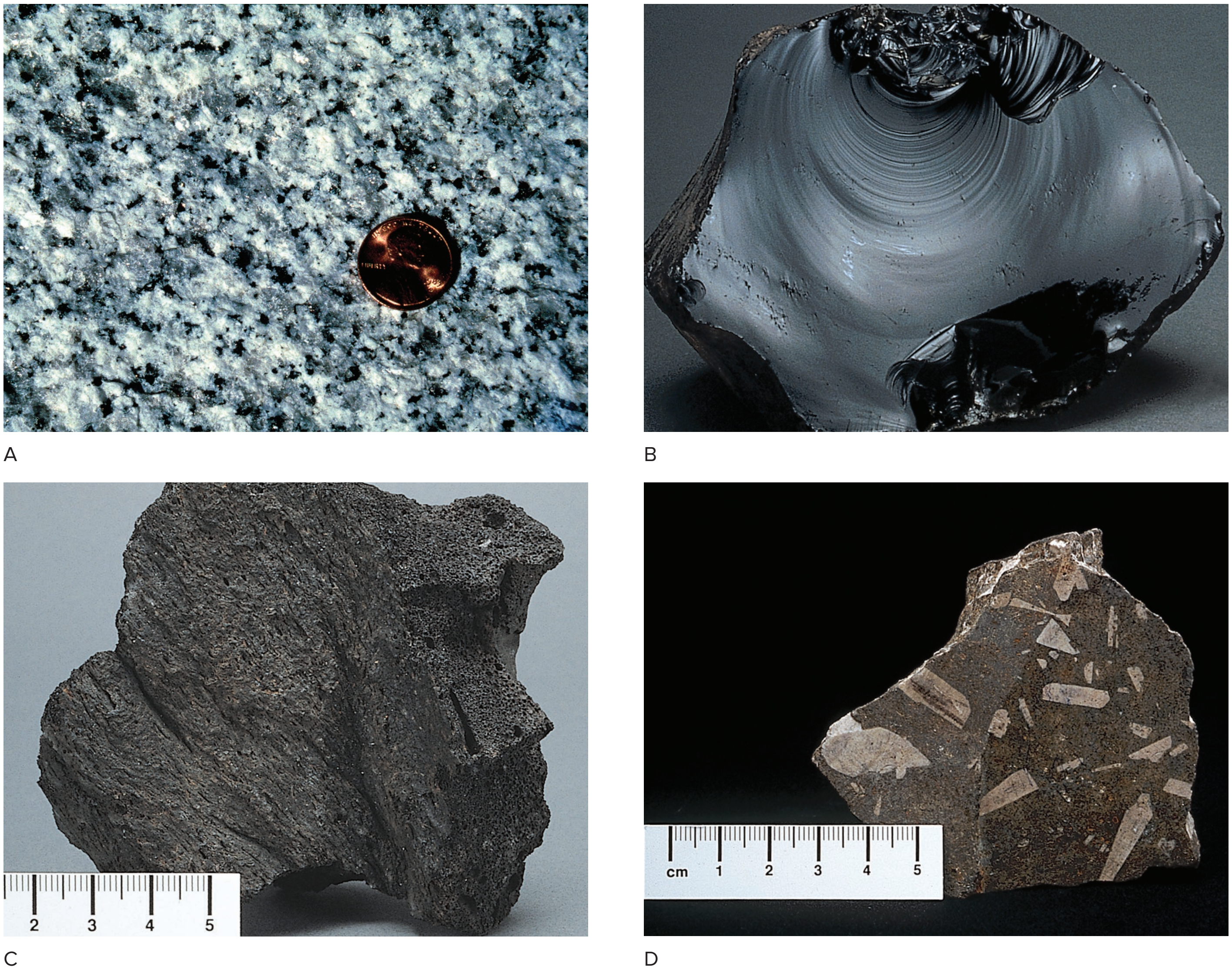


Figure 2.11

Igneous rocks, crystallized from melts. (A) Granite, a plutonic rock; this sample is the granite of Yosemite National Park. (B) Obsidian (volcanic glass). (C) Basalt, a volcanic rock. (D) Porphyry, an igneous rock with coarse crystals in a finer matrix. Note that the coarse crystals in the porphyry, growing while suspended in fluid magma, could develop recognizable, symmetric crystal faces. The minerals in the granite are all crystalline too, but as the melt crystallized completely, adjacent crystals slowly grew into each other at a variety of angles, so the resulting grain shapes are irregular.

Sources: (A) U.S. Geological Survey/Photograph by N. K. Huber; (B–D) ©McGraw-Hill Education/Bob Coyle, photographer.

weight of more sediments may pack the loose particles so tightly that they hold firmly together in a cohesive mass. Except with very fine-grained sediments, however, compaction alone is rarely enough to transform the sediment into rock. Water seeping slowly through rocks and sediments underground also carries dissolved minerals, which may precipitate out of solution to bind the sediment particles together with a natural mineral cement.

Clastic sedimentary rocks are most often named on the basis of the average size of the particles that form the rock. *Sandstone,* for instance, is a rock composed of sand-sized sediment particles, $\frac{1}{16}$ to 2 millimeters (0.002 to 0.08 inch) in diameter. *Shale* is made up of finer-grained sediments, and the individual grains cannot be seen in the rock with the naked eye. *Conglomerate* is a relatively coarse-grained rock, with fragments above 2 millimeters (0.08 inch) in diameter, and sometimes much larger. Regardless of grain size, clastic sedimentary rocks tend to have, relatively, considerable pore space between grains. This is a logical consequence of the way in which these rocks form, by the piling up of preexisting rock and mineral grains. Also, as sediment particles are transported by water or other agents, they may become more rounded and thus not pack together very tightly or interlock as do the mineral grains in an igneous rock.

Many clastic sedimentary rocks are therefore not particularly strong structurally, unless they have been extensively cemented.

Chemical sedimentary rocks form not from mechanical breakup and transport of fragments, but from crystals formed by precipitation or growth from solution. A common example is *limestone,* composed mostly of calcite (calcium carbonate). The chemical sediment that makes limestone may be deposited from fresh or salt water; under favorable chemical conditions, thick limestone beds, perhaps hundreds of meters thick, may form. Another example of a chemical sedimentary rock is *rock salt,* made up of the mineral halite, which is the mineral name for ordinary table salt (sodium chloride). A salt deposit may form when a body of salt water is isolated from an ocean and dries up.

Some chemical sediments have a large biological contribution. For example, many organisms living in water have shells or skeletons made of calcium carbonate or of silica (SiO_2, chemically equivalent to quartz). The materials of these shells or skeletons are drawn from the water in which the organisms grow. In areas where great numbers of such creatures live and die, the "hard parts"—the shells or skeletons—may pile up on the bottom, eventually to be buried and lithified. A sequence of sedimentary rocks may include layers of **organic sediments,** carbon-rich remains of living organisms; *coal* is an important example, derived from the remains of land plants that flourished and died in swamps.

Gravity plays a role in the formation of all sedimentary rocks. Mechanically broken-up bits of materials accumulate when the wind or water is moving too weakly to overcome gravity and move the sediments; repeated cycles of transport and deposition can pile up, layer by layer, a great thickness of sediment. Minerals crystallized from solution, or the shells of dead organisms, tend to settle out of the water under the force of gravity, and again, in time, layer on layer of sediment can build up. Layering, then, is a very common feature of sedimentary rocks and is frequently one way in which their sedimentary origins can be identified; see, for example, the chapter-opening photograph. **Figure 2.12** shows several kinds of sedimentary rocks.

Sedimentary rocks can yield information about the settings in which the sediments were deposited. For example, the energetic surf of a beach washes away fine muds and leaves coarser sands and gravels; sandstone may, in turn, reflect the presence of an ancient beach. Distribution of glacier-deposited sediments of various ages contributes to our understanding not only of global climate change but also of plate tectonics (see chapter 3).

Metamorphic Rocks

The name *metamorphic* comes from the Greek for "changed form." A **metamorphic** rock is one that has formed from another, preexisting rock that was subjected to heat and/or pressure. The temperatures required to form metamorphic rocks are not as high as the temperatures at which the rocks would melt. Significant changes can occur in a solid rock at temperatures well below melting. Heat and pressure commonly cause the minerals in the rock to recrystallize. The original minerals may form larger crystals that perhaps interlock more tightly than before. Also, some minerals may break down completely, while new minerals form under the new temperature and pressure conditions. Pressure may cause the rock to become deformed—compressed, stretched, folded, or compacted. All of this occurs while the rock is still solid; it does not melt during metamorphism.

The sources of the elevated pressures and temperatures of metamorphism are many. An important source of pressure is simply burial under many kilometers of overlying rock. The weight of the overlying rock can put great pressure on the rocks below. One source of elevated temperatures is the fact that temperatures increase with depth in the earth. In general, in most places, crustal temperatures increase at the rate of about 30°C per kilometer of depth (close to 60°F per mile)—which is one reason deep mines have to be air-conditioned! Deep in the crust, rocks are subjected to enough heat and pressure to show the deformation and recrystallization characteristic of metamorphism. Another heat source is a cooling magma. When hot magma formed at depth rises to shallower levels in the crust, it heats the adjacent, cooler rocks, and they may be metamorphosed; this is **contact metamorphism.** Metamorphism can also result from the stresses and heating to which rocks are subject during mountain-building or plate-tectonic movement. Such metamorphism on a large scale, not localized around a magma body, is **regional metamorphism.**

Any kind of preexisting rock can be metamorphosed. Some names of metamorphic rocks suggest what the earlier rock may have been. *Metaconglomerate* and *metavolcanic* describe, respectively, a metamorphosed conglomerate and a metamorphosed volcanic rock. *Quartzite* is a quartz-rich metamorphic rock, often formed from a very quartz-rich sandstone. The quartz crystals are typically much more tightly interlocked in the quartzite, and the quartzite is a more compact, denser, and stronger rock than the original sandstone. *Marble* is metamorphosed limestone in which the individual calcite grains have recrystallized and become tightly interlocking. The remaining sedimentary layering that the limestone once showed may be folded and deformed in the process, if not completely obliterated by the recrystallization.

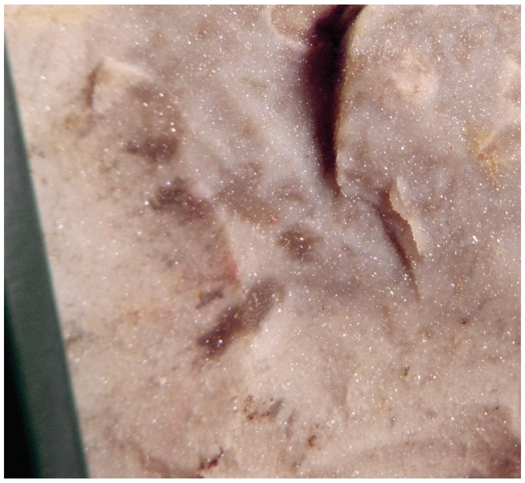
Some metamorphic-rock names indicate only the rock's current composition, with no particular implication of what it was before. A common example is *amphibolite,* which can be used for any metamorphic rock rich in amphibole. It might have been derived from a sedimentary, metamorphic, or igneous rock of appropriate chemical composition; the presence of abundant metamorphic amphibole indicates moderately intense metamorphism and the fact that the rock is rich in iron and magnesium, but not the previous rock type.

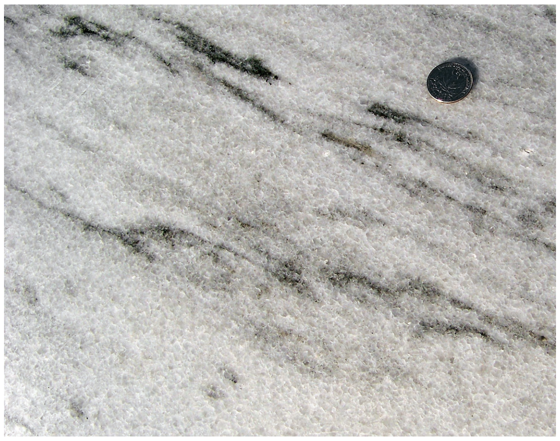
Other metamorphic rock names describe the characteristic texture of the rock, regardless of its composition. Sometimes the pressure of metamorphism is not uniform in all directions; rocks may be compressed or stretched in a particular direction *(directed stress)*. When you stamp on an aluminum can before tossing it in a recycling bin, you are technically subjecting it to a directed stress—vertical compression—and it flattens in that direction in response. In a rock subjected to directed stress, minerals that form elongated or platy crystals may line up parallel to each other. The resultant texture is described as **foliation,** from the Latin for "leaf" (as in the parallel leaves, or pages, of a book). *Slate* is a metamorphosed shale that has developed foliation

Figure 2.12

Sedimentary rocks, formed at low temperatures. (A) Limestone. (B) The fossils preserved in this limestone are *crinoids,* ancient echinoderms related to modern sea urchins and sea stars. (C) Shale, made of many fine layers of tiny clay particles. (D) Sandstone; when viewed closely, larger grains appear rounded. (E) Conglomerate, a coarser-grained rock similar to sandstone; many of the fragments here are rocks, not individual mineral grains. (F) Breccia. Note that the included fragments are much more angular than those in the conglomerate.

Sources: (A) U.S. Geological Survey/Photograph by I. J. Witkind; (B–F) ©Carla Montgomery.





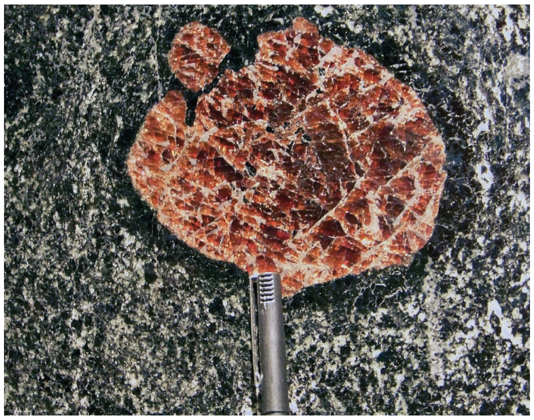


Figure 2.13

Metamorphic rocks have undergone mineralogical, chemical, and/or structural change. (A) Metaconglomerate; note that it has become so cohesive that the broken surface cuts through the pebbles rather than breaking around them (as in figure 2.12E). (B) Quartzite, metamorphosed sandstone; this sample shows the glittering, "sugary" appearance due to recrystallizing of the quartz. (C) Marble, metamorphosed limestone; look closely to see the coarse, interlocking crystals of recrystallized calcium carbonate. (D) Amphibolite (the dark crystals are amphibole). This sample also contains large crystals of garnet, a common metamorphic mineral, so it could be called a garnet amphibolite. (E) Slate, showing a tendency to split along parallel foliation planes. (F) Schist, with shiny surface due to reflection of light off mica flakes; darker lumps are garnet crystals. (G) Gneiss.

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under stress. The resulting rock tends to break along the foliation planes, parallel to the alignment of those minerals, and this characteristic makes it easy to break up into slabs for flagstones. The same characteristic is observed in *schist,* a coarser-grained, mica-rich metamorphic rock in which the mica flakes are similarly oriented. The presence of foliation can cause planes of structural weakness in the rock, affecting how it weathers and whether it is prone to slope failure or landslides. In other metamorphic rocks, different minerals may be concentrated in irregular bands, often with darker, ferromagnesian-rich bands alternating with light bands rich in feldspar and quartz. Such a rock is called a *gneiss* (pronounced "nice"). Because such terms as *schist* and *gneiss* are purely textural, the rock name can be modified by adding key features of the rock composition: "biotite-garnet schist," "granitic gneiss," and so on. Several examples of metamorphic rocks are illustrated in **figure 2.13**.

The Rock Cycle

It should be evident from the descriptions of the major rock types and how they form that rocks of any type can be transformed into rocks of another type or into another distinct rock of the same general type through the appropriate geologic processes. A sandstone may be weathered until it breaks up; its fragments may then be transported, redeposited, and lithified to form another sedimentary rock. It might instead be deeply buried, heated, and compressed, which could transform it into the metamorphic rock quartzite; or it could be heated until some or all of it melted, and from that melt, an igneous rock could be formed. Likewise, a schist could be broken up into small bits, forming a sediment that might eventually become sedimentary rock; more-intense metamorphism could transform it into a gneiss; or extremely high temperatures could melt it to produce a magma from which a granite could crystallize. Crustal rocks can be carried into the mantle and melted; fresh magma cools and crystallizes to form new rock; erosion and weathering processes constantly chip away at the surface. Note that the appearance (texture) of a rock can offer a good first clue to the conditions under which it (last) formed. A more comprehensive view of the links among different rock types is shown in generalized form in **figure 2.14**. In chapter 3, we will look at the rock cycle again, but in a somewhat different way, in the context of plate tectonics. Most interactions of people with the rock cycle involve the sedimentary and volcanic components of the cycle.

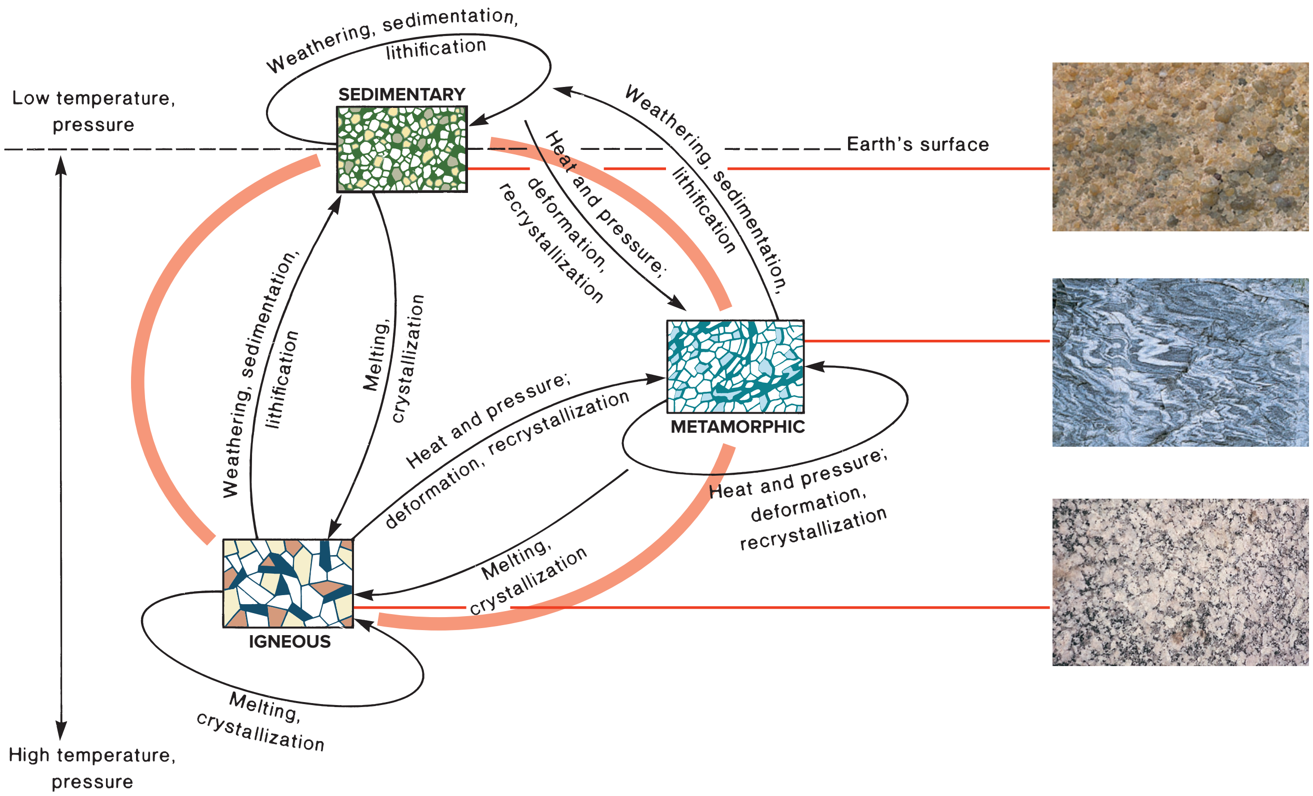


Figure 2.14

The rock cycle—a schematic view. Basically, a variety of geologic processes can transform any rock into a new rock of the same or a different class. The geologic environment is not static; it is constantly changing. The full picture, too, is more complex: Any type of rock may be found at the earth's surface, and weathered; though the melts that form volcanic rocks are created at depth, the melts crystallize into rock near the surface; and so on.

Igneous rock photograph by N. K. Huber, USGS Photo Library, Denver, CO; other photographs ©The McGraw-Hill Companies Inc./ Doug Sherman, photographer.

Summary

The smallest possible unit of a chemical element is an atom. Isotopes are atoms of the same element that differ in atomic mass number; chemically, they are indistinguishable. Atoms may become electrically charged ions through the gain or loss of electrons. When two or more elements combine chemically in fixed proportions, they form a compound.

Minerals are naturally occurring inorganic solids, each of which is characterized by a particular composition and internal crystalline structure. They may be compounds or single elements. By far the most abundant minerals in the earth's crust and mantle are the silicates. These can be subdivided into groups on the basis of their crystal structures, by the ways in which the silicon and oxygen atoms are arranged. The nonsilicate minerals are generally grouped on the basis of common chemical characteristics.

Rocks are cohesive solids formed from rock or mineral grains or glass. The way in which rocks form determines how they are classified into one of three major groups: igneous rocks, formed from magma; sedimentary rocks, formed from low-temperature accumulations of particles or by precipitation from solution; and metamorphic rocks, formed from preexisting rocks through the application of heat and pressure. Through time, geologic processes acting on older rocks change them into new and different ones so that, in a sense, all kinds of rocks are interrelated. This concept is the essence of the rock cycle.

Key Terms and Concepts

anion
atom
atomic mass number
atomic number
carbonate
cation
chemical sedimentary rock
clastic sedimentary rock
cleavage
compound
contact metamorphism
covalent bonding
crystalline
electron
ferromagnesian
foliation
glass
igneous
ion
ionic bonding
isotope
lava
lithification
magma
metamorphic
mineral
native element
neutron
nucleus
organic sediments
oxide
periodic table
plutonic
proton
regional metamorphism
rock
rock cycle
sediment
sedimentary
silicate
sulfate
sulfide
volcanic

Test Your Learning

1. Briefly define the following terms: *ion, isotope, compound, mineral,* and *rock.*
2. Know the two properties that uniquely define a specific mineral.
3. Give the distinctive chemical characteristics of each of the following mineral groups: silicates, carbonates, sulfides, oxides, and native elements.
4. Define *igneous rock* and explain how and why volcanic and plutonic rocks differ in texture.
5. Name and briefly describe the two principal classes of sedimentary rocks.
6. Explain how a granite might be transformed into a sedimentary rock.
7. Name several possible sources of the heat or pressure that can cause metamorphism. Describe the kinds of physical changes that may occur in a rock as a result.
8. Briefly outline the rock cycle, indicating the kinds of processes that can lead to transformation of one rock into another.

Exploring Further

1. The variety of silicate formulas arises partly from the different ways the silica tetrahedra are linked. Consider a single tetrahedron: If the silicon cation has a $+4$ charge, and the oxygen anion -2, there must be a net negative charge of -4 on the tetrahedron as a unit. Yet minerals must be electrically neutral. In quartz, this is accomplished by the sharing of all four oxygen atoms between tetrahedra, so only half the negative charge of each must be balanced by Si^{+4}, and there is a net of two oxygen atoms per Si (SiO_2). But in olivine, the tetrahedra share no oxygen atoms. If the magnesium (Mg) cation has a $+2$ charge, explain why the formula for a Mg-rich olivine is Mg_2SiO_4. Now consider a pyroxene, in which tetrahedra are linked in one dimension into chains, by the sharing of two of the four oxygen atoms.

Again using Mg^{+2} for charge-balancing, show that the formula for a Mg-rich pyroxene would be $MgSiO_3$. Finally, consider the feldspars. They are framework silicates like quartz, but Al^{+3} substitutes for Si^{+4} in some of their tetrahedra. Explain how this allows feldspars to contain some sodium, potassium, or calcium cations and still remain electrically neutral.

2. What kinds of rocks underlie your region of the country, and what do they indicate about the geologic history of the area? (Your local geological survey could assist in providing the information.) Many states have a state mineral and/or rock. Does yours? If so, what is it, and why was it chosen?
3. California was the first state to name a state rock, in 1965; that rock is serpentine. In 2010, some California legislators moved to remove serpentine as the state rock. Investigate what prompted this, the public reaction, and the outcome.

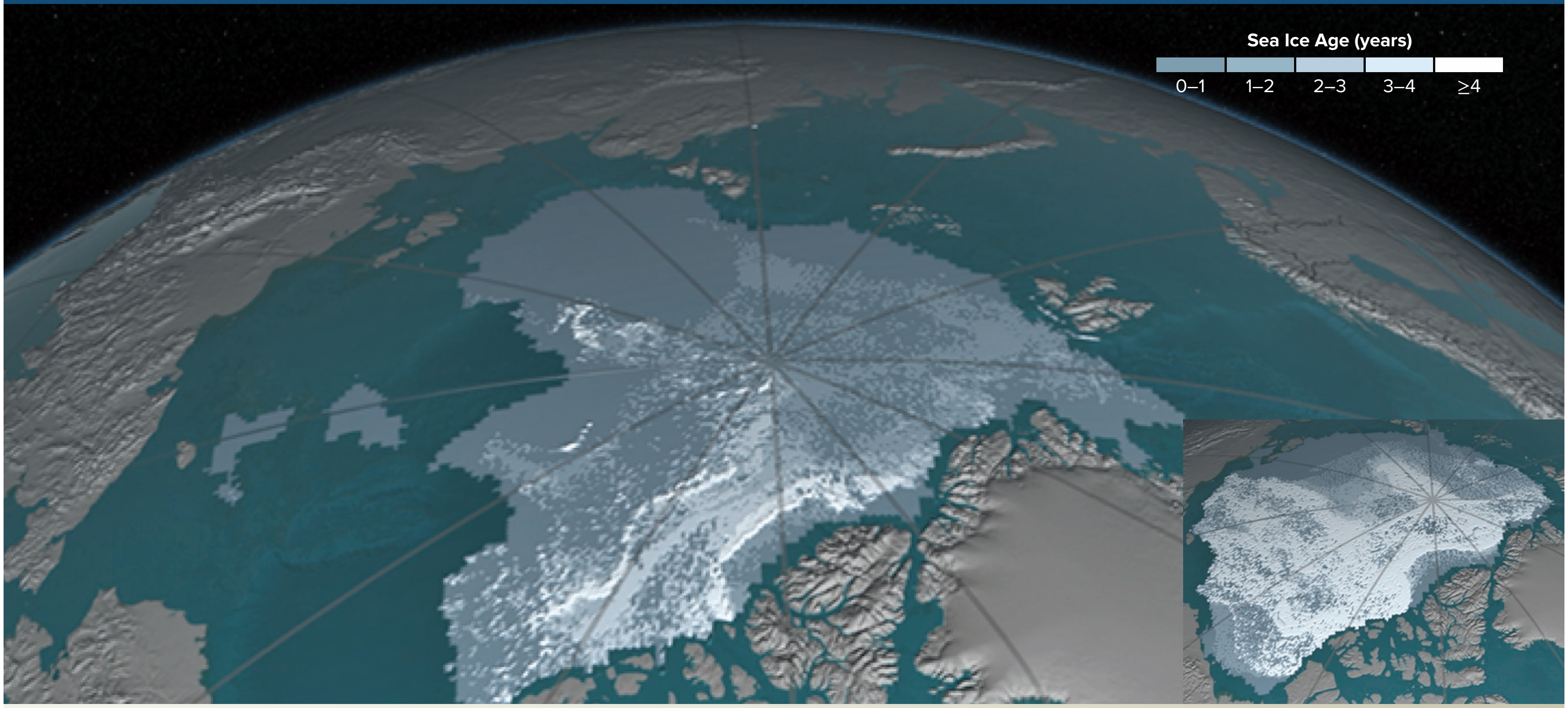
Dig Deeper: Connect, NetNotes, Readings

Test your recall, comprehension, and critical thinking skills on Connect, our digital homework platform, with homework, tests, 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 information and news related to chapter contents) and **Suggested Readings/References** (background on chapter material and additional issues/case studies).

CHAPTER 10

Climate—Past, Present, and Future



We all experience and deal with weather on a daily basis—sun and clouds, wind, rain, snow—and that weather can vary considerably from day to day or even hour to hour. *Climate* is, in a sense, weather averaged over longer periods of time; as such, it is less variable on a human timescale. But it certainly can and does change over the long span of earth's history, as the geologic record makes abundantly clear. Ice ages are just one example of natural climate fluctuation.

Both weather and regional climate can affect the operation or intensity of the surface processes examined in the previous four chapters, and thus the impact they have on human activities. While we can't do much about a day's weather, it has become increasingly evident that humans *can* influence climate on a regional or global scale, intentionally or otherwise. This chapter explores various influences on and effects of climate, evidence for climate change, and possible consequences of those changes. Such information will be relevant to discussions of such diverse topics as energy sources, air pollution, and environmental law and policy in future chapters.

As the Arctic warms, its polar sea ice dwindles, and increasingly, the summer melt claims older ice along with the young ice formed in the previous year or two. In the 1980s, about 20% of the Arctic polar ice was older ice (inset, 1984), which gave some stability to the ice cover. By the time of this image (September 2016), only about 3% of the summer ice was older ice, and the remaining older ice was a less coherent mass. These observations raise the prospect of future ice-free summers in the Arctic.

Images by Cindy Starr, NASA Scientific Visualization Studio.

10.1 Major Controls on Global Climate; The Greenhouse Effect

Climate is the result of the interplay of a number of factors. The main source of energy input to the earth is sunlight, which warms the land surface, which, in turn, radiates heat into the atmosphere. Globally, how much surface heating occurs is related to the sun's energy output and how much of the sunlight falling on earth actually reaches the surface. Incoming sunlight may be blocked by cloud cover or, as we have previously seen, by dust and sulfuric acid droplets from volcanic eruptions. In turn, heat (infrared rays) radiating outward from earth's surface may or may not be trapped by certain atmospheric gases, a phenomenon known as the **greenhouse effect.**

On a sunny day, it is much warmer inside a greenhouse than outside it. Light enters through the glass and is absorbed by the ground, plants, and pots inside. They, in turn, radiate heat: infrared radiation, not visible light. Infrared rays, with longer wavelengths than visible light, cannot readily escape through the glass panes; the rays are trapped, and the air inside the greenhouse warms up. The same effect can be observed in a closed car on a bright day.

In the atmosphere, molecules of various gases, especially water vapor and carbon dioxide, act similarly to the greenhouse's glass. Light reaches the earth's surface, warming it, and the earth radiates infrared rays back. But the longer-wavelength infrared rays are trapped by these gas molecules, and a portion of the radiated heat is thus trapped in the atmosphere. Hence the term "greenhouse effect." (See **figure 10.1**.) As a result of the greenhouse effect, the atmosphere stays warmer than it would if that heat radiated freely back out into space. In moderation, the greenhouse effect makes life as we know it possible: Without it, average global temperature would be closer to −17°C (about 1°F) than the roughly 15°C (59°F) it now is. However, one can have too much of a good thing.

The evolution of a technological society has meant rapidly increasing energy consumption. Historically, we have relied most heavily on carbon-rich fuels—wood, coal, oil, and natural gas—to supply that energy. These probably will continue to be important energy sources for several decades at least. One combustion by-product that all of these fuels have in common is carbon dioxide gas (CO_2).

A "greenhouse gas" in general is any gas that traps infrared rays and thus promotes atmospheric warming. Water vapor is, in fact, the most abundant greenhouse gas in the earth's atmosphere, but human activities do not substantially affect its abundance, and it is in equilibrium with surface water and oceans. Excess water in the atmosphere readily falls out as rain or snow. Some of the excess carbon dioxide is removed by geologic processes (see chapter 18), but since the start of the so-called Industrial Age in the mid-nineteenth century, the amount of carbon dioxide in the air has increased by over 40%—and its concentration continues to climb (**figure 10.2**). If the heat trapped by carbon dioxide were proportional to the concentration of carbon dioxide in the air, the increased carbon dioxide would by now have caused sharply increased greenhouse-effect heating of the earth's atmosphere.

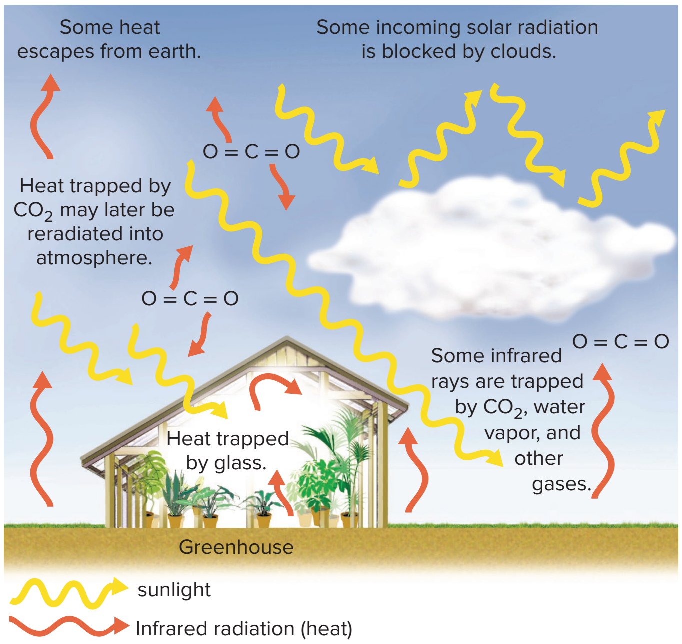


Figure 10.1

The "greenhouse effect" (schematic). Both glass and air are transparent to visible light. Like greenhouse glass, CO_2 and other "greenhouse gases" in the atmosphere trap infrared rays radiating back from the sun-warmed surface of the earth.

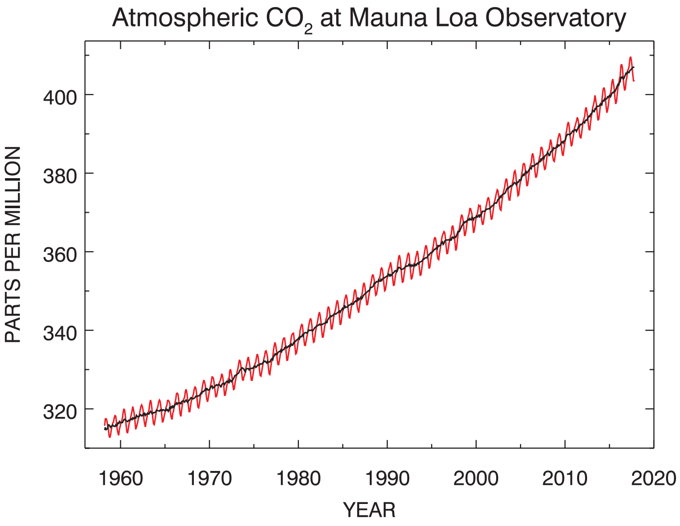


Figure 10.2

Rise in atmospheric CO_2 over past half-century is clear. (Zigzag pattern reflects seasonal variations in local uptake by plants.) Preindustrial levels in ice cores were about 280 ppm (parts per million). One ppm is 0.0001%.

Graph by Ed Dlugokencky and Pieter Tans, NOAA Earth Systems Research Laboratory.

So far, the actual temperature rise has been much more moderate; the earth's climate system is more complex. Indeed, measuring that increase directly, and separating it from the

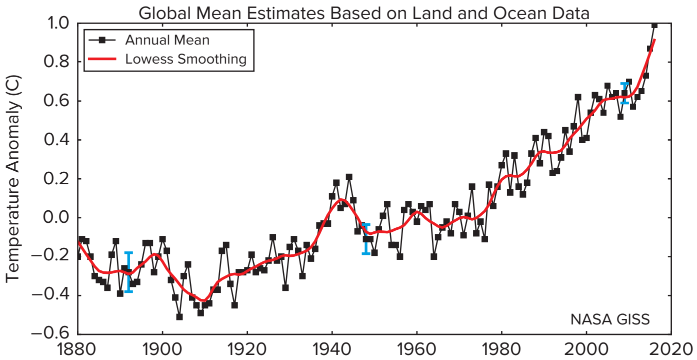


Figure 10.3

Global temperature rise emerges from background noise; blue bars indicate uncertainties, which have decreased with time as completeness of data has improved. (Vertical axis measures temperature deviation, in °C, from 1951–1980 average; "Lowess smoothing" is a statistical method of fitting a curve to the data so that trends can be seen more readily.)

Image by NASA Goddard Institute for Space Studies.

"background noise" of local weather variations, has historically been difficult. Locally, at any one time, a wide variety of local climates can obviously exist simultaneously—icy glaciers, hot deserts, steamy rain forests, temperate regions—and a given region may also be subject to wide seasonal variations in temperature and rainfall. One of the challenges in determining global temperature trends, then, is deciding just how to measure global temperature at any given time. Commonly, several different kinds of data are used, including air temperatures, over land and sea, at various altitudes, and sea surface temperatures. Satellites help greatly by making it possible to survey large areas quickly; see Case Study 10.

Altogether, since the start of the Industrial Age, global surface temperature has risen about 1.1°C (2.0°F) (**figure 10.3**). Trivial as this may sound, it is already having obvious and profound impacts in many parts of the world. Moreover, the warming is not uniform everywhere; some places are particularly strongly affected. A further concern is what the future may hold.

10.2 Climate and Ice Revisited

Early discussions of climate change related to increasing greenhouse-gas concentrations in the atmosphere tended to focus heavily on the prospect of global warming and the resultant melting of earth's reserves of ice, especially the remaining ice sheets. If *all* the ice melted, sea level could rise by over 75 meters (about 250 feet) from the added water alone, leaving aside thermal expansion of that water. About 20% of the world's land area would be submerged. Many millions, perhaps billions, of people now living in coastal or low-lying areas would be displaced, since a large fraction of major population centers grew up along coastlines and rivers. The Statue of Liberty would be up to her neck in water.

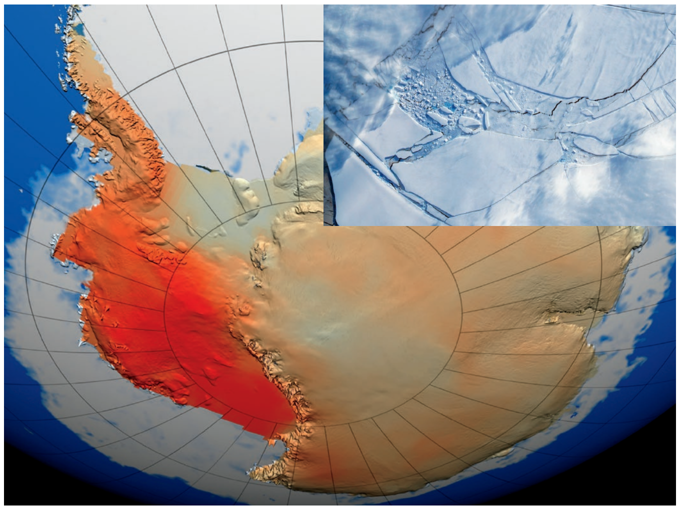


Figure 10.4

From 1957 to 2006, average Antarctic temperature rose about 0.6°C (1.1°F); in West Antarctica, 0.85°C (1.55°F). The West Antarctic ice sheet, grounded below sea level and bordered by floating ice shelves, is especially vulnerable to melting and breakup. Inset shows 2009 breakup of the Wilkins Ice Shelf along the Antarctic Peninsula.

Source: Trent Schindler, NASA/GSFC Scientific Visualization Studio; inset by Jesse Allen using data courtesy of NASA/GSFC/METI/ERSDAC/JAROS and the U.S./Japan ASTER Science Team.

Such large-scale melting of ice sheets would take time, perhaps several thousand years. On a shorter timescale, however, the problem could still be significant, as some areas are particularly vulnerable (**figure 10.4**). Complete melting of the West Antarctic ice sheet could occur within a few hundred years. The resulting 5- to 6-meter rise in sea level, though it sounds small, would nevertheless be enough to flood many coastal cities and ports, along with most of the world's beaches; see, for example, **figure 10.5**. This would be both inconvenient and extremely expensive. (The only

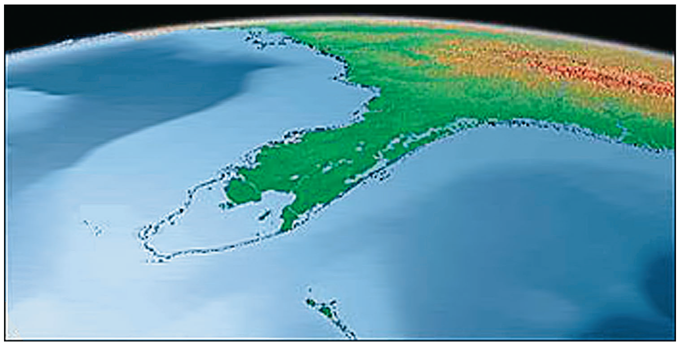
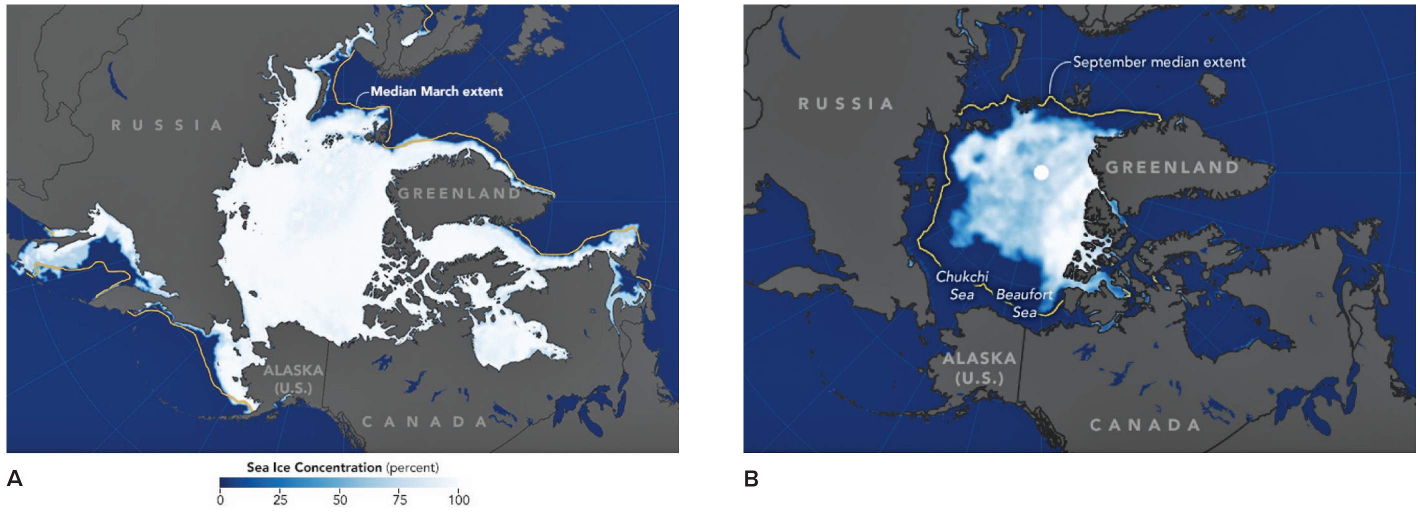


Figure 10.5

Impact on Florida of melting the West Antarctic and/or the Greenland ice sheet with a resultant sea-level rise of about 5 to 6 meters (16 to 20 feet).

Source: Image by William Haxby/NASA.



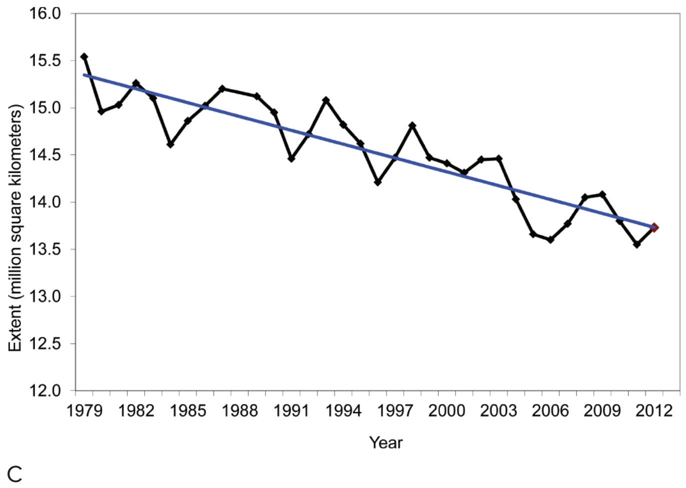


Figure 10.6

Average maximum Arctic Sea ice extent (A) has declined only moderately (here, March 2017, as compared to the median for 1981–2010, indicated by the yellow line), but the annual minimum (B) has declined sharply (here, September 2017, compared to the 1981–2010 median, indicated by the yellow line). Thus, on average, annual ice extent (area) has been declining (C). So has the ice thickness, meaning a net loss of large volumes of ice in the Arctic.

(A, B) images by Joshua Stevens using AMSR2 satellite data; (C) Graph courtesy National Snow and Ice Data Center.

consolation is that the displaced inhabitants would have decades over which to adjust to the changes.) Meanwhile, the smaller alpine glaciers are clearly dwindling, as seen in the last chapter. As sea level rises, too, the base levels of streams draining into the ocean are also raised, which would alter the stream channels and could cause significant flooding along major rivers; and this would not require nearly such a large sea-level rise.

Arctic polar ice is also demonstrably shrinking, in both area (**figure 10.6**) and thickness (see chapter-opening image). It is particularly vulnerable because, instead of sitting on long-chilled rock, it floats on the circulating, warming ocean. The good news is that, just as melting ice in a glass does not cause the liquid to overflow, melting sea ice will not cause a rise of sea level. However, concerns about Arctic ecosystems are being raised; for example, polar bears that hunt seals on the ice in Hudson Bay suffer when a shorter ice season reduces their food intake. Moreover, the Arctic is warming particularly rapidly, perhaps in part due to the melting polar ice: Ice reflects more sunlight than open ocean, so as the polar ice disappears, more sunlight is absorbed by the ocean, leading to more warming, and more melting ice.

The Hidden Ice: Permafrost

Warming is affecting more than the visible ice of cold regions. In alpine climates, winters are so cold, and the ground freezes to such a great depth, that the soil does not completely thaw even in the summer. The permanently frozen zone is **permafrost** (**figure 10.7**). The meltwater from the thawed layer

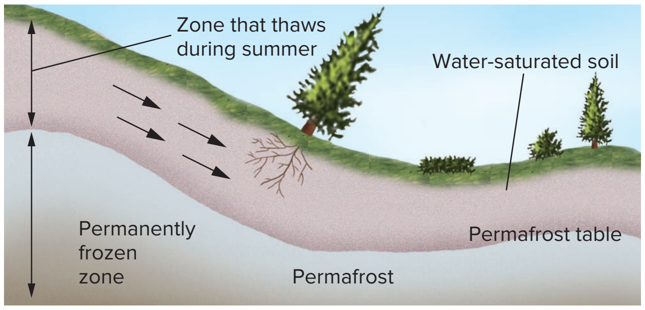


Figure 10.7

In cold climates, a permanently frozen soil zone, permafrost, may be found beneath the land surface.

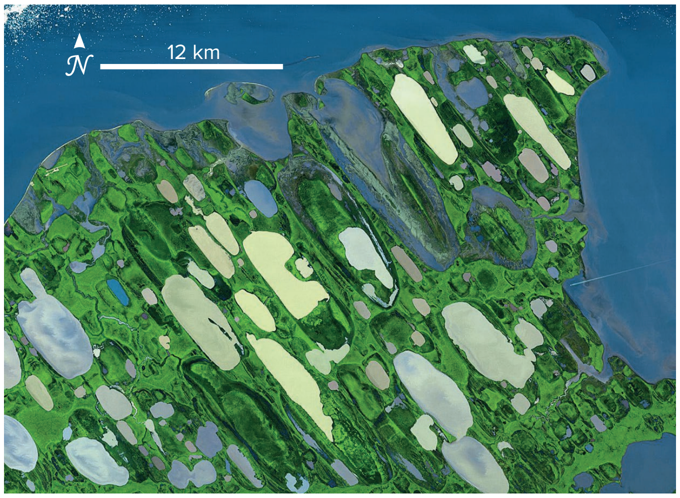


Figure 10.8

A portion of the north coast of the National Petroleum Reserve in Alaska. Abundant lakes reflect soggy soil over ice. Note elongated topographic features, a result of ice-sheet flow during the last ice age. Differences in suspended sediment content cause differences in water color in the many lakes.

Source: NASA/GSFC/METI/ERSDAC/JAROS, and the U.S./Japan ASTER Science Team.

Figure 10.9

From 1955 to 2007, coastal erosion rates in parts of northern Alaska have more than doubled, to about 15 meters (50 feet) per year, claiming structures along the coast in the process.

Source: U.S. Geological Survey/Photograph by Benjamin Jones.

cannot infiltrate the frozen ground below, so the terrain is often marshy (**figure 10.8**). Structures built on or in permafrost may be very stable while it stays frozen but sink into the muck when it thaws; vehicles become mired in the sodden ground, so travel may be impossible when the upper soil layers thaw.

Studies have shown that permafrost is also being lost as the world warms. Where some permafrost remains, the thaw penetrates deeper, and the frozen-ground season is shorter. Some areas are losing their permafrost altogether, and lakes drain abruptly when the last of the ice below melts away. Along the north coast of Alaska, a combination of melting permafrost and loss of protection from waves as sea ice dwindles has led to the collapse of coastal cliffs, and shoreline retreat of tens of meters per year (**figure 10.9**). All these changes are having effects on ecosystems, animal migrations, and the traditional lifestyles of some native peoples. They are even affecting oil exploration and the Trans-Alaska Pipeline, as we will see in later chapters.

10.3 Oceans and Climate

One reason that there is no simple correlation between atmospheric greenhouse-gas concentrations and land surface temperatures is the oceans. That huge volume of water represents a much larger thermal reservoir than the tenuous atmosphere. Coastal regions may have relatively mild climates for this reason: As air temperatures drop in winter, the ocean is there to release some heat to the atmosphere; as air warms in summer, the ocean water absorbs some of the heat. The oceans store and transport a tremendous amount of heat around the globe. A thorough discussion of the role of the oceans in global and local climate is beyond the scope of this chapter, but it is important to appreciate the magnitude of that role.

Recent studies of the balance between the energy received from the sun and the energy radiated back into space have confirmed a net excess of energy absorbed, an average of 0.85 watt per square meter per year. Such a rate of energy absorption, maintained for a thousand years, could melt enough ice to raise sea level by a hundred meters, or raise the temperature of the ocean's surface-water layer by 10°C (nearly 20°F). Much of this absorbed energy is being stored in the oceans (**figure 10.10**). In fact, recent research with deeper temperature probes has shown that it is not only near-surface water that is warming; see, for example, **figure 10.11**. All of this oceanic heat storage may in part account for an apparent "hiatus" in the rise of global surface temperatures early in this century, which is now evidently past (recall **figure 10.3**).

We have already seen that the oceans supply most of the water vapor to make rain and snow. Water absorbs heat when vaporizing, and more water will evaporate from warmer surface water. Heat from sea surface water supplies the energy to spawn hurricanes and other tropical storms. While meteorologists have not yet seen a systematic increase in the *number* of U.S. hurricanes each year, recent research does suggest a trend toward increasing *intensity* of hurricanes—not good news for residents of the Gulf Coast and Caribbean. These relationships will be examined further later in the chapter.

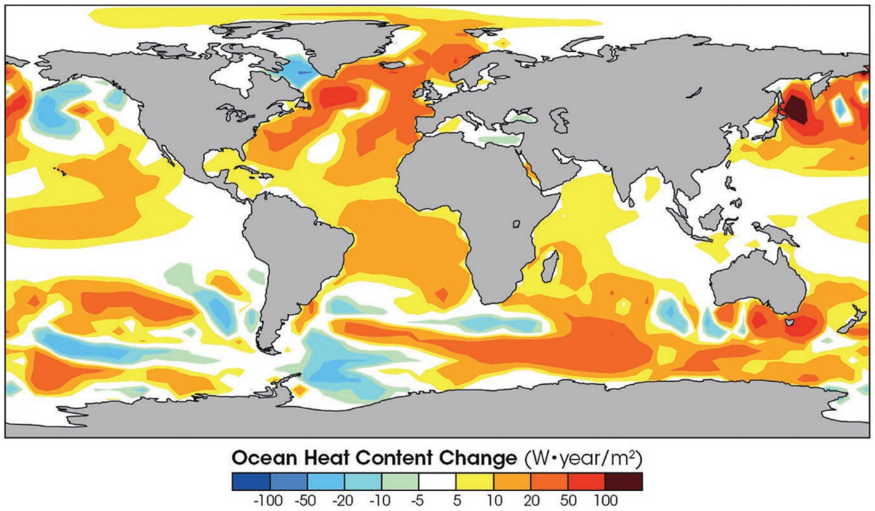


Figure 10.10

Modeled increase in the heat content of the upper 70 meters of the oceans, based on observations from 1993 to 2003. (A watt-year is the amount of energy supplied by 1 watt of power for a year; it equals 8.76 kilowatt-hours.)

NASA image courtesy Jim Hansen et al., *Goddard Institute for Space Studies.*

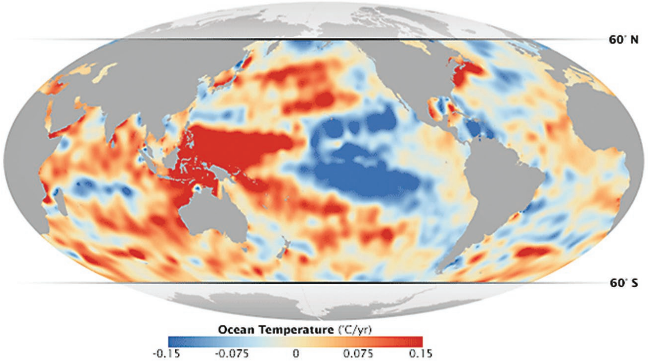


Figure 10.11

Ocean temperature change from 2003 to 2012 at a depth of 100–200 meters.

NASA Earth Observatory image by Joshua Stevens.

The Thermohaline Circulation

Broadly, oceanic circulation is driven by a combination of winds, which push surface currents, and differences in density within the oceans' waters, related to temperature and salinity. Cold water is denser than warm, and at a given temperature, density increases with increasing salinity. The roles of temperature and salinity are reflected in the name **thermohaline circulation** (remember, "halite" is sodium chloride, salt, the most abundant dissolved material in the oceans) given to the large-scale circulation of the oceans (**figure 10.12**). Among the notable features are the Gulf Stream, carrying warmed equatorial water to the North Atlantic, and the sinking of cold water in the polar regions. The informal name of "ocean conveyor" is sometimes given to this circulation system in recognition of its heat-transport role.

In the climate records described later in the chapter, scientists have found evidence of episodes of "abrupt climate change" in some locations. One proposed mechanism for sudden cooling of the North Atlantic is disruption of the thermohaline circulation to this region, reducing the influx of warm water. For instance, extensive melting of the Greenland ice sheet could create a pool of cool, fresh surface water that would block the incoming warm flow; or increased water evaporation around a warmer equator could increase the salinity of the surface water so much that it would sink rather than flowing northward. Much research is needed to test such hypotheses. In any case, to a geologist, "abrupt" climate change means change on a timescale of decades to centuries—not days to weeks as in recent movie fiction!

El Niño

Most of the vigorous circulation of the oceans is confined to the near-surface waters. Only the shallowest waters, within 100 to 200 meters of the surface, are well mixed by waves, currents, and winds, and warmed and lighted by the sun. The average temperature of this layer is about 15°C (60°F).

Below the surface layer, temperatures decrease rapidly to about 5°C (40°F) at 500 to 1000 meters below the surface. Below this is the so-called *deep layer* of cold, slow-moving, rather isolated water. The temperature of this bottommost water is close to freezing and may even be slightly below freezing (the water is prevented from freezing solid by its dissolved salt content and high pressure). This cold, deep layer originates largely in the polar regions and flows very slowly toward the equator.

When winds blow offshore, they push the warm surface waters away from the coastline also. This, in turn, creates a region of low pressure and may result in *upwelling* of deep waters to replace the displaced surface waters (**figure 10.13**). The deeper waters are relatively enriched in dissolved nutrients, in part because few organisms live in the cold, dark depths to consume those nutrients. When the nutrient-laden waters rise into the warm, sunlit zone near the surface, they can support abundant plant life and, in turn, animal life that feeds on the plants.

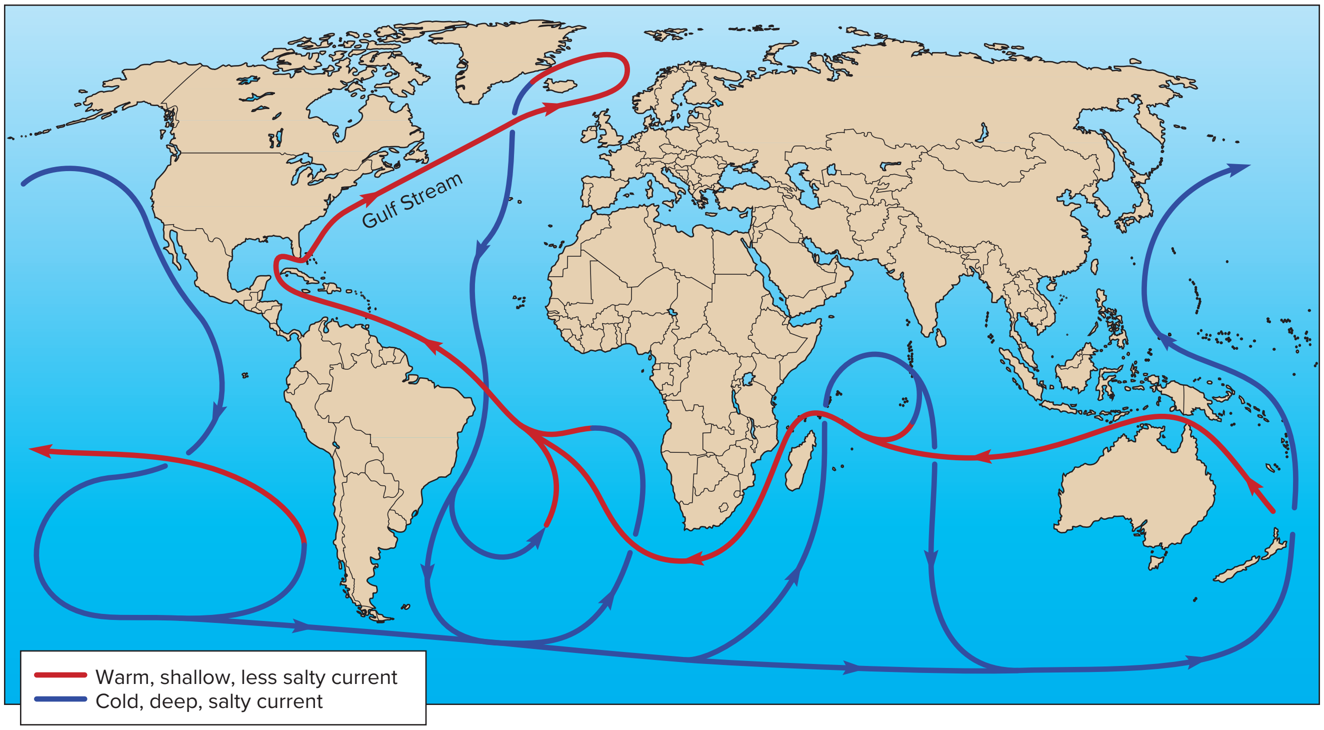


Figure 10.12

The thermohaline circulation, moving water—and thus heat—around the globe.

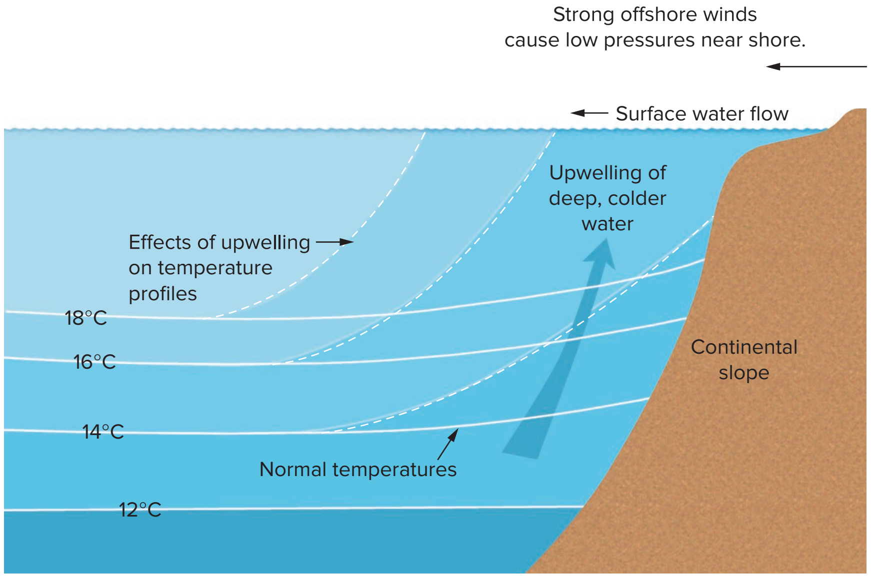


Figure 10.13

Warm surface water normally overlies colder seawater at depth. When offshore winds blow warm waters away from the South American shore and create local low pressure, upwelling of colder deep waters may occur (dashed lines). During an El Niño episode, the winds die down, and upwelling is suppressed (solid lines), so warm surface waters extend to the coast.

Many rich fishing grounds are located in zones of coastal upwelling. The west coasts of North and South America and of Africa are subject to especially frequent upwelling events.

From time to time, however, for reasons not precisely known, the upwelling is suppressed for a period of weeks or longer, as warm waters from the western South Pacific extend eastward to South America (**figure 10.14A**). Abatement of coastal winds, for one, reduces the pressure gradient driving the upwelling. The reduction in upwelling of the fertile cold waters has a catastrophic effect on the Peruvian anchoveta industry.

Such an event is called *El Niño* (“the [Christ] Child”) by the fishermen because it commonly occurs in winter, near the Christmas season.

At one time, El Niño events were believed to be rather sporadic and isolated, local events. Now it is recognized that they are cyclic in nature, occurring every four to seven years as part of the El Niño–Southern Oscillation (referring to the southern oceans). The opposite of an El Niño, a situation with unusually cold surface waters off western South America, has been named *La Niña* (**figure 10.14B**). Extensive shifts in seawater surface temperatures, in turn, cause large-scale changes in evaporation, and thus precipitation, as well as wind-circulation patterns (**figure 10.15**). Climatic changes associated with El Niño/La Niña events generally include changes in frequency, intensity, and paths of Pacific storms, short-term droughts and floods in various regions of the world, and changes in the timing and intensity of the monsoon season in India. Heavy rains associated with El Niño events have been blamed for major landslides along the Pacific coast of the United States; La Niña produces particularly heavy monsoon rains that contribute to disastrous flooding in south Asia. There is already some evidence that El Niño episodes are becoming more frequent, intense, and/or prolonged, and this can have especially devastating consequences to those nations whose much-needed rainy season is thereby disrupted.

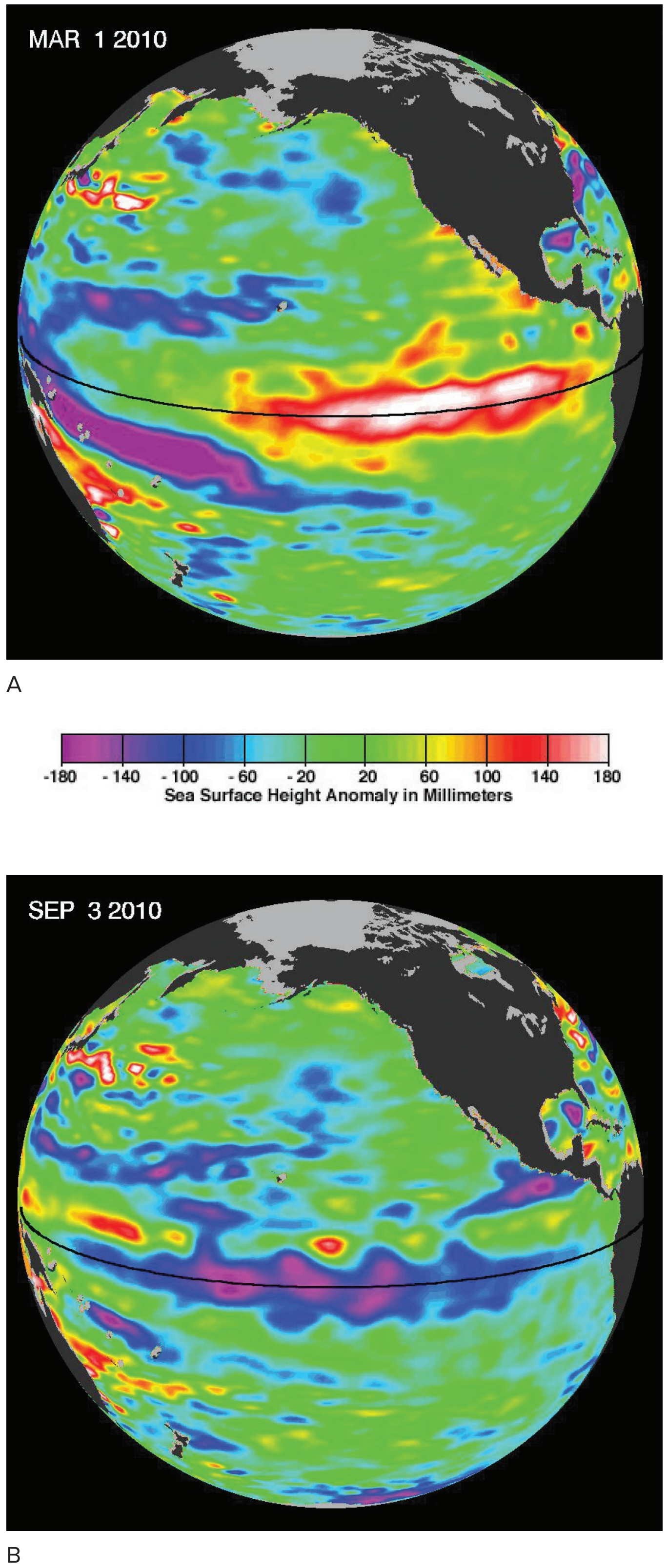


Figure 10.14

(A) El Niño: Unusually warm water appears as higher sea-level elevation, as indicated by key; warm water expands. (B) La Niña: Lower sea-level elevations show areas of cooler surface waters.

Images courtesy of JPL/NASA.

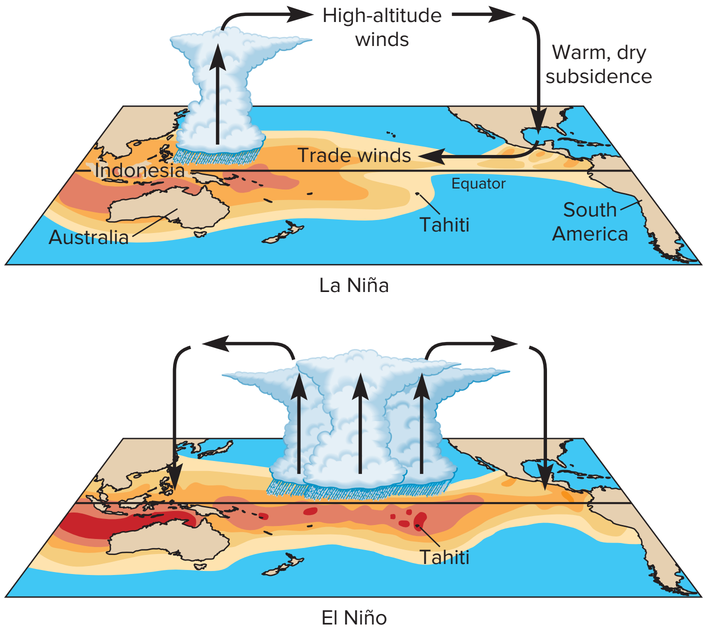


Figure 10.15

Under La Niña conditions, warm, wet air over the western Pacific dumps monsoon rains on southeast Asia as it rises and cools; when the air sinks and warms again, over the eastern Pacific, it is drying. During El Niño, surface waters in the eastern Pacific are warmer, which shifts the patterns of evaporation and precipitation; the monsoon season is much drier, while more rain falls on the western United States.

About 1996, investigators first recognized that underlying the El Niño/La Niña is a longer-term phenomenon, dubbed the Pacific Decadal Oscillation (PDO), with a cycle of fluctuating Pacific Ocean surface temperatures over a period of 20–30 years. The PDO, too, affects patterns of evaporation, precipitation, and wind. Still more recently, an Atlantic Multidecadal Oscillation (AMO) has been identified and named. It is entirely possible that more such cycles important to our understanding of climate/ocean relationships remain to be recognized.

10.4 Other Aspects of Global Change

As we have seen in previous sections, "global warming" means more than just a little warmer weather everywhere. There are consequences for ice amount and distribution, oceanic circulation, patterns of storms, and more, as will be explored below. It is very important to bear in mind, too, that "global" climate changes do not affect all parts of the world equally or in the same ways.

Changes in wind-flow patterns and amounts and distribution of precipitation will cause differential impacts in different areas, not all of which will be equally resilient (**figure 10.16**). A region of temperate climate and ample rainfall may not be seriously harmed by a temperature change of a few degrees, one way or the other, or several inches more or less rainfall. A modest temperature rise in colder areas may actually increase plant vigor and the length of the growing season (**figure 10.17**), and some dry areas may enjoy increased productivity with increased rainfall.

Warming and moisture redistribution also have potential downsides, of course. In chapter 9, we noted the impact of the loss of alpine glaciers on water supplies. **Figure 10.16** suggests potential water shortages as well in areas not relying now on glacial meltwater. In many parts of the world, agriculture is already only marginally possible because of hot climate and little rain. A temperature rise of only a few degrees, or loss of a few inches of rain a year, could easily make living and farming in these areas impossible. Recent projections suggest that summer soil-moisture levels in the Northern Hemisphere could drop by up to 40% with a doubling in atmospheric CO_2. This is a sobering prospect for farmers in areas where rain is barely adequate now, for in many places, irrigation is not an option. In the United States, both temperature and precipitation have been increasing, but the effects are unevenly distributed, with potentially problematic results (**figure 10.18**).

Recent evidence and computer modeling also indicate that global warming and associated climate changes may

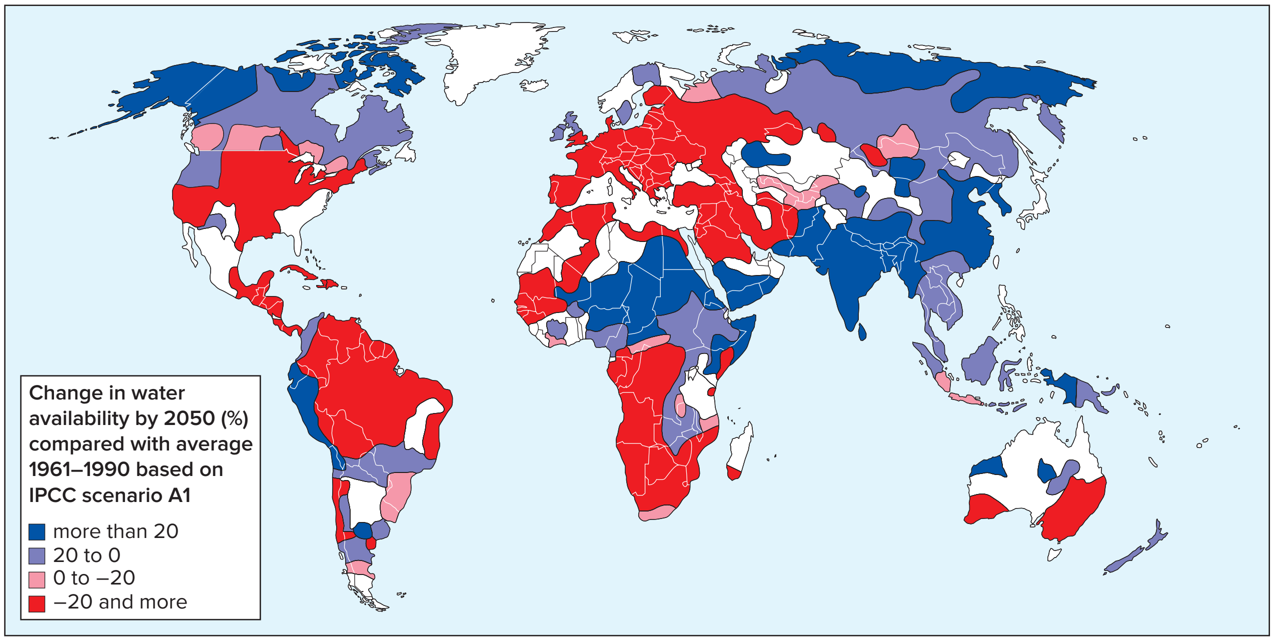


Figure 10.16

Climate modeling based on one scenario seen as likely by the Intergovernmental Panel on Climate Change reveals potentially large drops in water availability by mid-century. Areas such as southern Australia, the Middle East, and the southwestern United States can ill afford this.

Image by Philippe Rekacewicz after Arnell (2004), from UNEP/GRID-Arendal maps and graphics library 2009. old.grida.no/graphicslib/detail/the-contribution-of-climate-change-to-declining-water-availability_12c2.

Reprinted with permission UNEP. old.grida.no/graphicslib/collection/vital-water-graphics-2.

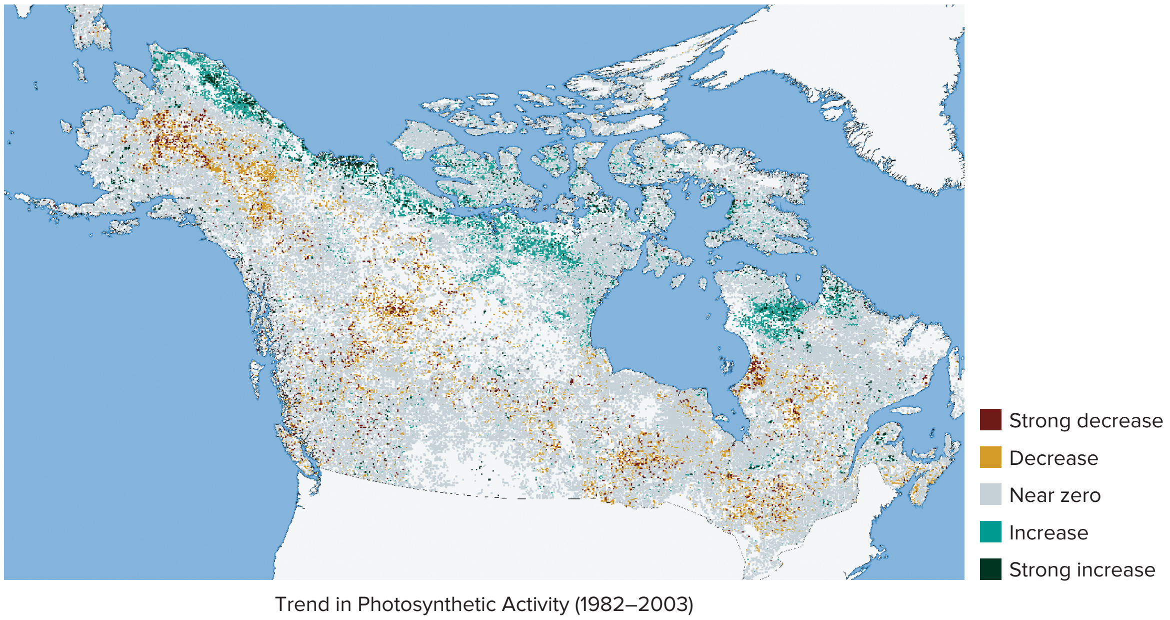


Figure 10.17

Plant activity in the northernmost reaches of Alaska and Canada is picking up with global warming, but note that it is declining over a much larger area farther south.

Image courtesy NASA, based on data from Scott Goetz, Woods Hole Research Center.

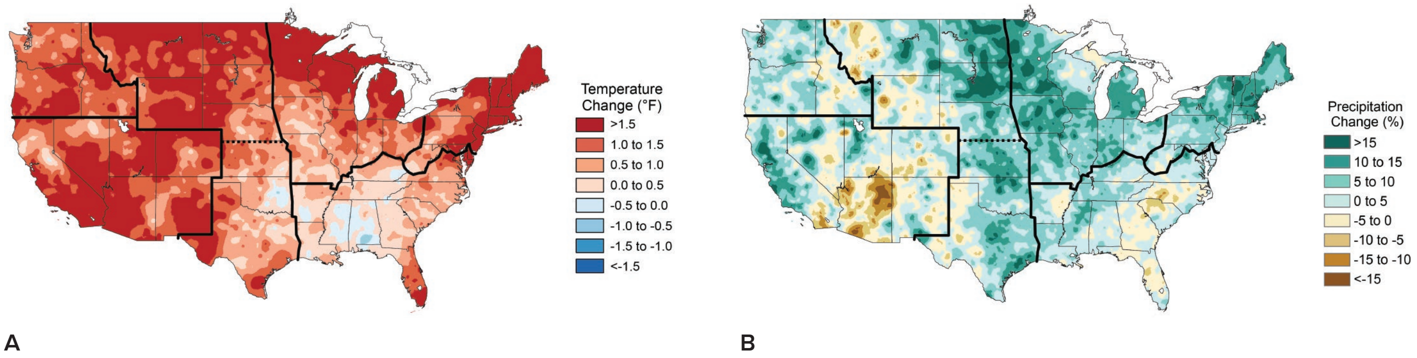


Figure 10.18

Changes in temperature (A) and precipitation (B) from 1991–2012, compared to the period 1901–1960. The year 2012 was the hottest on record for the United States (and three of the next four years after that were hotter still). Intense rainfall events have been increasing across the country; extreme heat and drought episodes have also become more frequent and intense, particularly in the Southwest, an area that is already hot and dry.

Images from the U.S. Global Change Research Program, courtesy NASA.

produce more extremes—catastrophic flooding from torrential storms, devastating droughts, "killer heat waves," and stronger storms. The combination of heat and drought led to deadly wildfires in southern Australia in early 2009, killing more than 200 people, and four years later, the heat was still worse across the whole continent (**figure 10.19**). The year 2011 saw records set for heat, drought, floods, wildfires, and tornadoes in the United States, and the extreme-weather disasters have kept coming. In 2012, the United States experienced $90 billion in storm-related damages (including Superstorm Sandy) and another $35 billion lost due to heat, drought, and wildfires, with several hundred deaths resulting from these events. A tally by the National Oceanic and Atmospheric Administration of extreme-weather events costing a billion dollars or more shows 9 such events in 2013, 8 in 2014, 10 in 2015, and 15 each in 2016 and 2017 (the latter

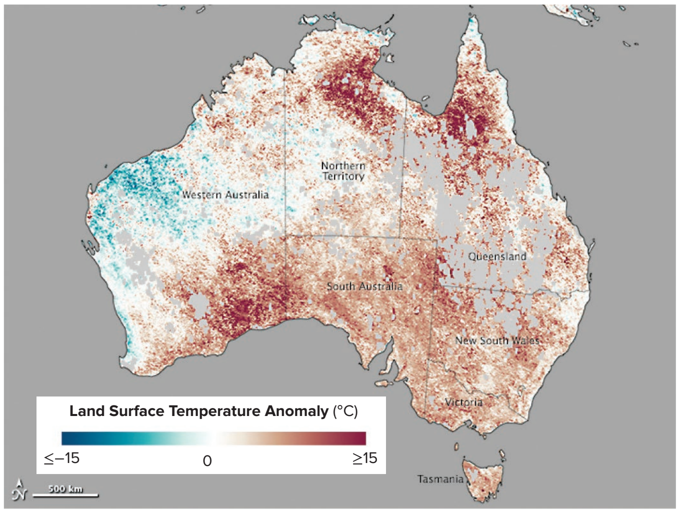


Figure 10.19

Unprecedented heat in southern Australia on 1–8 January 2013. The temperature anomalies reported are relative to the average for 2005–2012, already a warm period. On 6 January, the average temperature reached 40.3°C (104.6°F), across the *entire* continent.

Map by Jesse Allen, using data from the Land Processes Distributed Active Archive Center.

including Hurricanes Harvey, Irma, and Maria, the damages from which are still being assessed as this is written). While natural weather variability means that it is not possible to identify a particular extreme-weather event as wholly due to recent global warming/climate change, the trend is clear, and not surprising in light of what we know about relationships among heat, storms, and precipitation.

It has been argued that rising atmospheric CO_2 levels should be beneficial in promoting plant growth. After all, photosynthesis involves using CO_2 and water and solar energy to manufacture more complex compounds and build the plant's structure. However, controlled experiments have shown that not all types of plants grow significantly more vigorously given higher CO_2 concentrations in their air (recall **figure 10.17**), and even those that do may show enhanced growth only for a limited period of time. Moreover, the productivity of phytoplankton (microscopic plants) in the warming oceans has shown sharp declines (**figure 10.20**). The reason may be that as the surface water warms and becomes less dense, the warm-water layer becomes more firmly stabilized at the surface, suppressing upwelling of the nutrient-rich cold water below over much of the ocean and mixing of the cold and warm waters. The effect is like that of El Niño, but much more widely distributed. Because some whales and fish depend on the phytoplankton for food, a decline in phytoplankton has repercussions for those populations also, as well as for humans who may consume larger fish in that food web.

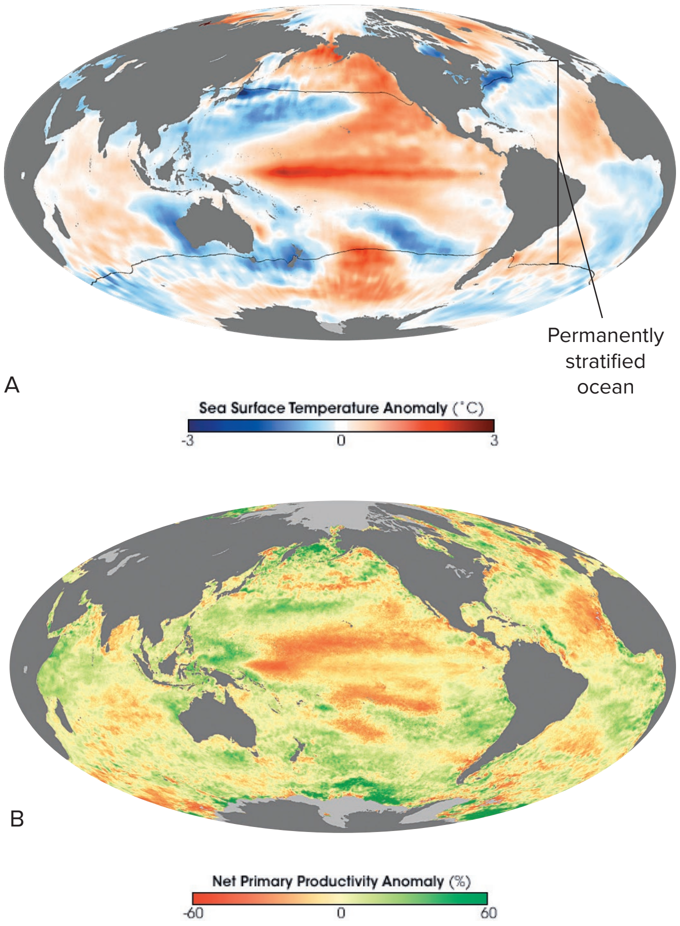


Figure 10.20

(A) Changes in sea surface temperature, 2000–2004. In the "permanently stratified" areas, the oceans show a distinct upper, warmer layer year-round. (B) In general, areas in which phytoplankton productivity declined from 2000 to 2004 are those where the water warmed over the same period.

NASA images by Jesse Allen, based on data provided by Robert O'Malley, Oregon State University.

Rising atmospheric CO_2 affects oceans in other ways too. With more CO_2 in the air, more CO_2 dissolves in the oceans, making more carbonic acid. This acidification makes it more difficult for corals and other marine organisms to build their calcium-carbonate skeletons. The combination of acidification and warming waters puts severe stress on coral reefs, for the warming causes another problem. Corals owe their colors to symbiotic algae; when water warms just a few degrees, the algae are expelled, and bare white coral skeletons result, a phenomenon known as *coral bleaching*. Without the algae, the corals also suffer from the loss of nutrients the algae provided. If the water cools soon enough, the algae return and the reef can recover; if the elevated water temperatures persist too long, the coral dies. The combination of rising ocean temperatures overall and more-intense El Niño events is causing more coral bleaching, and reef death, worldwide. And coral reefs are not merely beautiful; they support thousands of species in marine ecosystems.

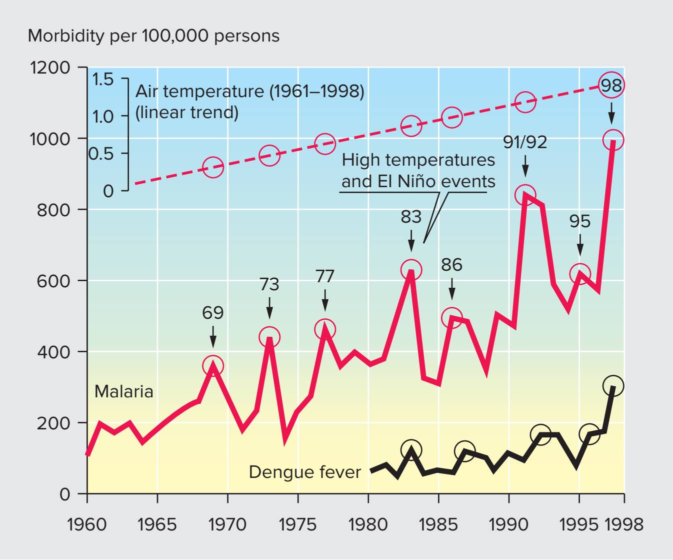


Figure 10.21

Occurrence of malaria and dengue fever in Colombia is correlated with temperature, spiking in warmer El Niño years, but also trending upward overall as temperatures rise.

Graph from United Nations Environment Programme/ GRID-Arendal.

Public-health professionals have identified yet another threat related to global change. Climate influences the occurrence and distribution of a number of diseases. Mosquito-borne diseases, such as malaria and dengue, will be influenced by conditions that broaden or reduce the range of their particular carrier species; the incidence of both has increased in recent years and is expected to expand further (**figure 10.21**). Similar concerns have been raised with respect to Zika. The expansion may be vertical, too: Researchers have found malaria occurring at higher altitudes in Ethiopia and Colombia as warming comes to the population of the highlands. Waterborne parasites and bacteria can thrive in areas of increased rainfall. Efforts to anticipate, and plan responses to, the climate-enhanced spread of disease are growing. Still other insect pests that die in winter in temperate climates—termites, for instance—may also expand their ranges in a warmer world.

U.N. studies further suggest that less-developed nations, with fewer resources, may be much less able to cope with the stresses of climate change. Yet many of these nations are suffering the most immediate impacts: The very existence of some low-lying Pacific island nations is threatened by sea-level rise; two such nations in the Pacific basin, Kiribati and the Maldives, have already developed evacuation plans. Reduced soil moisture and higher temperature quickly affect the world's "drylands," where many poorer countries are located. The tropical diseases are spreading most obviously in the Third World where medical care is limited. Much of Africa is vulnerable to multiple threats associated with climate change (**figure 10.22**). These differential impacts may have implications for global political stability as well.

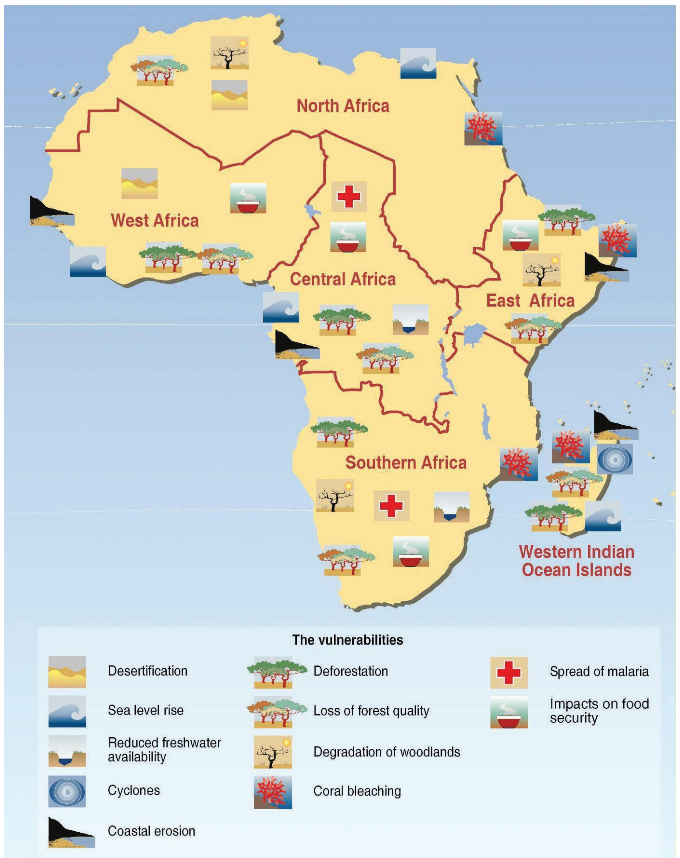


Figure 10.22

Different parts of Africa are vulnerable to different consequences of climate change.

Image by Delphine Digout after Anna Balance (2002), from UNEP/GRID-Arendal maps and graphics library, 2012. old.grida.no/graphicslib/detail/climate-change-vulnerability-in-africa_1387.

10.5 Evidence of Climates Past

An understanding of past climatic fluctuations is helpful in developing models of possible future climate change. A special challenge in reconstructing past climate is that we do not have direct measurements of ancient temperatures. These must be determined indirectly using various methods, sometimes described as "proxies" for direct temperature records.

Aspects of local climate change may often be deduced from the geologic record, especially surficial deposits and the

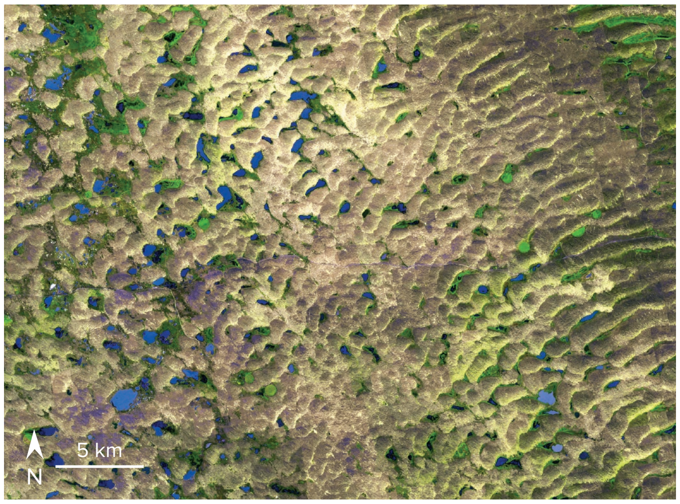


Figure 10.23

The Nebraska Sand Hills formed during the Ice Age: Sediment ground off the Rocky Mountains by the ice sheets became outwash in the plains. The dunes developed in dry conditions; now, many are vegetated, and small lakes have accumulated in low spots.

Source: NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team.

sedimentary-rock record. For example, the now-vegetated dunes of the Nebraska Sand Hills (**figure 10.23**) are remnants of an arid "sand sea" in the region 18,000 years ago, when conditions must have been much drier than they are now. Much of North Africa was fertile, wheat-growing land in the time of the Roman Empire; small reductions in rainfall, and the resultant crop failures, may have contributed to the Empire's fall. We have noted that glacial deposits further back in the rock record may be recognized in now-tropical regions, and this was part of the evidence for continental drift/plate tectonics. When such deposits were widespread globally, they indicate an ice age at the corresponding time. Conversely, coal deposits indicate warm, wet conditions, conducive to lush plant growth, perhaps in a swampy setting, and widespread coals reflect a warmer earth. Distinctively warm- or cold-climate animals and plants identified in the fossil record likewise provide evidence of the local environmental conditions at the time they lived.

Other proxies involve the chemistry of sediments, seawater, or snow and ice. For example, from marine sediments comes evidence of ocean-temperature variations. The proportion of calcium carbonate ($CaCO_3$) in Pacific Ocean sediments in a general way reflects water temperature, because the solubility of calcium carbonate is strongly temperature-related: It is more soluble in cold water than in warm. A good idea of global climate at a given time may be gained from compiling such data from many proxies and many places. From such information, we find that climate has, in fact, varied quite a lot throughout earth's history, at different times being somewhat cooler or substantially warmer than at present. Particularly when the climatic shifts were relatively large and (geologically speaking) rapid, they have been a factor in the natural selection that is a major force in biological evolution.

A particularly powerful tool involves variations in the proportions of oxygen isotopes in geological materials. By far the most abundant oxygen isotope in nature is oxygen-16 (^{16}O); the heaviest is oxygen-18 (^{18}O). Because they differ in mass, so do molecules containing them, and the effect is especially pronounced when oxygen makes up most of the mass, as in H_2O. Certain natural processes, including evaporation and precipitation, produce fractionation between ^{16}O and ^{18}O, meaning that the relative abundances of the two isotopes will differ between two substances, such as ice and water, or water and water vapor. (See **figure 10.24**.) As water evaporates, the lighter $H_2{}^{16}O$ evaporates preferentially, and the water vapor will then be isotopically "lighter" (richer in ^{16}O, poorer in ^{18}O) than the residual water. Conversely, as rain or snow condenses and falls, the precipitation will be relatively enriched in the heavier $H_2{}^{18}O$. As water vapor evaporated from equatorial oceans drifts toward the poles, depositing $H_2{}^{18}O$-enriched precipitation, the remaining water vapor becomes progressively lighter isotopically, and so does subsequent precipitation; snow falling near the poles has a much lower $^{18}O/^{16}O$ ratio than tropical rain, or seawater (**figure 10.24B**).

The fractionation between ^{18}O and ^{16}O in coexisting water vapor and rain or snow is temperature-dependent, more pronounced at lower temperatures. Therefore, at a given latitude, variations in the $^{18}O/^{16}O$ ratio of precipitation reflect variations in temperature. Similarly, oxygen isotopes fractionate between water and minerals precipitated from it. This fractionation, too, is temperature-dependent. Thus, variations in the $^{18}O/^{16}O$ ratio in the oxygen-rich carbonate ($CaCO_3$) or silica (SiO_2) skeletons of marine microorganisms give evidence of variations in the temperature of the near-surface seawater from which these skeletons precipitated, and they have been used to track past El Niño cycles.

The longevity of the massive continental glaciers—sometimes hundreds of thousands of years—makes them useful in preserving evidence of both air temperature and atmospheric composition in the (geologically recent) past. Tiny bubbles of contemporary air may be trapped as the snow is converted to dense glacial ice. The oxygen-isotope composition of the ice reflects seawater O-isotope composition and the air temperature at the time the parent snow fell. If those temperatures can be correlated with other evidence, such as the carbon-dioxide content of the air bubbles or the presence of volcanic ash layers in the ice from prehistoric explosive eruptions, much information can be gained about possible causes of past climatic variability (**figure 10.25**), and the climate-prediction models can be refined accordingly.

Case Study 10

Taking Earth's Temperature

Suppose that you were given the assignment of determining the earth's temperature so as to look for evidence of climate change. How would you do it?

Our main concern is clearly temperature at or near the surface, where we and other organisms reside. Thus we can disregard the earth's interior—fortunately, as we can't probe very far into it, and even deep-crustal drill holes are costly. It is also helpful that we focus on trends in temperature over time rather than instantaneous temperatures. We know from experience that, especially in the midlatitudes, temperatures can fluctuate wildly over short time periods; they can be very different over short distances at the same moment; and they can be quite different from year to year on any given date. If we are looking at global or regional trends, we will be more concerned with averages and how they may be shifting.

Land surface temperatures are the simplest to address. Many weather stations and other fixed observation points have been in place for over a century. Moreover, research has shown that temperature anomalies and trends tend to be consistent across broad regions. (For instance, if your city is experiencing a heat wave or acute cold spell, so are other cities and less-populated areas in the region.) So, data from a modest number of land-based sites should suffice to characterize land surface temperatures.

The oceans obviously present more of a challenge. There have been shipboard temperature measurements for centuries, but relatively far fewer, and typically not repeated at the same locations year after year. There are now stationary buoys that monitor ocean temperatures, but relatively few. Satellites have come into play here. For some decades, sea surface temperatures have been estimated using, as a proxy, radar measurements of sea surface elevation, as in **figure 10.14**. This is actually a reflection of the temperature through the uppermost layer of seawater, as it is expansion and contraction of that layer as it warms or cools that produces the surface-elevation anomalies. More recently, a more sophisticated approach has been implemented (**figure 1**). NASA's MODIS detector not only measures directly the infrared radiation (heat) coming from the sea surface. It also measures the concentration of atmospheric water vapor through which the radiated heat is passing—important because water vapor, as a greenhouse gas, will absorb some of that heat on its way to the satellite, a particular problem in the humid tropics. MODIS can correct for this, and also for interference from such sources as clouds and dust. The result is exceptionally accurate measurement of sea surface temperatures around the globe.

The average temperature for a given point over the course of a year can then be determined, and those data

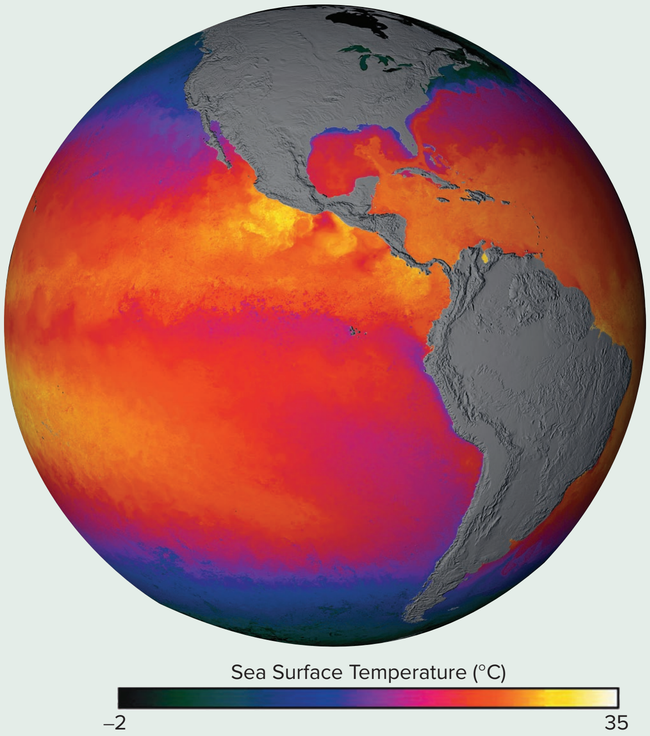


Figure 1

Sea surface temperatures, 1–8 January 2001, as measured by the Moderate-Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra satellite.

Source: NASA image by Jesse Allen based on data provided by the MODIS Ocean Team and the University of Miami Rosenstiel School of Marine and Atmospheric Science Remote Sensing Group.

The longest ice-core records come from Antarctica (**figure 10.26**); they span over 800,000 years. Records from the Greenland ice sheet go back about 160,000 years, and over that period, show a pattern very similar to the Antarctic results, indicating that the cores do capture global climate trends. The data show substantial temperature variations, spanning a range of about 10°C (20°F), some very rapid warming trends, and obvious correlations between temperature and the concentrations of carbon dioxide (CO_2) and methane (CH_4). Correlation does not show a cause-and-effect relationship, however. The warming might be a result of sharp increases in greenhouse gases in the atmosphere, or the cause (see discussion of climate feedbacks in the next section). One fact compared over longer periods of time, or averaged over the earth or a region of it. Each year, NASA publishes the resultant trend of global average temperatures (as in **figure 10.3**) and a map of temperature anomalies around the world (**figure 2**). The baseline used for reference is the average for the period 1951–1980, a period recent enough that plentiful data are available, long enough to smooth out a good deal of short-term variability, and long enough ago to allow us to look at trends in the last several decades. Clearly, global temperature is rising. In 2016, it was 0.99°C (1.8°F) above that baseline. Though the magnitude of the average increase may not yet look impressive, the anomalies are far from uniform around the globe; the much greater warming of the Arctic has caused particular concern.

Is this really due to the greenhouse effect? Still other measurements suggest that it is. Satellites can also measure atmospheric temperatures at various altitudes. Over the past few decades, temperatures in the troposphere (the lowest 10 km of the atmosphere) have been rising, while those in the stratosphere above it have been falling (**figure 3**). The greenhouse gases concentrate in the troposphere. Therefore, increasing greenhouse-gas concentrations in the atmosphere will mean more heat trapped in the troposphere and less escaping to warm the stratosphere (or radiate into space). The data are thus consistent with surface temperatures rising as a consequence of the observed increase in greenhouse gases.

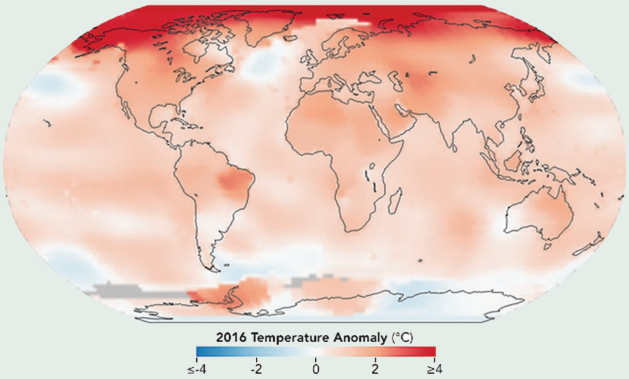


Figure 2

2016 global surface temperature anomalies, relative to 1951–1980 averages.

NASA Earth Observatory image by Joshua Stevens, based on data from the Goddard Institute for Space Studies.

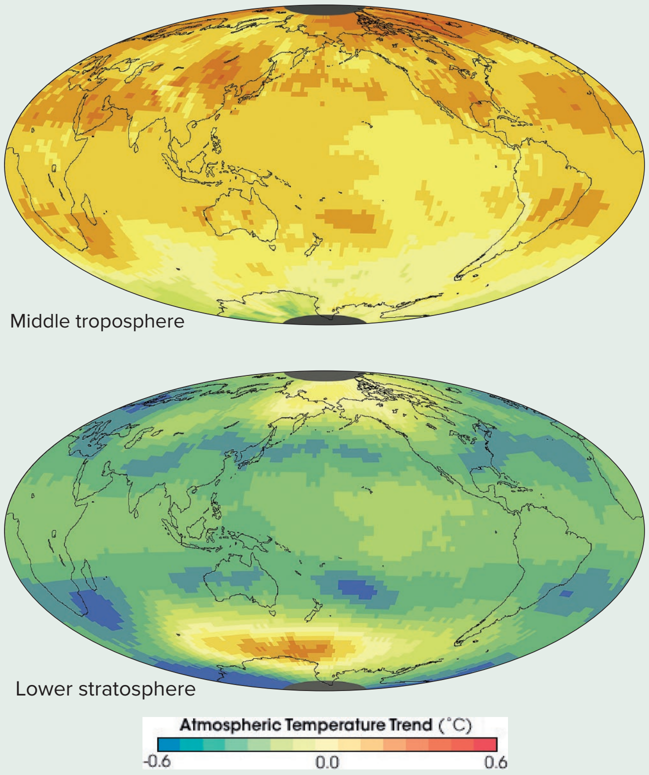


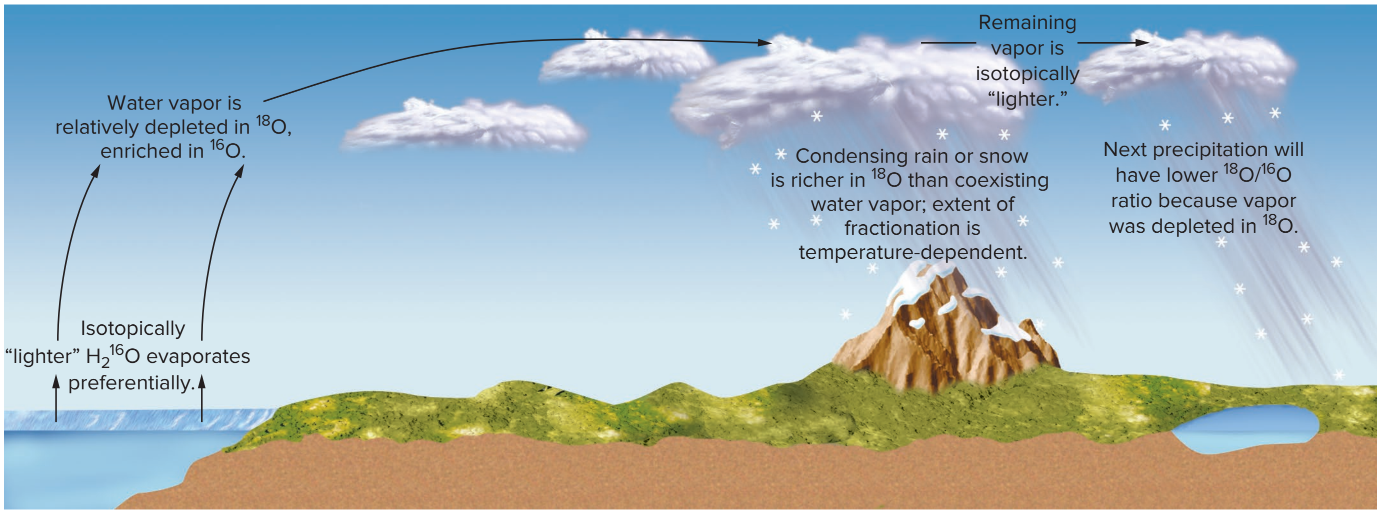
Figure 3

Temperature changes from January 1979 to December 2005 in the middle troposphere, about 5 kilometers (3 miles) above the surface, and in the lower stratosphere, 18 kilometers (11 miles) above the surface. The apparent stratospheric temperature anomalies near the poles may be related to special meteorological conditions of polar regions.

NASA image created by Jesse Allen, using data provided courtesy of Remote Sensing Systems.

is clear: The *highest* greenhouse-gas concentrations seen in the ice cores are about the levels in our atmosphere just prior to the start of the Industrial Age. Since then, we have pushed CO_2 concentrations more than 100 ppm higher still, and the numbers continue to climb.

The geologic record does indicate far higher atmospheric CO_2 levels during the much warmer periods of earth's history, long before the time represented by the ice cores. But those occurred tens of millions of years or more before humans occupied the planet, with distinctive ecosystems that presumably adapted to those warmer conditions as global temperatures rose. Modern CO_2 levels are unprecedented in the history of modern humans.



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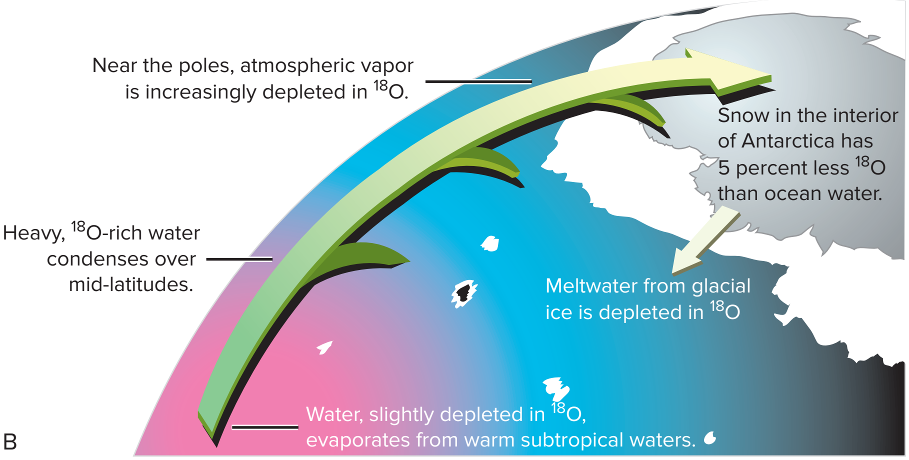
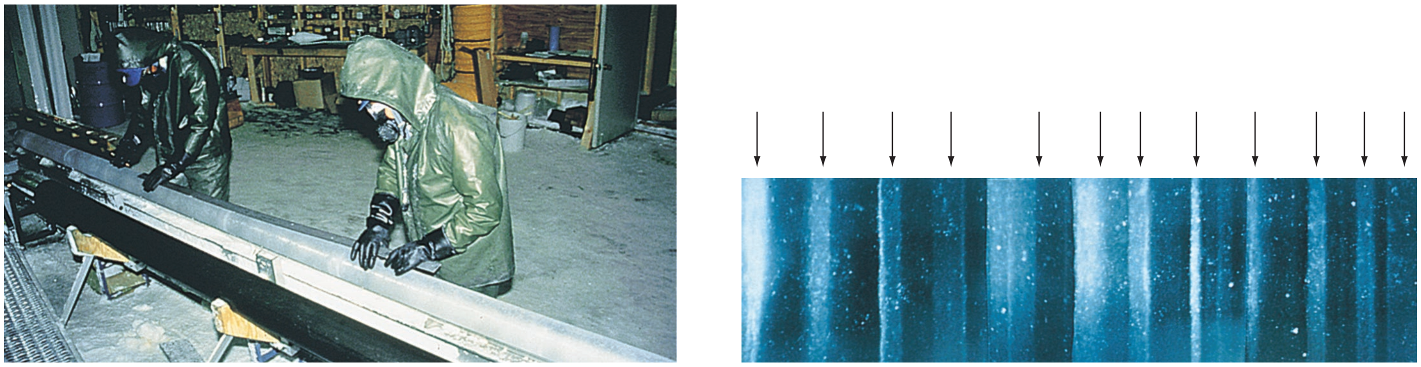


B

Figure 10.24

(A) Mass differences between ^{18}O and ^{16}O lead to different ^{18}O/^{16}O ratios in coexisting water and water vapor; the size of the difference is a function of temperature. (B) As the water vapor evaporated near the equator moves poleward and rain and snow precipitate, the remaining water vapor becomes isotopically lighter.

(B) Image by Robert Simmon, courtesy NASA.



A B

Figure 10.25

Ice coring in Greenland and Antarctica supports climate-trend investigations. (A) Cores must be kept frozen to preserve layered structure and trapped gases, so researchers must work in the cold. (B) This 19-cm (7.5-in.) section of Greenland core shows 11 annual layers, defined by summer dust blown onto ice. Core sections are dated by counting these layers.

Source: NOAA/National Geophysical Data Center/ (A) Photograph by Kendrick Taylor, DRI, University of Nevada–Reno; (B) Photograph by A. Gow, U.S. Army Corps of Engineers.

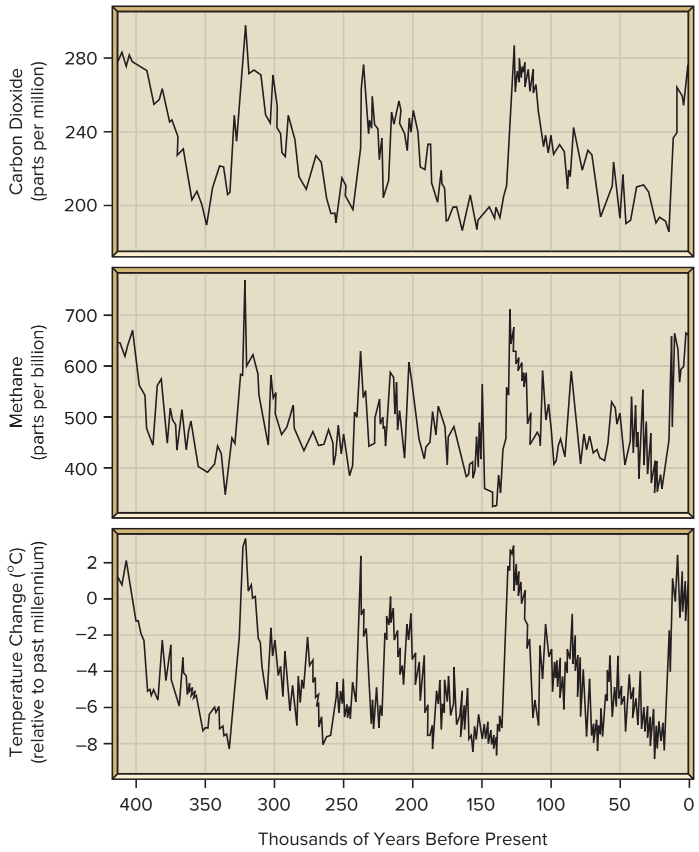


Figure 10.26

Ice-core data from Greenland and Antarctica reveal strong correlations between concentrations of the greenhouse gases carbon dioxide and methane, and temperature changes as indicated by oxygen isotopes.

Data from NOAA.

10.6 Whither for the Future? Climate Feedbacks, Predictive Uncertainty

We have already seen some of the many short-term responses of earth systems to global warming associated with increasing greenhouse gases. Trying to project the longer-term trends is complicated, in part, by the fact that some changes tend to reinforce a particular trend, while others tend to counter it and reverse climatic direction. A few examples will illustrate the challenge.

We see that as temperatures rise, one consequence is loss of glacial cover. This decreases the average *albedo* (reflectivity) of the earth's surface, which should mean more heating of the land by sunlight, and more infrared radiation back out into the atmosphere to be captured by greenhouse gases, and thus more heating, more ice melting, and so on. This is an example of positive feedback, a warming trend reinforced.

But wait—if air temperatures rise, evaporation of water from the oceans would tend to increase. Water vapor is a greenhouse gas, so that could further increase heating. However, more water in the air also means more clouds. More clouds, in turn, would reflect more sunlight back into space before it could reach and heat the surface, and that effect would be likely to be more significant. This is an example of negative feedback, in which warming induces changes that tend to cause cooling. Some speculate that over centuries, the world might then cool off, perhaps even enough to initiate another ice advance or ice age far in the future. In fact, many modelers identify cloud cover as the single largest source of uncertainty in projections of greenhouse-effect heating.

Now consider the oceans. Atmospheric carbon dioxide can dissolve in seawater, and more dissolves in colder water. So if global warming warms sea-surface water, it may release some dissolved CO_2 back into the atmosphere, where it can trap more heat to further warm the surface waters (positive feedback). Or will melting of polar and glacier ice put so much cool, fresh water on the sea surface that there will be more solution of atmospheric CO_2, removing it from the atmosphere and reducing the heating (negative feedback)? The recent observation that phytoplankton productivity declines in warmer surface waters indicates another positive-feedback scenario: Phytoplankton are plants, and photosynthesis consumes CO_2. Sharply reduced phytoplankton abundance, then, means less CO_2 removed from the atmosphere, and more left there to absorb heat.

Still more complexities exist. For instance, as permafrost regions thaw, large quantities of now-frozen organic matter in the soil can begin to decompose, adding CO_2 and/or CH_4 to the atmosphere—another positive-feedback scenario. If, overall, the positive feedbacks dominate, one could eventually have a "runaway greenhouse" effect such as exists on the surface of Venus, where the CO_2-rich atmosphere keeps the planet's surface hot enough to melt lead.

Beyond water vapor, CO_2, and CH_4, there are still more greenhouse gases produced by human activity, including nitrous oxide (N_2O), a product of internal-combustion engines, and the synthetic chlorofluorocarbons. Many of these are even *more* effective at greenhouse-effect heating of the atmosphere than is CO_2. So is methane. Methane is produced naturally during some kinds of decay of organic matter and during the digestive processes of many animals. Human activities that increase atmospheric methane include extraction and use of fossil fuels, raising of domestic livestock (cattle, dairy cows, goats, camels, pigs, and others), and the growing of rice in rice paddies, where bacterial decay produces methane in the standing water. Methane concentrations have also risen, but currently, CH_4 is still far less abundant than CO_2; its concentration in the atmosphere is below 2 parts per million (ppm). If the amounts of minor but potent greenhouse gases continue to rise, they will complicate climate predictions tied primarily to CO_2 projections.

In the near term, the dominant feedbacks are positive, for we see continued warming as CO_2 levels continue to rise. A 2014 assessment report by the Intergovernmental Panel on Climate Change projected further global temperature increases of 0.3 to 4.8°C (0.5 to 8.6°F) from present, already-elevated temperatures by 2100, depending on model assumptions; the lower projections require sharp reductions in global greenhouse-gas emissions. Considering the effects of the much smaller temperature rise of the last century or so, the implications are substantial. There are real questions about the extent to which humans and other organisms can cope with climate change as geologically rapid as this. We have already noted some of the observed impacts. One recent study has even suggested a possible link between thawing in arctic regions and the occurrence of large ice/rock avalanches.

Geoengineering?

The strategy most widely discussed for minimizing human-induced global warming and climate change is reduction in greenhouse-gas emissions. This is proving to be a challenge, both practically and politically. Thus, there is interest in *geoengineering,* trying to reduce the warming and its consequences by tinkering with earth systems in various ways.

For example, one approach would be to reduce incoming sunlight, whether by putting giant reflectors into space above the earth or, more simply, injecting clouds of sulfate aerosols into the stratosphere. The latter would mimic the cooling effects of explosive volcanic eruptions, as discussed in chapter 5. However, both modeling and observations of the aftereffects of natural eruptions show that the aerosols can cause redistribution of precipitation, producing floods in some areas and droughts in others—a climate-change phenomenon that is already a concern—and might contribute to acid rain as well. Another suggestion is to spray seawater into the air over the oceans, promoting the formation of more bright clouds to reflect more sunlight, but again, there are questions with respect to effects on precipitation. Yet another proposal is to fertilize the oceans to stimulate phytoplankton growth, the resulting photosynthesis to consume more atmospheric CO_2.

All such geoengineering proposals share certain issues. One country cannot "geoengineer" its own climate in isolation; these strategies will have widespread, typically global, impacts, which may not be positive for all those affected. There are political questions of who will choose and carry out what is to be done, and who will fund these activities. And while we have ever-better models to examine the probable effects of various strategies, earth's climate system is sufficiently complex that we may not correctly anticipate all the consequences of a given action. For the near future, then, attention is likely to be focused on other approaches: energy sources that do not produce CO_2 (explored further in chapter 15), research aimed at better understanding of the global carbon cycle and ways to moderate atmospheric CO_2 (chapter 18), and international agreements to limit greenhouse-gas emissions (chapter 19).

Summary

Modern burning of fossil fuels has been increasing the amount of carbon dioxide in the air. The resultant greenhouse-effect heating is melting alpine glaciers, parts of the Greenland and Antarctic ice sheets, Arctic sea ice, and permafrost, and contributing to the thermal expansion of seawater, causing a rise in global sea level. If this continues, flooding of many coastal areas could result. Global warming may influence the oceans' thermohaline circulation and the occurrence of El Niño events. Other probable consequences involve changes in global weather patterns, including the amount and distribution of precipitation, which may have serious implications for agriculture and water resources; more episodes of extreme temperature; and more-intense storms. Depressed productivity of phytoplankton in warmer seawater affects both the marine food web and atmospheric CO_2; ocean acidification and warming put stress on coral reefs. Warming appears to be expanding the occurrence of certain diseases, thus affecting human health.

Cores taken from ice sheets provide data on past temperature and greenhouse-gas fluctuations over 800,000 years. They document a correlation between the two, and the fact that current CO_2 levels in the atmosphere are far higher than at any other time during this period.

Climatic projections for the future are complicated by the number and variety of factors to be considered, including other greenhouse gases, a variety of positive and negative climate feedback mechanisms, and complex interactions between oceans and atmosphere. The current trend is clearly warming. The rock record shows that earth has been subject to many climatic changes. Global temperatures have been more extreme than at present, and other instances of geologically rapid climate change occurred long before human influences. However, such changes have inevitably affected biological communities and, more recently, human societies also. We already observe significant impacts from the warming and associated climatic changes of recent decades, and note that these impacts are much more pronounced in some parts of the globe; some of the results are likely to be irreversible. While various geoengineering solutions have been proposed, there are no assurances that they would succeed, and significant scientific, practical, and political questions to be answered before they could be implemented.

Key Terms and Concepts

greenhouse effect
permafrost
thermohaline circulation

Test Your Learning

1. Describe the greenhouse effect and its relationship to modern industrialized society.
2. Explain why Arctic sea ice is more vulnerable to melting than many land-based glaciers.
3. Define *permafrost*, and indicate why traveling in permafrost regions is more difficult during the summer thaw.
4. Identify what drives the thermohaline circulation in the oceans, and how this “conveyor” affects climate around the North Atlantic.
5. Describe what happens during an El Niño event, and how it influences both precipitation patterns in the Pacific and the productivity of coastal fishing grounds.
6. Explain how global warming is related to the spread of certain diseases.
7. Indicate how phytoplankton productivity is being affected by warmer sea-surface waters, and two concerns related to these observations.
8. Note two factors related to global change that are putting stress on corals, and how.
9. Describe any three kinds of evidence in the sedimentary-rock record for past global climate.
10. Explain how ice cores are used to investigate relationships between atmospheric greenhouse gases and temperature, and what is measured as the “proxy” for temperature.
11. Briefly describe one positive and one negative feedback process relating to global warming.
12. Water vapor and methane are both greenhouse gases. Suggest why the focus is so often on carbon dioxide instead.
13. Choose any proposed geoengineering scheme; note one question or potential drawback specific to that idea, and two problematic issues that would pertain to any geoengineering strategy.

Exploring Further

1. NASA’s Goddard Institute for Space Studies identified 2016 as the warmest year since 1880. (See **figure 2** in Case Study 10.) Examine the map, noting where the most marked warming occurred. In light of the material in this chapter, consider what the cause(s) and consequences of such pronounced warming in that region might be. Also, see if you can determine from the map if 2016 was an El Niño or La Niña year.
2. NASA’s Goddard Institute for Space Studies maintains a comprehensive global-temperature website at data.giss.nasa.gov/gistemp/. Use it to try the following:
   a. Via “Global maps,” make your own temperature-anomaly maps for some period(s) of interest. Compare a map for the years of the twenty-first century with the 1980s or 1990s; make a map for a single month and compare it with the corresponding full year, and so on.
   b. Use the “Animations” link to watch the temperature anomalies shift around the world over time. Where is the temperature variability greatest? least? Watch for the rise and fall of El Niño/La Niña events or other events that may reflect shifting ocean currents.
   c. Look at the “Zonal Means” data, showing the anomalies by latitude through time. At what latitudes does warming appear earliest? What latitudes first show consistently warm anomalies, and starting when? When does the earth first show warming from pole to pole?
3. Global temperature does not necessarily increase proportionately with atmospheric CO_2 levels, as we have noted, but both have tended to increase linearly over the last 30–40 years (see **figures 10.2** and **10.3**). Use those figures to estimate the average annual rate of increase of CO_2 and of temperature over that period, and calculate the resultant apparent rate of temperature increase for every 10-ppm increase in CO_2.

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