Environmental GEOLOGY

Fourth Edition

James S. Reichard

Georgia Southern University

McGraw Hill

ENVIRONMENTAL GEOLOGY, FOURTH EDITION

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 KVO 24 23 22 21 20

ISBN 978-1-260-36827-7 (bound edition)
MHID 1-260-36827-0 (bound edition)
ISBN 978-1-260-46486-3 (loose-leaf edition)
MHID 1-260-46486-5 (loose-leaf edition)

Portfolio Manager: *Michael Ivanov*
Product Developer: *Jodi Rhomberg*
Marketing Manager: *Kelly Brown*
Content Project Managers: *Melissa Leick/Rachael Hillebrand/Sandra Schnee*
Senior Buyer: *Susan K. Culbertson*
Senior Designer: *Beth Blech*
Content Licensing Specialist: *Abbey Jones*
Cover Image: *Jim Reichard*
Compositor: *SPi Global*

All credits appearing on page or at the end of the book are considered to be an extension of the copyright page.

Library of Congress Cataloging-in-Publication Data

Names: Reichard, James S., author.
Title: Environmental geology / James S. Reichard.
Description: Fourth edition. | New York, NY : McGraw-Hill Education, [2021] | Includes index.
Identifiers: LCCN 2019039509 | ISBN 9781260368277 (hardcover)
Subjects: LCSH: Environmental geology—Textbooks. | Earth sciences—Textbooks. | Environmental sciences—Textbooks. | Human beings—Effect of environment on—Textbooks.
Classification: LCC QE38 .R45 2021 | DDC 550—dc23
LC record available at https://lccn.loc.gov/2019039509

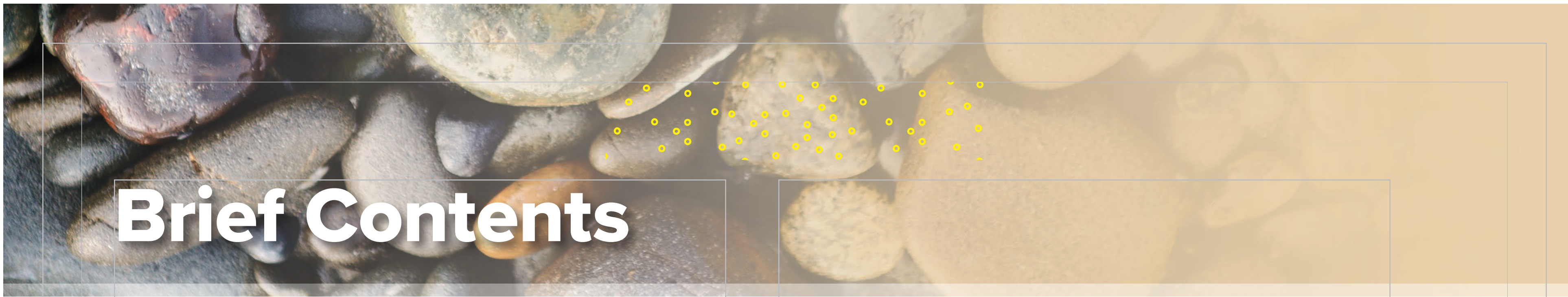
mheducation.com/highered

This book is dedicated to my wife Linda and children, Brett and Kristen. Their love and support has carried me through the many hours spent away from home. Words cannot express my love and gratitude.

—James Reichard

Jim Reichard

Jim Reichard and his family on the Highline Trail in Glacier National Park, Montana. From left to right: Jim, son Brett, daughter Kristen, and wife Linda.

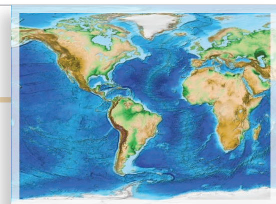


Brief Contents

Contents

Chapter 4

Earth's Structure and Plate Tectonics 95

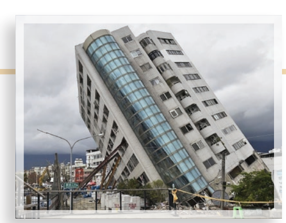


NOAA National Geophysical Data Center (NGDC)

PART TWO
Hazardous Earth Processes

Chapter 5

Earthquakes and Related Hazards 123



Kyodo News/Getty Images

Chapter 6

Volcanoes and Related Hazards 163

Lisa Lyons - Moments in Time/ Getty Images

Chapter 7

Mass Wasting and Related Hazards 197

Richard Atrero de Guzman/ NurPhoto via Getty Images

Chapter 8

Joe Raedle/Getty Images

Streams and Flooding 229

Chapter 9

John Greim/Getty Images

Coastal Hazards 267

PART THREE
Earth Resources

Chapter 10

Noam Armonn/Alamy Stock Photo

Soil Resources 305


Ingram Publishing/SuperStock


James Jordan Photography/Getty Images

Preface

Steve Cole/Getty Images

Environmental Geology, 4e focuses on the fascinating interaction between humans and the geologic processes that shape Earth's environment. Because this text emphasizes how human survival is highly dependent on the natural environment, students should find the topics to be quite relevant to their own lives and, therefore, more interesting. One of the key themes of this textbook is that humans are an integral part of a complex and interactive system scientists call the Earth system. Throughout the text the author explains how the Earth system responds to human activity and how our actions affect the very environment in which we live. A key point is that our activity often produces unintended and undesirable consequences. A good example from the text is how engineers have built dams and artificial levees to control flooding on the Mississippi River. But this has caused unintended changes in the geologic environment. For thousands of years, the rate at which the river deposited sediment in the Mississippi Delta was approximately equal to the rate that the sediment compacted under its own weight. Because the two rates were similar, the land surface remained above sea level. However, by using dams and artificial levees to confine the Mississippi River to its channel, humans disrupted the delicate balance between sediment deposition and compaction. Today large sections of the Louisiana coast, including New Orleans, are sinking below sea level, and at the same time sea level is rising due to global warming and climate change. This has not only caused severe coastal erosion, but greatly increased the chance that New Orleans will again be inundated during a major hurricane.

Another major theme in the fourth edition of *Environmental Geology* centers on a serious challenge facing modern society, namely, the need to continue obtaining large quantities of energy, and at the same time, making the transition from fossil fuels to carbon-free sources of energy that do not impact the climate system. *Environmental Geology* provides extensive coverage of the problems associated with our conventional fossil fuel supplies (Chapter 13), and an equally in-depth discussion of alternative energy sources (Chapter 14). The two chapters on energy are intimately linked to a comprehensive overview of global climate change (Chapter 16), which is arguably civilization's most critical environmental challenge.

"My overall impression after reading Chapter 16 "Global Climate Change" was that of an excellent coverage of a still very controversial topic. Reichard has managed to cover the most fundamental societal and scientific issues related to global climate change in a format accessible to undergraduate students with or without strong science background. Reichard provides an unbiased representation of facts and does not shy away from a critical discussion of opposing arguments resulting from the interpretation of the facts."

—Thomas Boving, *University of Rhode Island*

Environmental Geology also includes a sufficient amount of background material on physical geology for students who have never taken a geology course. The author believes this additional coverage is critical. Without a basic understanding of physical geology, students would not be able to fully appreciate the interrelationships between humans and the geologic environment. To meet the needs of courses with a physical geology prerequisite, this textbook was organized so that instructors could easily omit the few chapters that contain mostly background material. In addition, *Environmental Geology* does more than provide a physical description of water, mineral, and energy resources; it explores the difficult problems associated with extracting the enormous quantities of resources we need to sustain modern societies. With respect to geologic hazards (e.g., earthquakes, volcanic eruptions, and floods), the textbook goes beyond the physical science and examines the societal impacts as well as the ways humans can minimize the risks. The author also highlights the fact that as population continues to grow, the problems related to resource depletion, hazards, and climate change will become progressively more severe.

Finally, this textbook includes learning tools designed to make it easier for students to utilize information found in the text. For example, it is unreasonable to expect students to remember everything they read. For this reason, the text often cross references topics between chapters as a reminder that additional information can be found in other parts of the book. It is hoped that cross-referencing will encourage students to make better use of the index for locating additional information.

> *". . . I give the author credit for excelling in a very up-to-date assessment of alternative technologies, with some delightful examples of innovative systems that should interest the student reader. The author recognizes the importance of portraying the subject within the modern world that the student lives in."*
>
> —Lee Slater, *Rutgers University–Newark*

New for the Fourth Edition

Readers familiar with *Environmental Geology* should find that the changes to the fourth edition have significantly improved the already outstanding pedagogy and photo and art program of the previous editions. Perhaps the most significant improvement is the addition of five new case studies, bringing the total to 24. Increasing the number of case studies was a priority for the fourth edition because instructors commonly have students use case studies to explore chapter concepts in more detail. In addition to the new case studies, the chapter narratives have been thoroughly revised to include recent geologic events and scientific advances. Likewise, care was taken to ensure that all of the graphs and tables include the most recently available data at the time the text was revised. Several new photos were added to enhance the pedagogy and increase student interest. Finally, a considerable number of the existing graphics were modified to improve student comprehension.

Although changes in the fourth edition are too numerous to be listed individually, some of the more significant improvements are described below. Note that the chapters with the most revisions are those on conventional energy resources (Chapters 13) and pollution and waste disposal (Chapter 15).

Chapter 1—The opening photo was replaced with an aerial view of the skyline of Hong Kong, China, illustrating how humans have built complex societies by growing large amounts of food and extracting vast quantities of energy and water from the Earth system. In addition to the chapter opening, two photos were replaced (Figures 1.7 and 1.21) with ones that should help improve student comprehension. The most significant change to this chapter has been the addition of a new case study on how human modifications to the Earth system can lead to undesirable consequences for society. In this example, the author describes how draining the extensive swamps of Northwest Ohio and subsequent widespread use of agricultural fertilizers has led to increased algae blooms and water-quality problems on Lake Erie, which is the primary water supply for the region.

Chapter 2—In addition to minor text changes, the discussion on NASA's Near Earth Object program was updated to include the most recent results. Also, a discussion was added on NASA's new telescopes that are designed to continue the search for life on exoplanets. With respect to the graphics, minor modifications were made to the line art in Figures 2.7 and 2.36 to help improve accuracy and student comprehension. Lastly, the existing satellite images in Figure 2.25 depicting the ozone hole over Antarctica were replaced with higher quality images, including a more recent image from 2017.

Chapter 3—The section on igneous rocks has been moved so that it precedes sedimentary rocks rather than weathering processes. This was done in order to keep the three rock types together and to create a more logical sequence, which now goes from rock-forming minerals to weathering to the three rock types. Also in this chapter, more visually meaningful photos were found for Figures 3.13, 3.14, 3.19, 3.21, 3.24, and 3.32.

Chapter 4—A new photo (Figure 4.1) has been added showing an outcrop of strongly deformed sedimentary rocks, thereby providing a visual example of tectonic forces that operate in Earth's interior. Also, the photo in Figure 4.26 was replaced with a satellite image of the Appalachian Mountains so as to provide a better example of a suture zone at a convergent plate boundary. Lastly, Case Study 4.1 was renamed *The Wallace Line: An Example of Evolution and Plate Tectonics*.

Chapter 5—The opening photo was replaced with an image of an office building that collapsed during the 2018 earthquake in Hualien, Taiwan. The most significant change in this chapter has been the addition of a new case study on the earthquake hazards facing Anchorage, Alaska. Here the author demonstrates how the geologic setting puts the city at increased risk of structural failure, liquefaction, landslides, and tsunamis. In addition, new photos were used in Figures 5.1 and 5.20B and the line art in Figure 5.3 was re-labeled for improved clarity. Finally, a new laser image (Figure 5.40) was added, showing the trace of the San Andreas Fault through the urban area of Berkeley, California.

Chapter 6—The discussion on the 1883 Krakatau eruption under *Explosive Blast* hazards was completely rewritten to reflect the results from more recent research. This updated section also includes a new 2018 satellite image (Figure 6.16) showing Anak Krakatau emerging from the center of the original collapsed caldera. Similarly, the discussion on using geologic history and topographic changes to predict volcanic eruptions and hazards was largely rewritten and updated. Here a new map of Lassen Peak was added (Figure 6.30) to help illustrate how volcanic deposits can be used to assess volcanic hazards. Lastly, new and better photos were found and used to replace the existing photos in Figures 6.6B, 6.9A, 6.10, and 6.14.

Chapter 7—The opening photo was replaced with a new, dramatic image of one of the numerous landslides that occurred across northern Japan during an earthquake in 2018. Perhaps the most important change was that the section on *Slope Stability* and *Triggering Mechanisms* was rewritten to more accurately describe the relationship between shear force (weight) and shear resistance (internal friction and cohesive forces)—the discussion was previously too simplified and general. Likewise, the graphics in Figures 7.4 and 7.9 were modified to reflect the updated discussion on stress relationships. A new figure was added (Figure 7.10), consisting of two oblique aerial images to help illustrate the role climate and vegetation play in slope stability. Also, the section on *Climate and Vegetation* was rewritten and expanded to more accurately reflect the relationship between root systems and infiltrating water and how this affects slope stability. The mass wasting classification table in Figure 7.11 was modified and now includes slump movement as a separate category. In addition, the graphics in Figures 7.6, 7.7, 7.13, 7.22, and B7.4 were all modified for improved accuracy and clarity. Finally, the sinkhole photo in Figure 7.21 was replaced with a more meaningful example.

Chapter 8—In this chapter, the opening photo was replaced with a dramatic image showing rescue efforts in Houston, Texas, during the 2017 flooding associated with Hurricane Harvey. This historic flooding event is also the subject of new case study that focuses on Houston's chronic flooding problems and how they have been exacerbated by land-use changes, population growth, and climate change. The graphics in Figures 8.5, 8.14, 8.15, 8.18, and B8.5 underwent modifications to improve accuracy and clarity. Table 8.2 and the plot in Figure 8.20, which shows the relationship between discharge and recurrence interval, were updated based on the most recent stream data for the Tar River in North Carolina. A new pair of satellite photos was added to Figure 8.21 to help illustrate the severity of the historic Midwestern floods of 2019. Lastly, a new figure (Figure 8.22) was added that includes a set of photos showing overland flow actively taking place during a heavy rain event.

Chapter 9—This chapter opens with a new photo showing a beach house sitting in the surf zone during a passing storm. This photo illustrates how humans have put valuable infrastructure in harms way, which is now at increasing risk due to accelerated sea level rise. The chapter also has a new case study about the unusual string of powerful hurricanes that made landfall in the United States in 2017 and 2018. Here the author explores the question of whether this string of hurricanes, which includes 3 of the 6 costliest hurricanes in U.S. history, can be attributed to global warming and climate change. As part of the updated section on hurricanes, a new table (Table 9.2) lists the ten most costly hurricanes in U.S. history. The map in Figure 9.20 showing hurricane recurrence intervals in the U.S. was completely revised based on more current data. There were also a number of small, but significant improvements in the chapter content, such as a more detailed discussion on how tides result from the physical movement of the Earth, Moon, and Sun. Likewise, Figure 9.4 has been modified to reflect the more accurate explanation of the tides. A new photo was added to Figure 9.6 to help illustrate the physical changes that occur when waves approach shore and begin interacting with the seafloor. Similarly, a new photo was added (Figure 9.29) illustrating how buildings fall into the sea when storm waves undercut the bottom of the slope. Finally, the photos in Figures 9.12, 9.13, 9.23, and B9.2A were all replaced with more meaningful examples, and the graphics in Figures 9.10, 9.11, and 9.26A underwent modifications to improve accuracy and clarity.

Chapter 10—For this chapter, the opening photo was replaced with a new image that reinforces the chapter theme, namely, how our human food supply is inextricably linked to soils. Also, a new graphic (Figure 10.16) was added that helps illustrate the difference in permeability and drainage characteristics of clay-rich and sand-rich soils. Another new graphic (Figure 10.28) was added showing how removing natural vegetation from the landscape leads to increased overland flow and soil erosion. Lastly, the graphic in Figure 10.15 was modified to help improve clarity and student comprehension.

Chapter 11—A key graphic showing the hydrologic cycle (Figure 11.1) was modified and now includes the relative size of Earth's major water reservoirs in terms of volume percentages. Under the section on *Human Use of Freshwater*, a discussion was added on the need to prioritize water usage because of limited supplies and population growth. With respect to new graphics and photos, Figure 11.25 was added to show how freshwater can be produced from saline water using desalination techniques. Also new is Figure 11.27, which illustrates how municipalities can use treated wastewater for a variety of non-drinking purposes, thereby conserving drinking water supplies for human consumption. Related to this figure, the section on *Municipal Wastewater Recycling* was expanded and now includes a discussion on the direct and indirect reuse of treated wastewater. A new graphic was added in Figure 11.28 to help illustrate the process of aquifer storage and recovery, where surplus surface water is stored underground and then later removed during periods of high water demand. With respect to images, a new photo showing a hand-dug well was added to Figure 11.17, whereas the photos in Figures B11.3A and 11.31B were replaced with new, more meaningful examples. Finally, the plot of U.S. water withdrawals in Figure 11.4 was updated using the most recently available data.

Chapter 12—The opening chapter photo was replaced with a better example of a spinning bucket excavator in a surface mine. The section on *Rare Earth Elements* was rewritten to better reflect their important applications in modern society. This section was also expanded to include a discussion on lithium due to its major role in the production of rechargeable batteries. A new figure (Figure 12.17) was also included with examples of modern applications of rare earth elements and lithium that students should easily recognize. Three data tables (Tables 12.1, 12.4, and 12.5) were updated based on recently released USGS mineral reports. Similarly, new data from the USGS were used to update the plots showing U.S. mineral imports (Figure 12.25) and yearly mineral consumption (Figure 12.26).

Chapter 13—A photo of a drilling platform at sunset has replaced the opening photo to emphasize that fossil fuels, which our modern way of life has been based on, represent stored sunlight that accumulated as organic matter. With respect to the chapter content, much of the narrative and several section headings have been revised to reflect new developments in the supply and demand for fossil fuels. More specifically, the boom in U.S. tight oil and gas production has increased world supply, thereby keeping prices low. This has led to natural gas replacing coal as the primary means of producing electricity in the United States. Moreover, to minimize the impacts of climate change, the world is transitioning to clean sources of energy, which when combined with the low price of natural gas has led to a sharp decline in the use of coal. Also significant is that despite the recent boom in production, oil and gas are still finite resources, which means production will eventually decline. Therefore, even though the outlook for energy supplies has improved while economies around the world are transitioning to low-carbon sources of energy, there is still the potential that crude oil production will not be able to meet future demand. Due to the undesirable economic impacts associated with oil shortages, namely, price spikes and market volatility, the author explains why it is only prudent for society to make use of conservation and renewable energy sources to ensure that oil supplies continue to meet demand. In regards to specific changes, Figure 13.1 was added with a set of photos that reinforces the concept that fossil fuels still form the basis for modern societies. Also, a new plot in Figure 13.32 shows how the daily world demand for crude oil is projected to keep increasing to at least 2025. Figure 13.33 contains a new plot, which shows historical U.S. crude production and how production is expected to reach a plateau around 2030. Finally, the graphics in Figures 13.12 and 13.29 were modified for improved comprehension, and the graphs and charts in Figures 13.4, 13.23 through 13.27, 13.35, and 13.36 were updated using the most recently available data.

Chapter 14—The chapter narrative was revised to better reflect the current efforts of developed nations to try and minimize the impact of climate change by transitioning from fossil fuels to clean and renewable sources of energy. In addition to the overall chapter narrative, the section on *Photovoltaic Cells* was rewritten and now incorporates the significant improvements in battery technology and storage that have occurred in recent years. Similarly, the discussion on bird and bat fatalities under the *Wind Power* section was updated and expanded along with the sections on *Ocean Thermal Energy Conversion* and *Tidal Power*. Finally, the photo in Figure 14.12 was relabeled for improved clarity, and Table 14.1 and Figures 14.7, 14.13, 14.32, and 14.36 were updated with the most recent data.

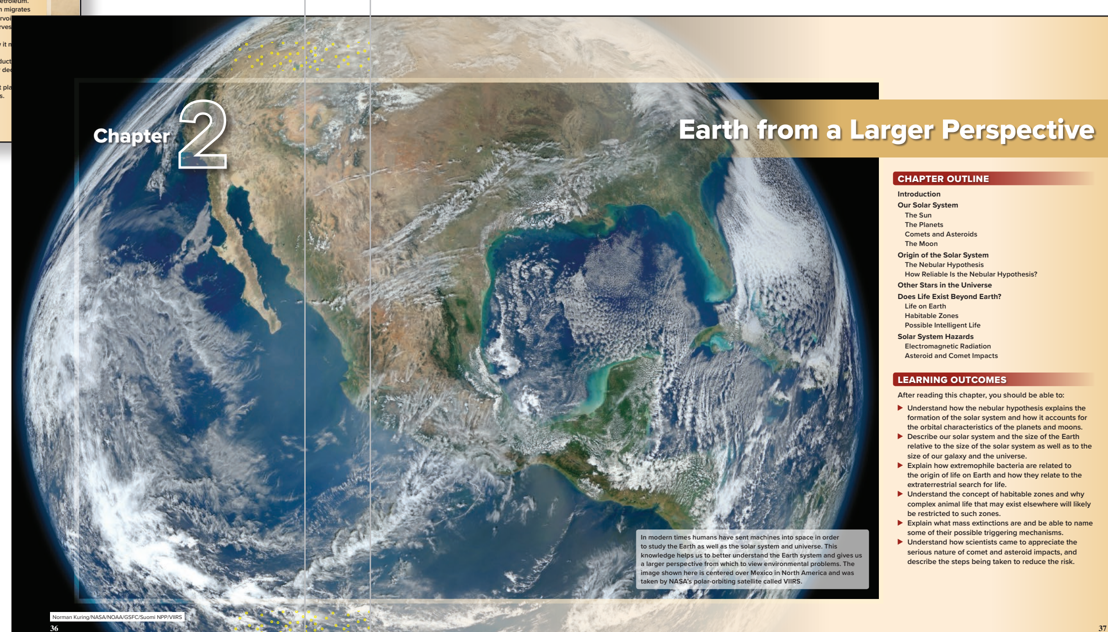
Chapter 15—A new opening photo showing municipal solid waste being compacted in a landfill illustrates the enormous amount of waste generated in modern societies. Related to this topic, a new case study on plastic pollution was added, describing the history behind plastics and the proliferation of plastic consumer products. Because plastics are so cheap to produce, we now have huge volumes of single-use plastics entering the municipal solid waste stream. Unfortunately, a significant portion of this waste ends up littering the landscape and then gets washed off into rivers and oceans. This plastic pollution is being broken down into smaller particles and is entering various food webs, which is a concern as the consequences to human health is not yet well understood. In addition, the section on *Municipal and Industrial Solid Waste* was expanded with a discussion on plastic recycling. A new section, called *Highway De-Icing Salt*, was added that describes how using rock salt to keep roads free of dangerous ice during the winter has contaminated streams and subsurface aquifers with high levels of chloride. The section *Radiation Hazard* also has an expanded discussion where the author puts various radiation risks in perspective by comparing exposure levels to natural background radiation. Finally, Table 15.1 and the graphics in Figures 15.14 and 15.42 were modified for improved comprehension, photos in Figures 15.1 and 15.36 were replaced with new examples, and the graphics and plots in Figures 15.3, 15.9, 15.13, 15.15, 15.16, 15.39, and 15.41 were updated using the most recently available data.

Chapter 16—The distinction between global warming and climate change was more clearly defined in the introduction, and greater care was taken throughout the chapter to use these terms in the appropriate manner. In addition to numerous minor updates that made the text more current, the latest temperature and sea-level rise projections by international scientists were used throughout the text. The section on *Strategy for Reducing Emissions* was expanded and now includes the decisions by the Trump Administration to withdraw from the Paris Climate Agreement and to replace the EPA's Clean Power Plan for reducing CO_2 emissions. With respect to changes in the art and photos, a new NASA graphic was used in Figure 16.5 that shows how Earth's global average temperature has been rising sharply since 1960, whereas solar output from the Sun has remained fairly steady. Also new is a photo of a wildfire in Figure 16.28 and a new ocean acidification graphic in Figure 16.38, which shows atmospheric CO_2 concentrations over time plotted along with dissolved ocean CO_2 and pH. Lastly, Table 16.1 and Figures 16.2, 16.13, 16.14, 16.25, 16.26, 16.37, 16.39, and 16.40 were all updated using the most recently available data.

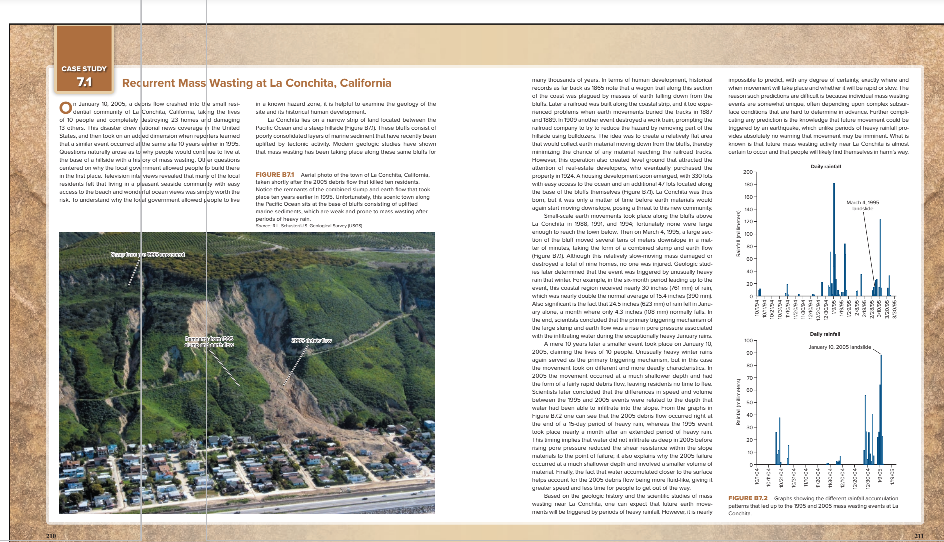
Key Features

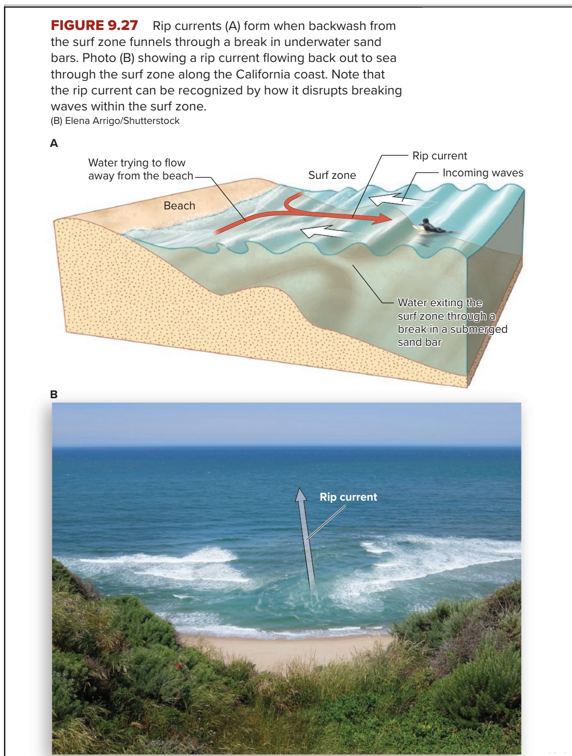
As with all college textbooks, there are differences among the various environmental geology books currently being offered. These are some of the more significant and noticeable differences you will find in *Environmental Geology*:

- **Learning Outcomes.** Each chapter is introduced with a list that provides valuable student guidance by stating key chapter concepts. This encourages students to be "active" learners as they complete the tasks and activities that require them to use critical thinking skills.
- **Chapter 2 Is Unique.** "Earth from a Larger Perspective" describes Earth's relationship to the solar system and universe, which helps to give students the broadest possible perspective on our environment. Here students learn how the Earth system is part of even larger systems before moving on to the remaining chapters that focus on our planet. Chapter 2 also gives instructors the opportunity to discuss some of the external forces that influence Earth's environment, such as solar radiation, asteroid impacts, and the effect of the Moon on our tides and climate. In addition, this chapter helps explain why Earth supports a diverse array of complex life, and why humans are so dependent on its unique and fragile environment. This sets the stage for a theme that is woven throughout the entire text—that human survival is intimately linked to the environment. Students can then see how being better stewards of the Earth is in our own best interest.

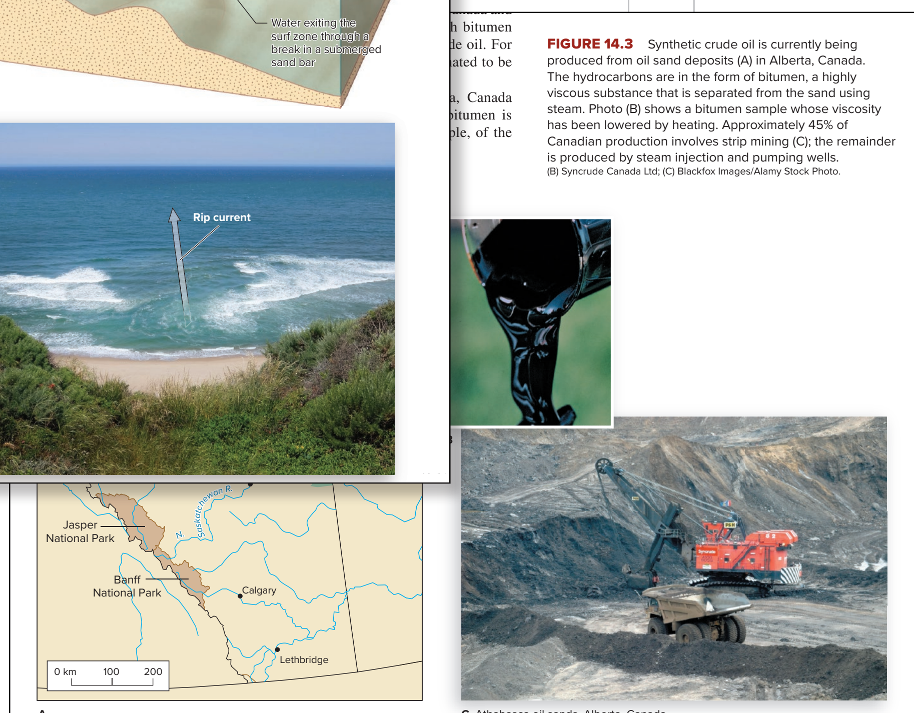


- **Case Studies.** Every chapter includes at least one case study that is designed to give students a more in-depth look at an environmental issue. A good example is Chapter 7, where the case study examines the recurring mass wasting problems at La Conchita, California. Here students are asked to consider why some people willingly live in a hazardous area, even when the risk is well understood. In Chapter 13, the case study explores the controversy over hydraulic fracturing and the development of tight oil and gas. Students are given an objective overview of both the science and policy sides of the issue, and are then expected to draw their own conclusion as to which side of the policy debate they would support.



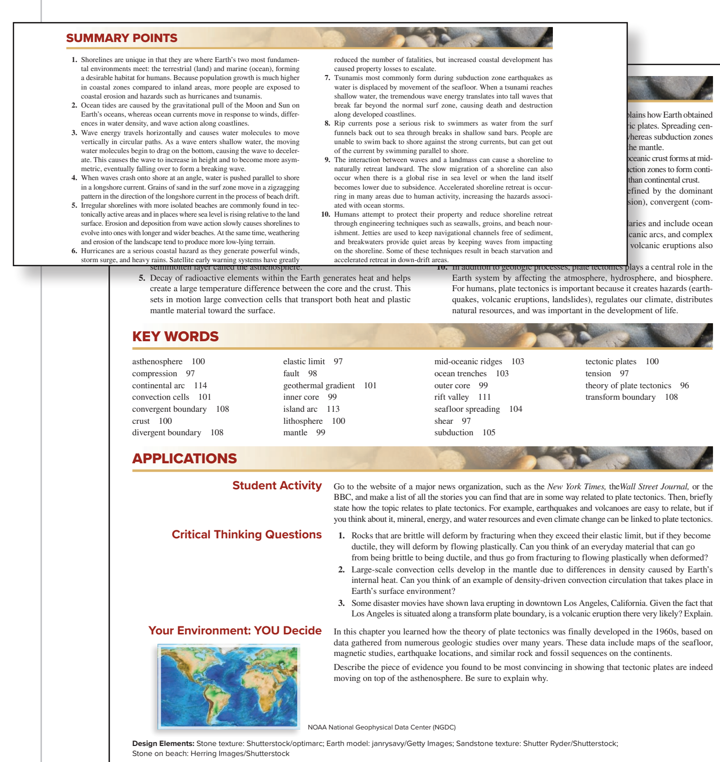


- **Photos and Illustrations.** It is well established in the field of education that most people are predominantly visual learners. Therefore, the author integrated very relevant photos and illustrations within the narrative so that abstract and complex concepts are easier to understand. The integrated use of visual examples within a narrative writing style should not only help increase student comprehension, but it should also encourage students to read more of the text.

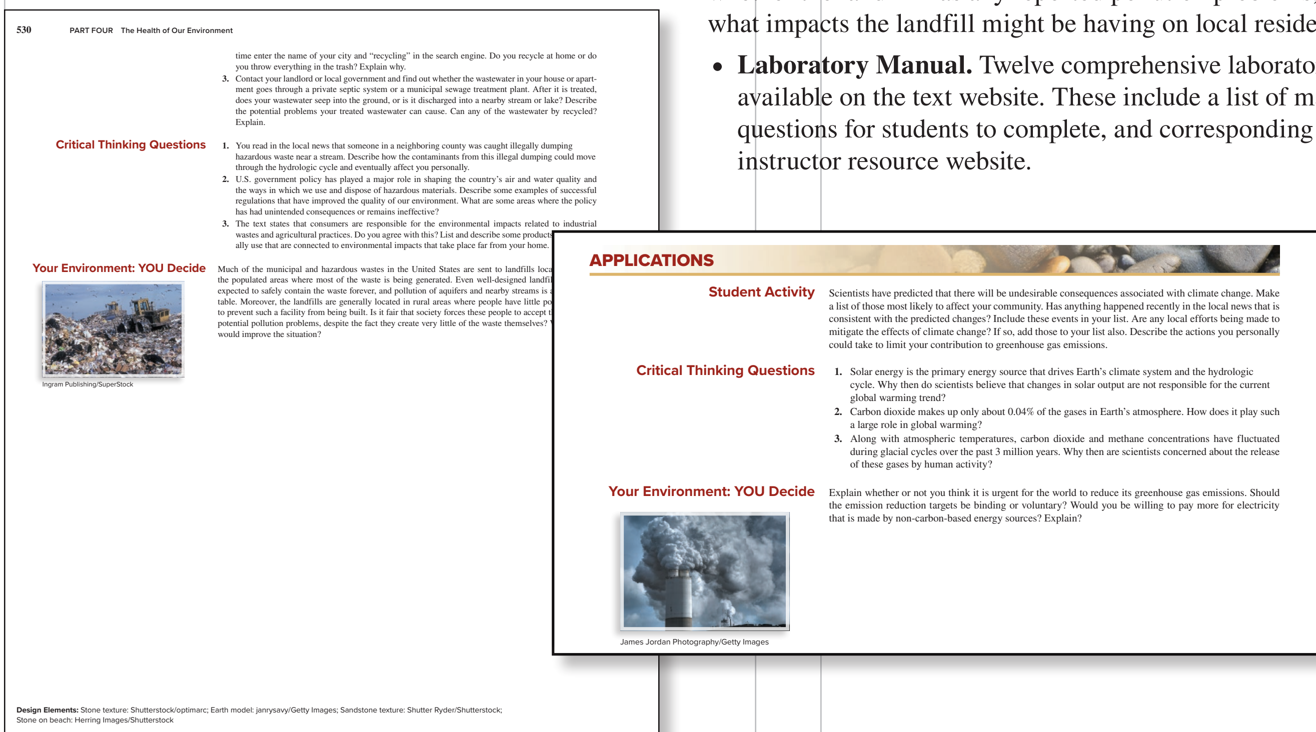


- **Summary Points.** Each chapter concludes with a list of Summary Points to provide students with a list of important concepts that should be reviewed in preparation for exams.

- **Key Words.** The study of geologic processes can be daunting due to the proliferation of unfamiliar terms. Each chapter includes a list of important terms with page references, so that terms can be viewed within the context of their use. Complete definitions are also provided in the Glossary at the back of the text.



- **Applications.** At the end of each chapter, sections called **Student Activity** and **Critical Thinking Questions** and **Your Environment: YOU Decide** encourage students to think about how their own lifestyles may be playing a role in environmental issues. For example, in Chapter 12 ("Mineral and Rock Resources") they are asked to think about the social implications of buying a diamond that comes from a part of the world where illegal proceeds support violent uprisings and civil war. In Chapter 15 ("Pollution and Waste Disposal") students are asked to contact their local government to determine the location of the landfill where their trash is being sent. They are then asked to investigate whether the landfill has any reported pollution problems, and if so, to describe what impacts the landfill might be having on local residents.
- **Laboratory Manual.** Twelve comprehensive laboratory exercises are available on the text website. These include a list of materials needed, questions for students to complete, and corresponding answer keys on the instructor resource website.


530 PART FOUR The Health of Our Environment

time enter the name of your city and "recycling" in the search engine. Do you recycle at home or do you throw everything in the trash? Explain why.

3. Contact your landlord or local government and find out whether the wastewater in your house or apartment goes through a private septic system or a municipal sewage treatment plant. After it is treated, does your wastewater seep into the ground, or is it discharged into a nearby stream or lake? Describe the potential problems your treated wastewater can cause. Can any of the wastewater by recycled? Explain.

Critical Thinking Questions

1. You read in the local news that someone in a neighboring county was caught illegally dumping hazardous waste near a stream. Describe how the contaminants from this illegal dumping could move through the hydrologic cycle and eventually affect you personally.
2. U.S. government policy has played a major role in shaping the country's air and water quality and the ways in which we use and dispose of hazardous materials. Describe some examples of successful regulations that have improved the quality of our environment. What are some areas where the policy has had unintended consequences or remains ineffective?
3. The text states that consumers are responsible for the environmental impacts related to industrial wastes and agricultural practices. Do you agree with this? List and describe some products ... ally use that are connected to environmental impacts that take place far from your home.

Your Environment: YOU Decide

Much of the municipal and hazardous wastes in the United States are sent to landfills loca... the populated areas where most of the waste is being generated. Even well-designed landfi... expected to safely contain the waste forever, and pollution of aquifers and nearby streams is ... table. Moreover, the landfills are generally located in rural areas where people have little po... to prevent such a facility from being built. Is it fair that society forces these people to accept t... potential pollution problems, despite the fact they create very little of the waste themselves? ... would improve the situation?

Ingram Publishing/SuperStock

Design Elements: Stone texture: Shutterstock/optimarc; Earth model: janrysavy/Getty Images; Sandstone texture: Shutter Ryder/Shutterstock; Stone on beach: Herring Images/Shutterstock

APPLICATIONS

Student Activity

Scientists have predicted that there will be undesirable consequences associated with climate change. Make a list of those most likely to affect your community. Has anything happened recently in the local news that is consistent with the predicted changes? Include these events in your list. Are any local efforts being made to mitigate the effects of climate change? If so, add those to your list also. Describe the actions you personally could take to limit your contribution to greenhouse gas emissions.

Critical Thinking Questions

1. Solar energy is the primary energy source that drives Earth's climate system and the hydrologic cycle. Why then do scientists believe that changes in solar output are not responsible for the current global warming trend?
2. Carbon dioxide makes up only about 0.04% of the gases in Earth's atmosphere. How does it play such a large role in global warming?
3. Along with atmospheric temperatures, carbon dioxide and methane concentrations have fluctuated during glacial cycles over the past 3 million years. Why then are scientists concerned about the release of these gases by human activity?

Your Environment: YOU Decide

Explain whether or not you think it is urgent for the world to reduce its greenhouse gas emissions. Should the emission reduction targets be binding or voluntary? Would you be willing to pay more for electricity that is made by non-carbon-based energy sources? Explain?

James Jordan Photography/Getty Images

Organization

In most environmental geology courses the list of topics includes some combination of geologic hazards and resources along with waste disposal and pollution. Consequently, this book is conveniently organized so instructors can pick and choose the chapters that coincide with their particular course objectives. The chapters are organized as follows:

Part One Fundamentals of Environmental Geology
- Chapter 1 Humans and the Geologic Environment
- Chapter 2 Earth from a Larger Perspective
- Chapter 3 Earth Materials
- Chapter 4 Earth's Structure and Plate Tectonics

Part Two Hazardous Earth Processes
- Chapter 5 Earthquakes and Related Hazards
- Chapter 6 Volcanoes and Related Hazards
- Chapter 7 Mass Wasting and Related Hazards
- Chapter 8 Streams and Flooding
- Chapter 9 Coastal Hazards

Part Three Earth Resources
- Chapter 10 Soil Resources
- Chapter 11 Water Resources
- Chapter 12 Mineral and Rock Resources
- Chapter 13 Conventional Fossil Fuel Resources
- Chapter 14 Alternative Energy Resources

Part Four The Health of Our Environment
- Chapter 15 Pollution and Waste Disposal
- Chapter 16 Global Climate Change

> *"I found the chapter [16] to overall be very well written, very interesting, and logically organized. I am especially impressed by the thorough summary the author provides on the Earth's climate system."*
>
> —John C. White, *Eastern Kentucky University*

McGraw Hill connect®

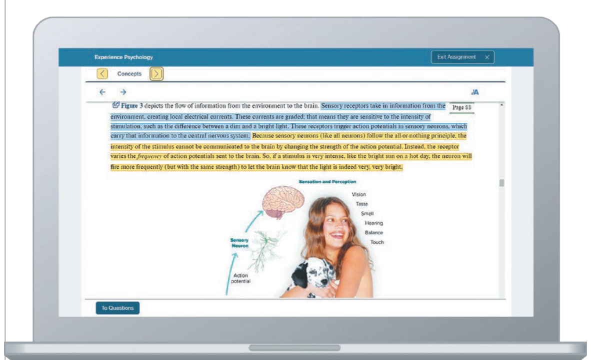
FOR INSTRUCTORS

You're in the driver's seat.

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

65%

Less Time Grading



Laptop: McGraw-Hill; Woman/dog: George Doyle/Getty Images

They'll thank you for it.

Adaptive study resources like SmartBook® 2.0 help your students be better prepared in less time. You can transform your class time from dull definitions to dynamic debates. Find out more about the powerful personalized learning experience available in SmartBook 2.0 at **www.mheducation.com/highered/connect/smartbook**

Make it simple, make it affordable.

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

Padlock: Jobalou/Getty Images

Solutions for your challenges.

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

Checkmark: Jobalou/Getty Images

SUPPORT AT every step

FOR STUDENTS

Effective, efficient studying.

Connect helps you be more productive with your study time and get better grades using tools like SmartBook 2.0, which highlights key concepts and creates a personalized study plan. Connect sets you up for success, so you walk into class with confidence and walk out with better grades.

Study anytime, anywhere.

Download the free ReadAnywhere app and access your online eBook or SmartBook 2.0 assignments when it's convenient, even if you're offline. And since the app automatically syncs with your eBook and SmartBook 2.0 assignments in Connect, all of your work is available every time you open it. Find out more at **www.mheducation.com/readanywhere**

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

Calendar: owattaphotos/Getty Images

No surprises.

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

Learning for everyone.

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

Top: Jenner Images/Getty Images, Left: Hero Images/Getty Images, Right: Hero Images/Getty Images

Acknowledgments

The fourth edition of *Environmental Geology* allowed me to improve upon the outstanding features of the original text. This required the help of many different people. In particular, I would like to thank the McGraw-Hill team that worked on this project, including Jodi Rhomberg (Senior Product Developer), Melissa Leick (Senior Content Project Manager), Beth Blech (designer), Abbey Jones (Content Licensing Specialist), Kelly Brown (Marketing Manager), Michael Ivanov Ph.D. (Brand Manager), and Thomas Timp (Managing Director). In addition to the publishing team, a special thanks goes to my wife, Linda. The demands placed on me by publishing deadlines, teaching schedules, and research commitments were at times overwhelming. Linda not only took on nearly all of the family responsibilities, giving me the time I needed, but her unwavering support and encouragement helped me get through it all. I can never thank her enough.

I would also like to thank the many individuals, companies, and government agencies who generously supplied the noncommercial photos. In many cases, this involved people taking time from their busy schedules to search photo archives and retrieve the high-resolution photos that I wanted to use. Because far too many people contributed to this effort for me to acknowledge here, their contributions are listed in the photo credits within the book. However, I do want to recognize the following individuals for producing special photos and graphics for this textbook:

James Bunn *National Oceanic and Atmospheric Administration*
Eleanor Camann *Red Rocks Community College*
Chris Daly *Oregon State University*
Carolyn Donlin *U.S. Geological Survey*
Lundy Gammon *IntraSearch*
Robert Gilliom *U.S. Geological Survey*
Bob Larson *University of Illinois*
Jake Crouch *National Oceanic and Atmospheric Administration*
Naomi Nakagaki *U.S. Geological Survey*
Matt Sares *Colorado Geological Survey*
Christie St. Clair *U.S. Environmental Protection Agency*
Cindy Starr *National Aeronautics and Space Administration*
Trent Schindler *National Aeronautics and Space Administration*
Jeremy Weiss *University of Arizona*

I would also like to acknowledge different government agencies for supporting programs that address important environmental issues around the globe. This textbook made use of publically available reports, data, and photographs from the following agencies:

Australian Commonwealth Scientific and Industrial Research Organization
Environment Canada
Geological Survey of Canada, Natural Resources Canada
National Aeronautics and Space Administration (NASA), U.S. Government
National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce
Natural Resources Conservation Service, U.S. Department of Agriculture
United States Department of Energy
United States Environmental Protection Agency
United States Fish and Wildlife Service, Department of the Interior
United States Geological Survey, Department of the Interior

I would also like to thank Trent McDowell and Gina Szablewski, who wrote and reviewed learning goal oriented content for LearnSmart.

Finally, I would like to thank all those who reviewed various parts of the manuscript during the course of this project. Their insightful comments, suggestions, and criticisms were of immense value.

Mary I. Abercrombie *Florida Gulf Coast University*
Lewis Abrams *University of North Carolina–Wilmington*
Christine N. Aide *Southeast Missouri State University*
Michael T. Aide *Southeast Missouri State University*
Diana M. Alexander *Youngstown State University*
Erin P. Argyilan *Indiana University Northwest*
Richard W. Aurisano *Wharton County Junior College*
Dirk Baron *California State University—Bakersfield*
Jessica Barone *Monroe Community College*
Mark Baskaran *Wayne State University*
Robert E. Behling *West Virginia University*
Ray Beiersdorfer *Youngstown State University*
Prajukti Bhattacharyya *University of Wisconsin–Whitewater*
Thomas Boving *University of Rhode Island*
David A. Braaten *University of Kansas*
Eric C. Brevik *Dickinson State University*
Charles Brown *George Washington University*
Patrick Burkhart *Slippery Rock University of Pennsylvania*
Ernest H. Carlson *Kent State University*
James R. Carr *University of Nevada–Reno*
Patricia H. Cashman *University of Nevada–Reno*
Elizabeth Catlos *Oklahoma State University*
Karrie Champneys Wood *Glendale Community College, Arizona*
Robert Cicerone *Bridgewater State College*
Gary Cwick *Southeast Missouri State University*
Katherine Folk Clancy *University of Maryland*
Jim Constantopoulos *Eastern New Mexico University*
Geoffrey W. Cook *University of Rhode Island*
Heather M. Cook *University of Rhode Island*
Raymond Coveney *University of Missouri–Kansas City*
Ellen A. Cowan *Appalachian State University*
Anna M. Cruse *Oklahoma State University*
Gary J. Cwick *Southeast Missouri State University*
George E. Davis *California State University–Northridge*
Jennifer L. Demchak *Mansfield University*
Hailang Dong *Miami University of Ohio*
Joseph Donoghue *University of Central Florida*
Timothy W. Duex *The University of Louisiana–Lafayette*
Yoram Eckstein *Kent State University*
Dori J. Farthing *SUNY–Geneseo*
Larry A. Fegel *Grand Valley State University*
James R. Fleming *Colby College*
Christine A. M. France *University of Maryland–College Park*
Tony Foyle *Penn State Erie, The Behrend College*
Alan Fryar *University of Kentucky*
Heather L. Gallacher *Cleveland State University*
Alexander E. Gates *Rutgers University–Newark*
David H. Griffing *Hartwick College*
John R. Griffin *University of Nebraska–Lincoln*
Syed E. Hasan *University of Missouri–Kansas City*
Chad Heinzel *Minot State University*

Donald L. Hoff *Valley City State University*
Brad Johnson *Davidson College*
Neil E. Johnson *Appalachian State University*
Steven Kadel *Glendale Community College*
Chris R. Kelson *University of Georgia*
John Keyantash *California State University–Dominguez Hills*
Karin Kirk *Carleton College*
Christopher Kofp *Mansfield University*
Gerald H. Krockover *Purdue University*
Glenn C. Kroeger *Trinity University*
Michael A. Krol *Bridgewater State College*
Jennifer Latimer *Indiana State University*
Liliana Lefticariu *Southern Illinois University*
Adrianne A. Leinbach *Wake Technical Community College*
Gene W. Lené *St. Mary's University of San Antonio*
Nathaniel Lorentz *California State University–Northridge*
Marek Matyjasik *Weber State University*
James B. Maynard *University of Cincinnati*
Richard V. McGehee *Austin Community College*
Gretchen L. Miller *Wake Technical Community College*
Barry E. Muller *ERG Consult, LLC*
Klaus Neumann *Ball State University*
Barry E. Muller *ERG Consult, LLC*
Suzanne O'Brien *Stonehill College*
Duke Ophori *Montclair State University*
David L. Ozsvath *University of Wisconsin–Stevens Point*
Evangelos K. Paleologos *University of South Carolina–Columbia*
Alyson Ponomarenko *San Diego City College*
Libby Prueher *University of Northern Colorado*
Fredrick J. Rich *Georgia Southern University*
Paul Robbins *University of Arizona*
Michael Roden *University of Georgia*
Thomas J. Rossbach *Indiana University-Purdue University Indianapolis*
Lee D. Slater *Rutgers University–Newark*
Edgar W. Spencer *Washington and Lee University*
Michelle Stoklosa *Boise State University*
Eric C. Straffin *Edinboro University of Pennsylvania*
Christiane Stidham *Stony Brook University*
Benjamin Surpless *Trinity University*
Sam Swanson *University of Georgia*
Gina Seegers Szablewski *University of Wisconsin–Milwaukee*
James V. Taranik *University of Nevada–Reno*
J. Robert Thompson *Glendale Community College*
Jody Tinsley *Clemson University*
Daniel L. Vaughn *Southern Illinois University*
Adil M. Wadia *University of Akron, Wayne College*
Miriam Weber *California State University–Monterey Bay*
David B. Wenner *University of Georgia*
John C. White *Eastern Kentucky University*
David Wilkins *Boise State University*
Crystal Wilson *Appalachian State University*
Neena Williams-Strange *State Fair Community College, Sedalia, MO*
Ken Windom *Iowa State University*

Meet the Author

James Reichard James Reichard is a Professor and Department Chair in the Department of Geology and Geography at Georgia Southern University. He obtained his Ph.D. in Geology (1995) from Purdue University, specializing in hydrogeology, and his M.S. (1984) and B.S. (1981) degrees from the University of Toledo, where he focused on structural and petroleum geology. Prior to earning his Ph.D., he worked as an environmental consultant in Cleveland, Ohio, and as a photogeologist in Denver, Colorado.

James (Jim) grew up in the flat glacial terrain of northwestern Ohio. Each summer, he went on a three-week road trip with his family and traveled the American West. It was during this time that Jim was exposed to a variety of scenic landscapes. Although he had no idea how the landscapes formed, he was fascinated nonetheless. It was not until college, when Jim had to satisfy a science requirement, that he finally came across the field of geology. Here, he discovered a science that could explain how different landscapes actually form. From that moment on, he was hooked on geology. This eventually led Jim to a graduate degree in geology, after which he was able to fulfill his dream of living and working in Colorado. Then, due to one of life's many unexpected turns, he accepted a position with an environmental firm back in Ohio. This ultimately led to a Ph.D. from Purdue and a faculty position at Georgia Southern University, where he currently enjoys teaching and doing research in environmental geology and hydrogeology. His personal interests include hiking, camping, and sightseeing.

It is through this textbook that Professor Reichard hopes to excite students about how geology shapes the environment in which we live, similar to the way he became excited about geology in his youth. To help meet this goal, he has tried to write this book with the student's perspective in mind in order keep it more interesting and relevant. Hopefully, students who read the text will begin to share some of Professor Reichard's fascination with how geology plays an integral role in our everyday lives.

Crater Lake National Park, Oregon

Jim Reichard

Environmental GEOLOGY

PART ONE Fundamentals of Environmental Geology

Chapter 1

George Hammerstein/Corbis/Glow Images

Humans and the Geologic Environment

Aerial view showing the skyline of Hong Kong, China. Modern humans have been able to thrive due to our ability to grow large amounts of food and extract vast quantities of energy and water from the Earth. However, population growth is threatening to outstrip Earth's ability to provide the resources needed to sustain our population. Humans therefore must find a way to stabilize population growth and limit our consumption of resources.

CHAPTER OUTLINE

LEARNING OUTCOMES

After reading this chapter, you should be able to:

- Describe the major focus of the discipline called environmental geology.
- Characterize how scientists develop hypotheses and theories as a means of understanding the natural world.
- Describe the concept of geologic time and how the geologic time scale was constructed.
- Explain how geologic time and the rate at which natural processes operate affect how humans respond to environmental issues.
- Describe how Earth operates as a system and why humans are an integral part of the system.
- Explain the concept of exponential population growth and how it relates to geologic hazards and resource depletion.
- Define the concept of sustainability in terms of the living standard of developed nations and also in terms of the human impact on the biosphere.

Introduction

StockTrek/Getty Images

Earth is unique among the other planets in the solar system in that it has an environment where life has been able to thrive, evolving over billions of years from single-cell bacteria to complex plants and animals. There have been three critical factors that have led to the diversity of life we see today. One is that Earth's surface temperatures are in the range where water can exist in three states: solid, liquid, and vapor. The second is that our planet was able to retain its atmosphere, which in turn allows the water to move between the three states in a cyclic manner. Last, Earth has a natural mechanism for removing carbon dioxide from the atmosphere, namely, the formation of carbonate rocks (e.g., limestone). This has prevented a buildup of carbon dioxide and a runaway greenhouse effect, similar to what happened on Venus, where surface temperatures today exceed 800°F (425°C). With respect to humans *(Homo sapiens),* our most direct ancestors have been part of Earth's biosphere for only the past 200,000 years, whereas other hominid species go back as far as 6 to 7 million years. Compared to Earth's 4.5-billion-year history, humans have existed for a very brief period of time. However, rapid population growth combined with the Industrial Revolution has resulted in profound changes in Earth's surface environment and atmosphere. The focus of this textbook will be on the interaction between humans and Earth's geologic environment. We will pay particular attention to how people use resources such as soils, minerals, and fossil fuels and how we interact with natural processes, including floods, earthquakes, landslides, and so forth.

One of the key reasons humans have been able to thrive is our ability to understand and modify the environment in which we live. For example, consider that for most of history people lived directly off the land. To survive they had to be keenly aware of the environment in order to find food, water, and shelter. This forced some people to travel with migrating herds of wild animals, who in turn were following seasonal changes in their own food and water supplies. Eventually we learned to clear the land and grow crops in organized settlements. As they practiced agriculture, humans became skilled at recognizing those parts of the landscape with the most productive soils. The best soils, however, were commonly found in low-lying areas along rivers and periodically inundated by floodwaters. To reduce the risk of floods, people learned to seek out farmland on higher ground and place their homes even higher, thereby avoiding all but the most extreme floods. In addition to reducing the risk of floods and other natural hazards, we learned how to take advantage of Earth's mineral and energy resources. This led directly to the Industrial Revolution and the modern consumer societies of today.

Although humans have benefited greatly by modifying the environment and using Earth's resources, this activity has also resulted in unintended and undesirable consequences. For example, in order to grow crops and build cities it was necessary to remove forests and grasslands that once covered the natural landscape. This reduced the land's ability to absorb water, thereby increasing the frequency and severity of floods. Also, the use of mineral and energy resources by modern societies creates waste by-products that can poison our streams and foul the air we breathe. The prolific use of fossil fuels is even altering the planet's climate system and contributing to the problem of global warming. It has become abundantly clear that the human race is an integral part of the Earth system and that our actions affect the very environment upon which we depend.

While the link between environmental degradation and human activity may be clear to scientists, it is not always so obvious to large segments of the population. A well-established concept with respect to environmental degradation is known as the **tragedy of the commons**, which is where the self-interest of individuals results in the destruction of a common or shared resource. A common resource includes such things as a river used for water supply, wood in a forest, grassland for grazing animals, and fish in the sea. Consider a coastal village whose primary source of food is the local fishing grounds offshore. This resource is renewable as long as the fish are not harvested at a faster rate than they can reproduce; hence, everyone in the village benefits. However, if the village grows too large, the increased demand can make the fishing unsustainable. As the fish become scarcer, the competition for the remaining fish gets more intense as the individual fisherman try to feed their families. The fisherman's self-interest creates a downward spiral where all members of society ultimately suffer as the fishery becomes so depleted that it collapses and is unable to recover.

Another phenomenon that can contribute to environmental degradation is when citizens in consumer societies become disconnected from the natural environment. An example is the United States, where many people now live and work in climate-controlled buildings and get their food from grocery stores as opposed to growing their own (Figure 1.1). People then tend to lose their sense of being connected with the natural world, despite the fact they remain dependent upon the environment as were our ancient ancestors. As with the tragedy of the commons, a lack of environmental awareness can lead to serious problems and hardships for society.

FIGURE 1.1 In modern consumer societies few people live directly off the land, but instead buy most of their food in stores. This trend has led to a greater disconnection between people and the natural environment upon which they still depend.
(left) Glow Images; (right) Andrew Resek/McGraw-Hill Education

A

B

C

FIGURE 1.2 Rock and mineral deposits (A) provide the raw materials used for building (B) and operating our modern societies. The geologic resources known as fossil fuels provide the bulk of the energy used for powering (C) the industrial, transportation, and residential sectors of society.
(A) Dr. Parvinder Sethi; (B) Fuse/Getty Images; (C) TebNad/iStock/Getty Images

A

B

FIGURE 1.3 In addition to locating resources, geologists study hazardous earth processes and use this knowledge to help society avoid or minimize the loss of life and property damage. Photo (A) shows a building that was destroyed during the 1995 earthquake in Kobe, Japan, and (B) shows the results of an earthquake-induced landslide in Las Colinas, El Salvador, in 2001.
(A) *Source:* Roger Hutchinson/NOAA; (B) *Source:* USGS

What Is Geology?

The science of **geology** is the study of the solid earth, which includes the materials that make up the planet and the various processes that shape it. Many students who are unfamiliar with geology tend to think it is just a study of rocks, and therefore must not be very interesting. However, this perception commonly changes once students realize how intertwined their own lives are with the geologic environment. For example, the success of our high-tech society is directly tied to certain minerals whose physical properties are used to perform vital tasks. Perhaps the most important are minerals containing the element copper, a metal whose ability to conduct electricity is absolutely essential to our modern way of life. Imagine doing without electric lights, refrigerators, televisions, cell phones, and the like. Because geologists study how minerals form, mining companies hire geologists to look for places where valuable minerals have become concentrated (Figure 1.2). Equally important is the ability of geologists to locate deposits of oil, gas, and coal, as these serve as society's primary source of energy. Geologists also provide valuable information as to how society can minimize the risk from hazardous Earth processes such as floods, landslides, earthquakes, and volcanic eruptions (Figure 1.3).

Geology has traditionally been divided into two main subdisciplines: physical geology and historical geology. **Physical geology** involves the study of the solid earth and the processes that shape and modify the planet, whereas **historical geology** interprets Earth's past by unraveling the information held in rocks. The most important geologic tool in both disciplines is Earth's 4-billion-year-old collection of rocks known as the *geologic rock record.* This vast record contains a wealth of information on topics ranging from the evolution of life-forms to the rise and fall of mountain ranges to changes in climate and sea level. Over the past 30 years or so a new subdiscipline has emerged called **environmental geology**, whereby geologic information is used to address problems arising from the interaction between humans and the geologic environment. Environmental geology is becoming increasingly important as population continues to expand, which in turn is leading to widespread pollution and shortages of certain resources, particularly water and energy. Population growth has also resulted in greater numbers of people living in areas where floods, earthquakes, volcanic eruptions, and landslides pose a serious risk to life and property.

The first step in solving our environmental problems is to understand the way in which various Earth processes operate and how humans interact with these processes. Once this interaction is understood, appropriate action can be taken to reduce or minimize the problems. The most effective way of accomplishing this is through *science,* which is the methodical approach developed by humans for learning about the natural world. Because science is critical to addressing our environmental problems, we will begin by taking a brief look at how science operates.

Scientific Inquiry

By our very nature, humans are curious about our surroundings. This natural curiosity has ultimately led to the development of a systematic and logical process that tries to explain how the physical world operates. We call this process *science,* which comes from the Latin word *scientia,* meaning "knowledge." Over the past several thousand years the human race has accumulated a staggering amount of scientific knowledge. Although we now understand certain aspects of the natural world in great detail, there is still a lot we do not understand. Throughout this period of discovery the public has generally remained fascinated with what scientists have learned about the physical world. Evidence for this fascination is the continued popularity of science programs currently available on television. It seems rather odd then that one of the common complaints in science courses is that nonscience majors find the subject boring. This raises the question of what is it about science courses that tends to cause students to lose their natural interest in science?

One reason, perhaps, for the loss of interest is that students are often required to memorize trivial facts and terminology. The problem is compounded when it is not made clear how this information is relevant to our own lives. Focusing on just the facts is unfortunate because it is the *explanation* of the facts that makes science interesting, not necessarily the facts themselves. Take, for example, the fact that coal is found on the continent of Antarctica, which sits directly over the South Pole (Figure 1.4). Because coal forms only in swamps where vegetation and liquid water are abundant, we can logically conclude that Antarctica at one time must have been relatively ice-free. This means that either the climate was much warmer in the past, or Antarctica was once located much closer to the equator. This leads us to ask the obvious: What could have caused the global climate to change so dramatically? Conversely, how could this giant landmass actually move to its present position? To answer these questions scientists must gather additional data (i.e., facts). This data will likely result in even more questions that need to be answered.

Science therefore can be thought of as a method by which people use data to discover how the natural world operates. Unlocking the secrets of nature is truly exciting, which is why most scientists love what they do. Anyone who has found a fossil or an old coin, for example, can relate to the thrill of discovery. A key point here is that nearly everyone practices science each and every day. When we observe dark clouds moving toward us we process this information (i.e., data) along with past observations, and logically conclude that a storm is approaching and that it is wise to seek shelter. A fisherman who keeps changing lures until he or she finds one that attracts a certain type of fish is also practicing science. Because science is fundamental to the topics discussed in this textbook, we will explore the actual process in more detail in the next section.

How Science Operates

Modern scientific studies of the physical world are based on the premise that the entire universe, not just planet Earth, behaves in a consistent and often predictable

FIGURE 1.4 The basic goal of science is to use facts or data to explain different aspects of our natural world. For example, the coal beds shown here in Antarctica are a scientific fact. It's also a fact that coal forms only in lush swamps, which means Antarctica must have been ice-free at some point in the geologic past. The best explanation for this is that Earth's climate was much warmer in the past, or that Antarctica was once much closer to the equator.
Steve McLoughlin

manner. When an event or phenomenon is observed repeatedly and consistently, it can be described as having a pattern. Discovering patterns in nature is important because it allows us to predict future events. For example, people long ago observed that the ocean rises and falls along coastlines on a regular basis. This pattern, known as the tides, is so regular that we can accurately predict when the sea will reach its maximum and minimum heights each day. In contrast, events such as floods and volcanic eruptions occur repeatedly, but on a more irregular or random basis. The random nature of certain types of events means that scientists can only predict their future occurrences in terms of statistical probabilities. Although recognizing natural patterns is a key component of science, the goal is to explain *how* and *why* things happen in the first place.

The process by which the physical world is examined in a logical manner is commonly referred to as the **scientific method**. The basic approach is to first gather factual data about the world through observations or by conducting experiments. Examples of data include such things as temperature readings, frequency of floods, and fossils preserved within rocks. Note that all scientific data can be observed and/or physically measured. Also, data are considered to be facts provided that scientists working independently of each other are able to repeat the work and obtain similar results. Once data are collected, scientists then seek to develop an explanation for the data itself and any patterns it may contain. For example, suppose a researcher collects marine fossils from rock layers that are 10,000 feet above sea level. The next step would be to develop a scientific explanation for the fossils that is consistent with other known data. In this case, any explanation would have to be consistent with the fact that the planet does not contain enough water for sea level to ever have been 10,000 feet higher than it is today. Logic dictates then that any plausible explanation must include a mechanism for uplifting the fossil-bearing rocks from sea level to their present position.

The term **hypothesis** refers to a scientific explanation of data that can be tested in such a way that it can be shown to be false or incorrect; something scientists refer to as being *falsifiable*. Supernatural explanations are not considered scientific simply because they are not testable and cannot be shown to be false. This concept of a hypothesis being falsifiable may seem odd since people generally think about trying to prove ideas to be true rather than false. Nevertheless, this is an important concept in science because a hypothesis is considered valid so long as additional testing does not show it to be false. Take, for example, how fossil evidence shows that dinosaurs went extinct 65 million years ago, whereas the first fossils of primitive humans (hominids) do not show up in the rock record until around 7 million years ago. Scientists have logically concluded, or hypothesized, that humans never coexisted with dinosaurs. This hypothesis would be proven to be false if hominid fossils are ever found in rocks of the same age as those that contain dinosaur fossils. Because extensive searches have never yielded such hominid fossils, the hypothesis that people and dinosaurs did not coexist remains valid.

Another key aspect of the methodology we call science is that during the early stages of an investigation researchers commonly come up with more than one plausible hypothesis for a given set of data. As shown in Figure 1.5, scientists refer to these different explanations as **multiple working hypotheses**, which are all considered valid so long as they are consistent with existing data. Because the goal of science is to seek out the best possible explanation, researchers continue to collect new data as they try to disprove one or more of the hypotheses. If an individual hypothesis is shown to be false, then it must either be modified or removed from consideration. Over time, this process of eliminating and refining hypotheses by gathering new data gives scientists

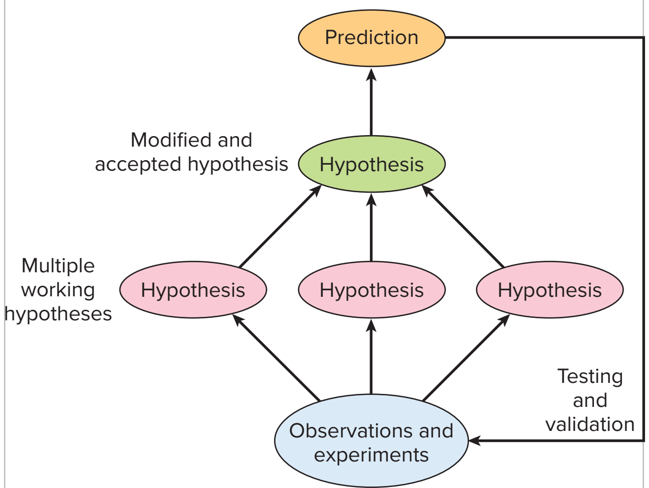


FIGURE 1.5 A scientific hypothesis is an explanation of known observations and experimental data. Multiple hypotheses are commonly developed, with most being discarded or modified as new data are gathered during testing and validation. Over time, a refined hypothesis normally emerges from the process and becomes generally accepted by the scientific community. Validation involves the ability of a hypothesis to predict future events.

greater and greater confidence in the validity of the remaining hypotheses. Note in Figure 1.5 that hypotheses are validated by their ability to predict future observations or experimental data. It should be emphasized that geology is more of an observational science than an experimental one, such as chemistry. This means that geologic hypotheses are typically tested or validated by making predictions that are confirmed through additional observations as opposed to controlled lab experiments. A good example is the hypothesis that humans and dinosaurs did not coexist, something that cannot be tested in a lab, but rather by observing more of the fossil record.

The terms *theory* and *hypothesis* are sometimes used interchangeably, but actually have different meanings. As indicated in Figure 1.6, a **theory** describes the relationship between several different and well-accepted hypotheses, providing a more comprehensive or unified explanation of how the world operates. In other words, a theory ties together seemingly unrelated hypotheses and allows us to see the "big picture." For example, the theories of atomic matter, relativity, and evolution unify various hypotheses within their respective disciplines of chemistry, physics, and biology. In geology the central unifying theory is known as the theory of plate tectonics (Chapter 4). This important theory explains how Earth's rigid crust is broken up into separate plates, which are in constant motion due to forces associated with the planet's internal heat. The movement of tectonic plates influences the location of continents and circulation of ocean currents, and consequently has a strong effect on the global climate system and biosphere on which we humans depend. As with all scientific theories, the theory of plate tectonics provides scientists with a larger context for understanding an array of different hypotheses. It should be emphasized that when scientists use the term *theory,* it has an entirely different meaning compared to its use by the general public. In common everyday language, the word "theory" is used to describe some educated guess or speculation. In science, however, a theory is a widely accepted and logical explanation of natural phenomena that has survived rigorous testing. Later we will examine how these different meanings of *theory* can impact public debate and policy considerations of environmental issues.

There are some phenomena in nature where the relationship between different data occurs so regularly and with so little deviation that scientists refer to the relationship as a **law**. In some cases a law can be expressed mathematically, as in Newton's three laws of motion and gravitational law. An example of a law in geology is the *law of superposition,* which states that in a sequence of layered rocks derived from weathering and erosion (i.e., sedimentary rocks, Chapter 3), the layer on top is the youngest and the one on the bottom is the oldest. This simple and intuitive idea that sedimentary layers become progressively older with depth has been invaluable in using the geologic rock record to unravel Earth's history. Scientific laws, therefore, are quite useful despite the fact they do not necessarily unify different hypotheses and provide grand explanations as do theories.

A good example of how knowledge is advanced through the use of science is the discovery of the planet Neptune. Early astronomers noted strange wobbles in the elliptical orbits of the planets around the Sun, but could not explain the wobbling with the existing knowledge. It was not until after Isaac Newton published his theory of gravitation in 1687 that astronomers could explain that the wobbling was caused by the gravitational effects of planets in adjoining orbits. In the 1800s, scientists remained puzzled by the wobble in the orbit of Uranus since it was the outermost known planet at the time. This led some astronomers to predict that an unknown planet existed beyond Uranus's orbit and was causing the wobble. The planet Neptune was then discovered in 1846 when astronomers pointed a telescope at the exact position in

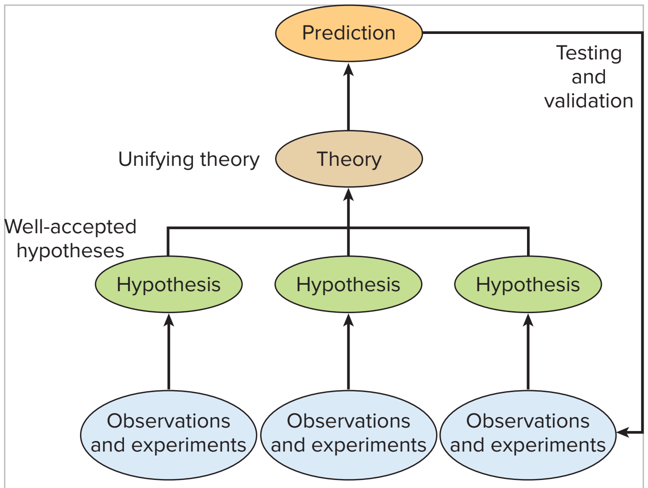


FIGURE 1.6 Scientific theories describe the relationship among different hypotheses and provide a more comprehensive or unified explanation of how the natural world operates. As with all scientific explanations, theories undergo repeated testing and validation.

the sky where Newton's laws predicted a planet would be. Because of this and other successful predictions, scientists soon accepted the validity of Newton's theories.

In the early 1900s, Albert Einstein stunned the scientific community when his special theory of relativity (1905) and general theory of relativity (1915) proved that Newton's gravitational law produced significant errors in situations of unusually strong gravity or high velocities. However, Einstein's work did not invalidate Newton's law, but rather represented a modified or improved version that was accurate under more extreme conditions. This example helps highlight the fact that scientific theories and hypotheses can be improved and modified through continued testing. Although it is rare, well-established theories are sometimes rejected when they fail to explain new data, or when a better explanation is presented. Perhaps the most well-known example is how the scientific community completely abandoned the Earth-centered theory of the solar system during the 1500s. A Sun-centered theory, based on the earlier work of Nicolaus Copernicus, eventually gained acceptance because it provided a much simpler explanation for the known movements of the planets.

Science and Society

Over the centuries scientists have accumulated a vast amount of knowledge regarding the natural world. Highly trained scientists in today's specialized fields are naturally the ones who best understand the details of this knowledge, whereas all of society benefits from the results. Consider how advances in medical research have led to an increase in doctors specializing in fields such as cardiology, neurology, gynecology, and dermatology. Today if a person has a medical problem he or she can go to a specialist for a more accurate diagnosis and more sophisticated treatment. This, in turn, greatly increases the chance of being cured of a serious illness. Also consider the scientists with specialized knowledge on the complex interactions between hurricanes and the atmosphere and oceans. This area of science has progressed to the point now where sophisticated computer models routinely make projections of where hurricanes will make landfall, thereby saving large numbers of lives.

Although scientists are able to make useful predictions based on well-established theories, it is important to realize that there is almost always some degree of uncertainty associated with any prediction. The amount or degree of uncertainty usually depends on the nature of the process and the amount of error involved in making measurements. Take, for example, how scientists use Newton's laws of motion and gravity to predict, with great confidence and accuracy, the future position of the planets as they orbit the Sun. These laws were used to land a spacecraft on Saturn's moon Titan in 2005 and on a comet in 2014, which were impressive feats considering the individual crafts traveled seven and ten years through space before meeting up with their respective targets orbiting the Sun. Also consider how hydrologists can predict with great certainty that deforestation will lead to increased flooding. Due to the sporadic nature of flood events, however, predicting an actual flood can only be done using statistical probabilities.

Nearly everyone in a modern society benefits from science, but problems can arise when people have a poor understanding of science and then take the benefits for granted. For example, when you enter a friend's number into your cell phone you probably never think about all the science behind the wireless technology that makes your call possible. Likewise, when we put gas in our vehicles or enjoy a warm house, few of us think about how the science of geology enables oil companies to locate petroleum deposits hidden deep within the Earth. Or, we may not consider how it took years of medical research before surgeons could perform open-heart operations that extend the lives of our loved ones. Although society reaps great benefits from science, history is full of examples where new knowledge met considerable resistance. Much of this resistance can be attributed to the tendency of knowledge to create change. In some instances scientific advances present society with new moral and ethical questions that must be addressed, as is the case with stem-cell research and its potential to develop cures for different diseases. Other times people feel their religious views are being threatened by science, as with the theory of evolution and how it explains the development of the biosphere. Perhaps the most common reason people resist scientific knowledge is that it often triggers changes that threaten established economic interests within a society. Pollution controls on coal-burning power plants, elimination of lead in gasoline, and restriction of ozone-depleting refrigerant gases are but a few examples where science identified a clear threat to human health, but corrective measures were strongly opposed by business and political interests.

It is not surprising then to find science thrust into public debates whenever new information runs counter to the interests of economic, political, or religious groups. A common reaction from interest groups is to try to discredit scientific information by referring to it as “only a theory.” This reaction, of course, takes advantage of the common misperception that a scientific theory is just speculation or an educated guess. Another well-used tactic is to create doubt about the science by saying “scientists are not certain.” The implication being that the science is untrustworthy, conveniently ignoring that all scientific work by its very nature has some level of uncertainty. Perhaps the best example is how the tobacco industry, for over 30 years, used scientific uncertainty to effectively sow doubt regarding the link between smoking and lung cancer. Today we see the words “theory” and “uncertainty” again being misused in an effort to convince the public that the threat of global warming is a hoax (Chapter 16).

Another common tactic by interest groups is to create doubt by putting forth nonscientific work whose results run counter to the legitimate work of scientists. Here the nonscientific work is simply labeled “scientific,” which is usually effective because most people find it difficult to distinguish between good, solid science and so-called *junk science*. The key difference is that good scientific explanations are always capable of being proved false and are consistent with *all* the data, not just selective data that fit a particular viewpoint. Another measure of good scientific work is whether it has passed the so-called *peer-review process* before being published. Here scientists submit their work to scientific organizations so it can undergo rigorous scrutiny, not just by any scientists, but by leading experts within a particular field. In this process, papers are published and presented to the public only if their conclusions are supported by physical data and by methods that can be verified.

Finally, because scientific knowledge is so vital to society, scientists often find themselves trying to educate policymakers on important environmental issues, many of which are politically charged. Although science itself is objective and nonpolitical, scientists commonly speak out publicly so that policymakers can base decisions on the best information available. Since today’s students will be the decision makers of tomorrow, it is especially important for you to understand not only the science behind environmental issues, but also how science itself operates.

FIGURE 1.7 Homes in this residential neighborhood on the big island of Hawaii being threatened by lava from the 2018 eruption of Kilauea volcano. Lava flows have been taking place on the big island for the past 700,000 years and have resulted in the formation of the island itself (the other Hawaiian islands are much older). Although lava flows are a natural geologic process that creates habitable living space, they also pose a serious risk to human life and property.
Source: U.S. Geological Survey

Environmental Geology

Environmental problems related to geology generally fall into one of two categories: *hazards* and *resources*. We will define a **geologic hazard** as any geologic condition, natural or artificial, that creates a potential risk to human life or property. Examples include earthquakes, volcanic eruptions, floods, and pollution. Some geologic processes, such as the eruption of volcanic lava (Figure 1.7), present a clear hazard to society. Ironically, what we consider as geologic hazards are often processes that play an important role in maintaining our habitable environment. Volcanic eruptions, for example, are as old as the Earth itself and have been instrumental in the development of the atmosphere and oceans. Also interesting is the fact that human activity can affect certain types of geologic processes, increasing the severity of an existing hazard and making it more costly in terms of the loss of life and property. A good example is the use of engineering controls to minimize flooding in one area, which often end up increasing the flooding somewhere else. Human interference in natural processes also commonly produces unintended consequences, as in the loss of wetlands. By destroying wetlands, humans inadvertently disrupt the food web within critical ecosystems, which ultimately results in the loss of sport and commercial fisheries.

Pollution is considered a hazard because it directly impacts human health and the ecosystems on which we depend. Although pollution can occur naturally, human activity is by far the most common cause (Figure 1.8). An example is metallic mercury, which cycles through the biosphere after being released during the natural breakdown of certain types of minerals. Mercury tends to accumulate in wetlands due to the acidic and oxygen-poor conditions there, but is then periodically released into the atmosphere when droughts allow fires to sweep through dried-out wetlands. Since the Industrial Revolution, humans have been releasing mercury into the environment by burning vast quantities of coal, which are ancient swamp deposits that naturally contain mercury-bearing minerals (Chapters 13 and 15). Consequently, the amount of mercury in the biosphere is now significantly higher than natural background levels. Mercury is a problem because it bonds with carbon atoms and creates highly toxic compounds capable of moving through the aquatic food chain and into humans. Of particular concern are pregnant or nursing women who eat mercury-contaminated fish and unknowingly pass the toxic compounds on to their children. This results in children with elevated levels of mercury, who run a higher risk of developing severe and irreversible brain damage. A somewhat different form of pollution is the emission of greenhouse gases (e.g., carbon dioxide) from the burning of fossil fuels, which is contributing to the problem of global warming (Chapter 16). Although greenhouse gases are natural and have helped regulate Earth's climate system for millions of years, the volume of gases being released into the atmosphere by humans is disrupting the atmosphere's natural equilibrium, which in turn threatens to disrupt the planet's entire ecosystem. This type of pollution is global in nature and has the potential to threaten all of humanity.

FIGURE 1.8 Pollution of air and water resources is a serious problem that affects both natural ecosystems and our quality of life, particularly human health.
(left) Steve Cole/Getty Images; (right) Doug Menuez/Getty Images

The other major area of environmental geology relates to **earth resources**, which include water, soil, mineral, and energy resources. Resource issues generally involve society trying to maintain adequate supplies and minimizing the pollution that results from resource extraction and disposal of waste by-products. Freshwater and soil resources are the most critical since they form the basis of our agricultural food supply (Figure 1.9). As soils continue to be lost through erosion and water supplies become stretched to their limit, rapid population growth may soon outstrip world food production. Depletion of soil and water resources therefore is potentially one of humanity's greatest challenges. Moreover, by removing the natural vegetation from the landscape in order to grow food and expand urban areas, we inadvertently create a problem known as *sediment pollution.* When soils are left exposed, excessive amounts of sediment wash off the landscape and into our natural waterways. This destroys the natural ecology of streams and fills the channels with sediment, leaving them more prone to flooding.

In addition to soil and water resources, modern society is also highly dependent on nonrenewable supplies of energy and minerals. Mineral resources (Chapter 12) are critical because they provide most of the raw materials used in building our modern infrastructure. Of particular importance are iron for making steel, copper for electrical systems, and limestone for making concrete. Despite being nonrenewable, some mineral resources such as limestone, sand, and gravel are so abundant that their supplies are essentially inexhaustible. In contrast, there are some minerals with very specific and critical applications whose supply is so limited that they are considered to be of strategic importance. Examples include chromium and cobalt minerals needed to produce high-performance jet engines for military aircraft. Equally important are the energy resources that power the industrial, transportation, commercial, and residential sectors of an economy. Crude oil is especially critical because it is the primary source of our transportation fuels, and it serves as the raw material for making plastics and agricultural chemicals. Because oil is truly the lifeblood of modern societies, one of our major challenges is replacing our dwindling oil supplies with alternative sources of energy (Chapters 13 and 14).

FIGURE 1.9 Our ability to use water and soil resources in conjunction with fossil fuel–based fertilizers and pesticides has resulted in high rates of food production. Depletion of these resources threatens society's long-term ability to feed our growing population.
(top) Reed Kaestner/Corbis; (bottom) Comstock/PunchStock

Environmental Problems and Time Scales

One of the key factors that influences the way in which humans respond to environmental problems is the nature of the geologic processes involved and the time scales over which they operate. Some geologic hazards such as earthquakes, for example, happen suddenly and have unmistakable consequences that we easily recognize. In areas where earthquakes are common, society typically takes steps to minimize the future loss of life and property damage. This usually involves constructing buildings that resist ground shaking and having emergency personnel better equipped and trained for earthquake disasters. Pollution, in contrast, is a problem that may occur gradually over many years and whose effects on human health are not so readily apparent. Because the effects take place gradually, society often delays taking corrective measures until the consequences become more severe and noticeable.

With respect to geologic hazards that occur suddenly and in a random or sporadic manner, society's response is governed in part by the frequency at which the events recur relative to the human life span. Generally speaking, once those with a living memory of a hazardous event begin to die off, the generations that follow tend to forget or become complacent about the hazard and its

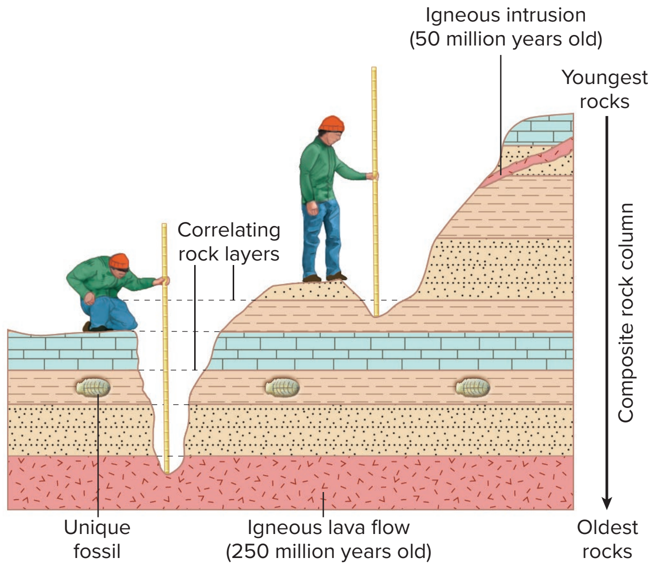


FIGURE 1.10 In a sequence of undisturbed sedimentary rocks, the oldest rocks always lie on the bottom. By correlating specific layers at different exposures across a wide area, geologists can establish the relative age of an entire rock column. Should igneous rocks which formed from magma be present, radiometric dating can be used to determine an age range for the sedimentary column.

consequences. On the other hand, if a hazard happens frequently enough, we are less complacent and tend to take steps to reduce the risk. A good analogy is how people commonly carry an umbrella or wear rain gear in areas where it rains frequently. Hardly anyone is going to bother taking similar precautions in desert climates since the chance of getting caught in the rain is quite low. In much the same way, humans tend to become complacent about geologic hazards that recur on the order of decades or centuries. Because geologic processes often operate on time scales unfamiliar to humans, we need to briefly explore the concept of geologic time.

Geologic Time

During the late 1800s and early 1900s, geologists began systematically studying sections of sedimentary rocks exposed at the surface. Sedimentary rocks (Chapter 3) are unique in that they are derived from the erosion and weathering of older rocks and then deposited in layers. These rocks are important because they hold clues to the environmental conditions and life-forms present at the time the rocks were deposited. As indicated in Figure 1.10, geologists studying the exposed parts of a sedimentary rock sequence will typically record the composition of each layer and describe any fossils it may contain. They also determine the **relative age** of each layer using the *law of superposition,* which states that the bottom layers must have been deposited first, and are therefore the oldest. Also note in Figure 1.10 how individual layers can be correlated across valleys from one exposure to another. By studying sedimentary sections that correlate and overlap with one another, geologists have been able to construct large, composite sections called *rock columns* (Figure 1.10). Together, sedimentary rock columns from around the world have provided scientists with a reliable record of Earth's environmental changes and the evolutionary history of its plants and animals. This worldwide rock record has also led to the development of the **geologic time scale**, which classifies all rocks according to their relative or chronological age. From Figure 1.11 one can see that the geologic time scale uses various names to subdivide Earth's rock record into progressively smaller time intervals. Perhaps the most familiar interval is the Jurassic period of the Mesozoic era, whose rocks contain dinosaur fossils.

Although early geologists understood that the rocks on which the geologic time scale is based represent an enormous amount of time, they had no way of quantifying the actual or **absolute age** of the rocks in terms of years. What they needed was to find some characteristic of the rocks that forms at a steady and reliable rate. By knowing the rate they could then measure time, similar to using a stopwatch. In the early 1900s, scientists discovered that as uranium atoms undergo radioactive decay they are transformed into lead atoms at a dependable rate; the term *half-life* describes the time required for half of the radioactive atoms in a given sample to decay into stable atoms (Chapter 15). Because nearly all igneous rocks contain uranium-bearing minerals, scientists could now use uranium's known decay rate (i.e., half-life) to calculate the number of years that passed since the original magma (molten rock) solidified into igneous rock. All that was needed was some means of measuring the amount of uranium and lead atoms in a rock—older rocks will contain progressively more lead atoms. By the 1950s, instruments called *mass spectrometers,* which measure the ratio of different atoms, were refined to the point that lead-uranium dating became quite precise. This was highly significant because igneous rocks often come into contact with and cut across sedimentary sequences (see Figure 1.10). Therefore, sedimentary rocks within the geologic time scale could now be assigned absolute dates in terms of years.

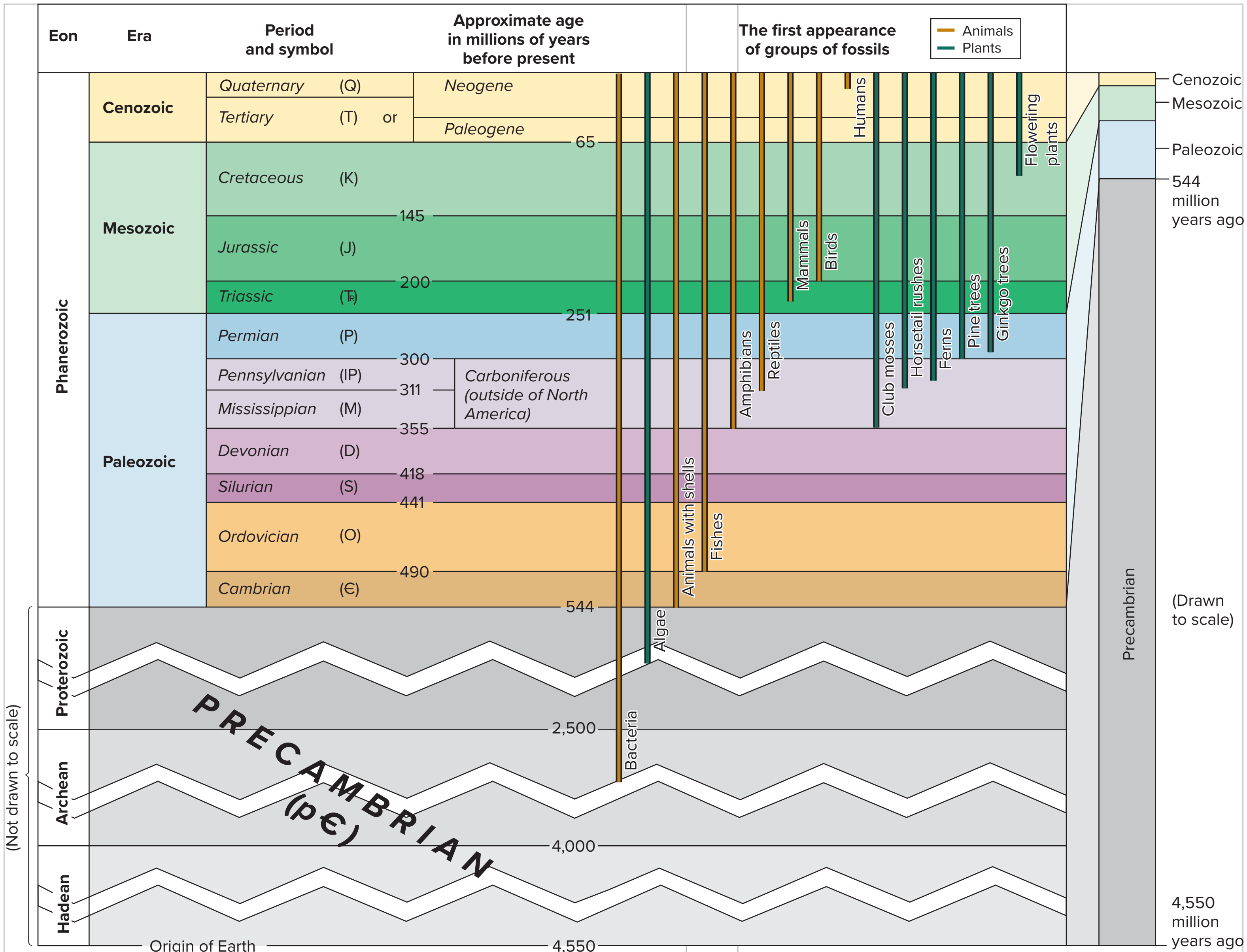


FIGURE 1.11 The geologic time scale was first developed by determining the relative age of sedimentary rocks from around the world. Radiometric dating was later used to establish the absolute dates of the various divisions within the scale. This 4.5-billion-year-old rock record holds the key to understanding the evolution of plants and animals as well as the changes in Earth's environment over time.

Note that lead-uranium dating is a specific type of **radiometric dating**, which is the general term applied to absolute dating techniques involving any type of radioactive element and its decay product. Moreover, different radioactive elements decay at different rates, which allows scientists to obtain reliable dates for events ranging anywhere from thousands to billions of years old. Elements that decay rapidly are used to date younger events, and those with slower decay rates are better suited for older events (see Chapters 14 and 15 for details on radioactive decay).

TABLE 1.1 Milestones in Earth's 4.5-billion-year history as represented on a compressed calendar year consisting of 365 24-hour days.

Beginning of Earth history	January 1
Oldest surviving rocks	Middle February
Oldest fossils—single-cell cyanobacteria	Early March
First fossils of animals with hard body parts	Middle October
First dinosaur fossils	December 11
Last dinosaur fossils	December 26
First modern human fossils	23 minutes before midnight, December 31
Egyptian civilization	35–14 seconds before midnight
Roman civilization	18–11 seconds before midnight
Columbus arrives in North America	3.5 seconds before midnight
Past 20 years	0.14 seconds before midnight

Another important outcome of radiometric dating is that scientists were able to determine that the Earth solidified approximately 4.5 billion years ago. Because humans personally experience time in intervals ranging from seconds to decades, it can be difficult for people to grasp time measured in millions or billions of years, something geologists refer to as **geologic time**. To better understand geologic time, imagine someone handing you a dollar bill every second, 24 hours a day. For you to reach a million dollars you would have to stay awake for 11.6 days. To reach a billion dollars would require 32 years of continuous counting. Another useful analogy is to compress all 4.5 billion years of Earth's history into a single calendar year of 365 days. This means that a 24-hour day would equal 12.6 million years of actual time. Table 1.1 lists some important historical milestones in terms of this compressed calendar, with January 1 representing the beginning of Earth's history and December 31 being the most recent time. On this scale the first rudimentary life-forms show up in the rock record in early March, whereas the first dinosaurs do not come into existence until December 11. Note that the dinosaurs ruled for nearly 200 million years, which represents only 15 days on the compressed calendar. In contrast, the entire 200,000 years of modern human existence correspond to just 23 minutes. Also notice how Columbus reaches North America a mere 3.5 seconds before the clock strikes midnight on New Year's Eve. Even more striking is how the life span of a 20-year-old student represents only fourteen hundredths (0.14) of a second! It should be clear from this analogy that Earth's 4.5-billion-year history represents an immense amount of time, and that our human presence on the planet has been exceedingly brief.

Determining the age of the Earth through radiometric dating also confirmed something geologists had long suspected, namely that our planet's physical features formed by both sudden and slow processes. Prior to radiometric dating, a popular concept called *catastrophism* held that Earth's features were the result of sudden, catastrophic events, such as earthquakes, floods, and volcanic eruptions. Once the true age of the Earth was established, a concept known as *uniformitarianism* was used to explain how most of the planet's features are formed by slow processes acting over long periods of time. While geologists recognized that some features do indeed form by catastrophic processes, features such as deep canyons and thick sedimentary sequences could be more easily explained by very slow processes. For example, suppose that sediment being deposited at the mouth of a river accumulates at a rate of only one millimeter per year. If this continued for just a million years, the result would be a sediment sequence 1,000 meters or 3,280 feet thick. Likewise, given a sufficient amount of geologic time, slow rates of erosion can carve deep canyons and wear down entire mountain ranges. The Grand Canyon, shown in Figure 1.12, is an excellent example of how slow processes can do tremendous work over time. Because of the geologic time scale and absolute dating techniques, geologists now know that the sedimentary sequence within the Grand Canyon accumulated over hundreds of millions of years. The area was later uplifted along with the Rocky Mountains by forces within the Earth, causing the Colorado River to begin cutting downward into the sequence of sedimentary rocks. The canyon we see today formed over the past 5 to 6 million years by the slow downcutting of the river combined with mass wasting processes (Chapter 7) that have acted to widen the canyon.

FIGURE 1.12 The Grand Canyon is an example of how slow processes can create dramatic features when given a sufficient amount of time. The thick sequence of sedimentary rocks in the canyon required hundreds of millions of years to accumulate. Later, as the area was uplifted by forces within the Earth, the Colorado River began cutting downward into the sedimentary section. The canyon we see today is the result of between 5 and 6 million years of downcutting by the river and mass wasting processes, which have widened the canyon.
Jim Reichard

Environmental Risk and Human Reaction

We will define an **environmental risk** as the chance that some natural process or event will produce negative consequences for an individual or society as a whole. The level of risk is based on the probability of an event taking place and its expected consequences, which can be expressed with the following relationship:

$$\text{risk} = (\text{probability of an event}) \times (\text{expected consequences})$$

The matrix in Table 1.2 illustrates how the risk level is a function of probability and severity of consequences.

An example of an environmental risk is an earthquake in San Francisco, California. Here the risk is considered high because there is a high probability of a large earthquake taking place in the next 30 years, and the damage is expected to be severe. Another example is an asteroid hitting the Earth. Although small fist-sized asteroids routinely strike our planet (i.e., high probability), the actual risk is low since the potential damage is negligible. If an asteroid a mile in diameter were to strike the Earth, the damage would be catastrophic, but the risk can still be considered low since the probability of such a strike in the near future is extremely low. The differences in probability in this example are due to the fact that there are very few mile-sized asteroids compared to fist-sized ones. Therefore, when evaluating risk, one should not simply focus on the consequences without considering the probability of the event itself.

This leads us to the concept of *risk management,* which involves taking steps to identify and reduce, or *mitigate,* a specific risk. Before any steps can be taken, it is of course necessary to identify the threat itself. This requires that the scientific method be used to understand those aspects of the physical world that pose a threat to society. Once a threat is identified, the risk can be mitigated by using science and engineering to: (a) reduce the probability of an event taking place; and (b) minimize the impact or consequences. For example, driving a car puts people at high risk of being injured or killed in an accident. You can greatly reduce this risk by driving defensively, which lowers the probability of an accident. You can also minimize the potential consequences (injuries) by wearing a seat belt and driving a car with air bags. Another example is how society mitigates the risk of flooding by constructing dams and levees (lowers probability), and passes zoning laws that limit development on floodplains (minimizes consequences). Throughout this textbook we will focus on how science can be used to identify environmental risks, and then develop solutions to lower the probability of an event and minimize its consequences.

One of the key factors that affects how people respond to environmental risk is the different nature of geologic processes and the time scale over which they operate. Natural processes can be classified as

TABLE 1.2 Matrix showing the level of risk, which is based on the probability that an event will occur versus its severity. Mitigation efforts are more likely to take place as the level of risk increases.

Probability ↑ / Consequences →	Minor	Moderate	Severe
Near Certain	Low	Medium	High
Likely	Low	Medium	Medium
Rare	Low	Low	Low

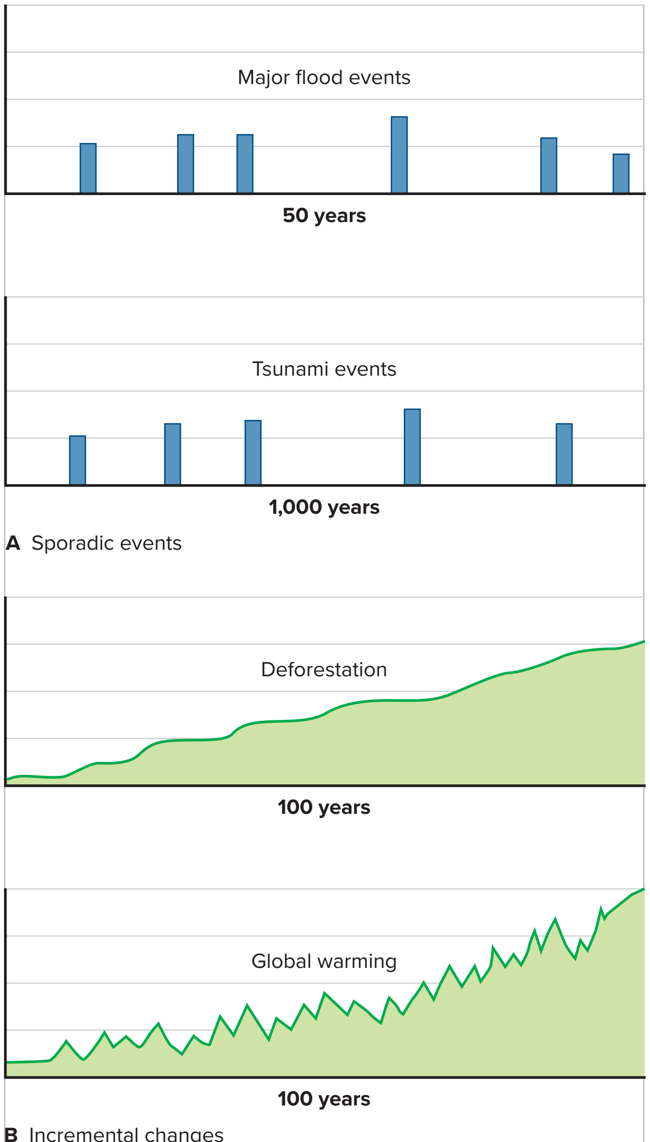


FIGURE 1.13 Natural processes generally operate in either a sporadic (A) or incremental manner (B). When sporadic events occur infrequently, it becomes more likely that a human generation will pass between events, causing people to be complacent about the risk. With incremental processes, people are typically slow to recognize environmental problems because the changes from year to year are small. Most difficult to recognize are incremental problems where upward and downward swings mask the overall change.

being either incremental or sporadic. An *incremental process* is one that generates small changes with time, such as the forces that are uplifting and eroding the sedimentary rocks in the Grand Canyon. Although incremental forces operate continuously, the rates of change are so small that their impact on the day-to-day lives of people is inconsequential. On the other hand, the incremental loss of topsoil due to erosion is occurring at such a rapid rate that significant amounts of soil have been lost in a matter of decades. This is a serious environmental issue since it reduces society's ability to grow food (Chapter 10). Therefore, if the rate of an incremental process is high enough, it is more likely that undesirable changes will occur within the life span of humans.

In contrast, *sporadic processes* are those that take place somewhat randomly as discrete events. Examples include floods, volcanic eruptions, earthquakes, and landslides. Sporadic processes are commonly referred to as *hazards* when they produce dramatic and sudden changes that humans consider undesirable. Events with particularly severe consequences are typically called *disasters* or *catastrophes.* Although sporadic processes occur randomly, they generally repeat in somewhat regular intervals, with the frequency depending on the process itself. For example, floods occur with greater frequency than do volcanic eruptions. Also important is how small-magnitude events are more common than large, catastrophic ones. Consider how minor floods occur more frequently than do major floods—similar to how your chances of winning a small daily lottery are much higher than those of winning a million-dollar jackpot.

The fact that geologic processes operate differently is important because of the way it influences how humans respond to environmental risks. To illustrate this point consider the sporadic nature of major floods and tsunamis shown by the graphs in Figure 1.13A. Notice that the floods occur frequently enough that a person is likely to experience several major floods within his or her lifetime. The relatively high risk of flooding helps explain why people living along rivers have historically reduced their risk by building settlements on the highest ground possible. On the other hand, major tsunamis (Chapters 5 and 9) occur much less frequently, which means several generations may pass between events such that people have no living memory of the previous tsunami. In this case some people may be completely unaware of the danger, whereas others are aware but feel that the benefits of living on flat ground next to the sea outweigh the risk. A tragic example of this phenomenon is the massive tsunami that swept into coastal villages around the Indian Ocean in 2004 (Figure 1.14). Over 230,000 people lost their lives when they suddenly found themselves in harm's way with no means of escape.

Finally, environmental problems associated with incremental processes are particularly challenging to address since they can be hard to recognize. Take for example the process of deforestation (Figure 1.13B), where the amount of forest lost each year through logging can be so small that many people do not notice the overall change taking place. Because the forest looks pretty much the same as it did the year before, people tend to believe that things are "normal"—a phenomenon some refer to as *creeping normalcy.* By the time the forest is gone and erosion has washed the topsoil into nearby stream channels, there may be no one with a living memory of the environment that once existed. Even harder to recognize are slow incremental processes that vary naturally from year to year, such as the global warming example in Figure 1.13B. Here natural swings in temperature from year to year can easily mask the incremental change taking place. It was because of natural temperature swings that scientists were slow to recognize that Earth is currently in an accelerated warming trend.

A B

FIGURE 1.14 Before and after photos of a coastal city in Indonesia that was completely obliterated by the 2004 tsunami. The low frequency of tsunamis means that several generations may pass between events, thereby lulling people to live in harm's way. People either become ignorant of the hazard or choose to accept the risk as they understand that the probability of such an event is low.
(A–B) Digital Globe/Getty Images

Earth as a System

It is clearly in society's best interest to avoid environmental problems and minimize their impacts, regardless of whether it's a problem we create (e.g., pollution) or that is natural and cannot be prevented (e.g., earthquakes). One of the keys is to have an appreciation of the time scale over which natural processes operate as this helps us identify problems, and allows us to make better risk management decisions. From the field of geology we now understand that Earth's history is one of constant change where everything evolves, including the atmosphere, oceans, continents, and, of course, plants and animals. In addition to an appreciation of geologic time, another important lesson is that humans are part of a complex natural system, and that our actions impact the very environment in which we live and depend on. For example, modern societies have grown and prospered because of our ability to modify the landscape for growing food, extracting natural resources, and constructing cities. These activities, however, have also produced unintended and undesirable consequences, such as increased flooding, pollution, and destruction of wildlife habitats. By using science to understand how the Earth operates as a large system, we can learn to minimize our environmental problems and avoid creating new ones.

Recall that science strives to understand how the natural world operates, which in turn has led to many remarkable achievements. As our knowledge of the world has grown more detailed, we have seen the emergence of specialized fields within science, namely mathematics, physics, chemistry, biology, and geology. Today there are subdisciplines within each of these fields where specialists study rather narrow aspects of the physical world in great detail. In geology there are many specialized fields, including the study of minerals (mineralogy), rocks (petrology), ancient life (paleontology), chemical reactions within the earth (geochemistry), movement of groundwater (hydrogeology), and Earth's internal structure (geophysics). Many of these subdisciplines are *interdisciplinary* in nature, which means they are a combination of two or more scientific fields. For example, geochemistry is the study of both geology and chemistry.

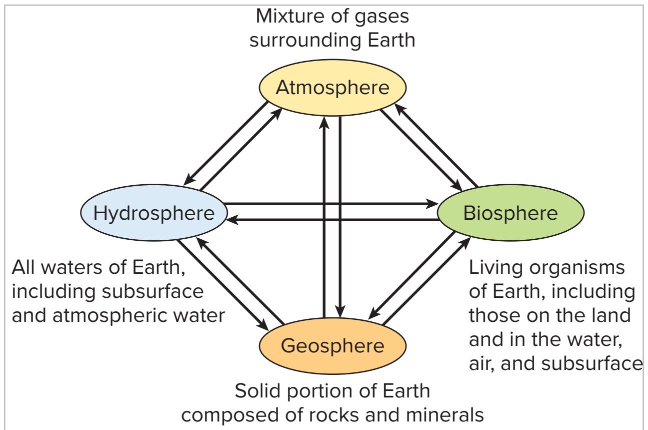
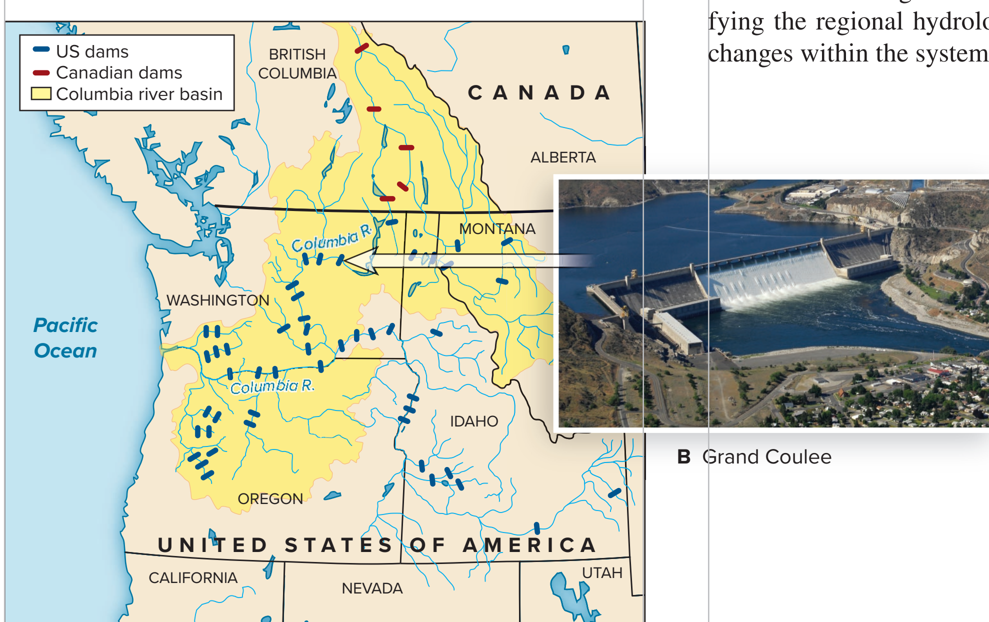


FIGURE 1.15 The Earth system is composed of four major subsystems that interact in a highly complex and integrated manner, where changes in one subsystem affect the others.

The downside of specialization has been that scientists sometimes lose sight of the larger picture. In recent years, however, there has been a growing interest in studying the interconnections that exist between major scientific fields. For instance, fisheries biologists have learned that individual fish species breed or spawn in very specific locations or habitats within river systems. These unique habitats are often found to be related to the type of sediment in the riverbed and to zones of groundwater discharge (springs), both of which are controlled by geologic processes. Scientists are learning that the natural world is highly interrelated, where individual processes depend on one or more other processes. Moreover, the entire Earth is now seen as operating as a single system where all natural processes are interconnected in one way or another. Scientists now understand that Earth's entire history is one of constant change where everything evolves.

Today this concept that all natural processes are interrelated and in a constant state of change has led to a new, comprehensive field of study called **Earth systems science**. In this field the Earth is seen to be operating as a dynamic system made up of four major subsystems or components: the *atmosphere, hydrosphere, biosphere,* and *geosphere* (solid earth). As illustrated in Figure 1.15, these subsystems are an integral part of the larger system and continually interact with one another. The Earth system is said to be *dynamic* because when one component undergoes a change it almost invariably induces a change in one or more of the other subsystems. A good example is the damming of the Columbia River and its tributaries in North America (Figure 1.16). Groups that originally promoted the dams emphasized that the project would bring cheap electrical power and jobs to the Pacific Northwest. Plus, the vast amounts of water to be stored behind the dams would make large-scale agricultural production possible throughout the region. Unfortunately the dams also disrupted the natural hydrology of the region, resulting in the collapse of the salmon fisheries within the biosphere. The once-thriving fisheries that had sustained indigenous populations for thousands of years are now all but gone. This has resulted in a loss of fishing-related jobs and a host of other changes for the small communities throughout the region. By modifying the regional hydrology to achieve certain benefits, humans set in motion changes within the system that produced some rather undesirable consequences.



B Grand Coulee

A

FIGURE 1.16 The construction of dams along the Columbia River system, such as the Grand Coulee Dam shown here, provides electrical power and water to large areas of the Pacific Northwest. The dams also prevent the migration of salmon, which has led to the collapse of the region's salmon fishing industry and traditional way of life.
(B) *Source:* U.S. Bureau of Reclamation

In some cases human activity produces changes that ripple through the entire Earth system. A good example is clearing the land through deforestation. The sequence of satellite images in Figure 1.17 shows the tremendous loss of forest in parts of South America in just 25 years. The photo from Indonesia in Figure 1.18 gives a more immediate view of the devastating environmental impact of deforestation, particularly in areas of more rugged terrain. What was once a dense forest with a diverse array of plants and animals is now relatively devoid of life. Moreover, the lack of forest cover will lead to landslides and extensive soil loss. In terms of the Earth system (see Figure 1.15), deforestation in the biosphere has a major impact on the geosphere. In addition, as the excess sediment washes off the landscape and begins filling nearby stream channels, it destroys the habitat of aquatic species within the streams and disrupts their entire ecosystems. The filling of stream channels with sediment also impacts the hydrosphere component of the Earth system by leaving less room for water to

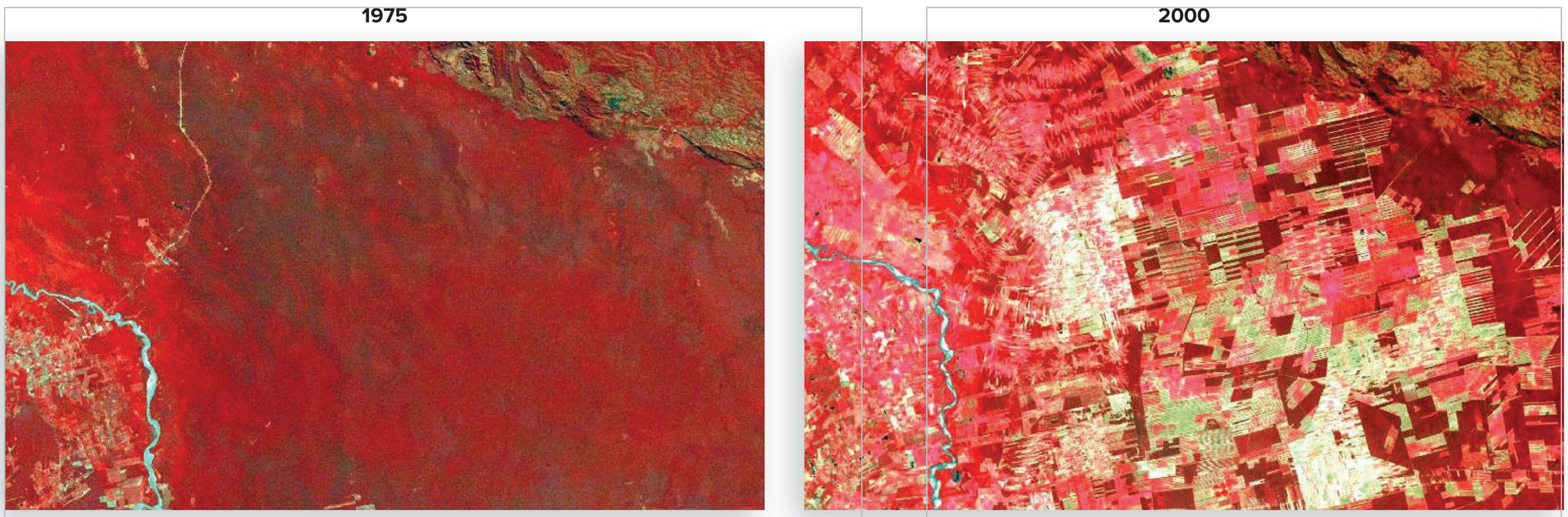


FIGURE 1.17 Sequence of false-color satellite images near Santa Cruz de la Sierra, Bolivia, showing extensive deforestation taking place over a mere 25-year span. Areas of forests and dense vegetation are shown in deeper shades of red, whereas areas cleared of trees are in lighter shades.
(all) *Source:* U.S. Geological Survey

flow, which increases the chance of floods during heavy rain events. Finally, we need to consider what happens to the biosphere itself. During deforestation much of the wood is converted into lumber, but a significant portion is simply burned, releasing carbon dioxide gas into the atmosphere. Deforestation therefore contributes to the problem of global warming since carbon dioxide is known to trap some of the heat Earth radiates out into space (Chapter 16). The contribution to global warming is compounded by the fact that the trees that were removed had been an important means of removing carbon dioxide from the atmosphere.

Throughout this text we will examine numerous environmental issues in which scientists use the concept of Earth as a system to first identify the underlying cause of a problem, and then develop effective solutions based on our knowledge of how the system operates.

The Earth and Human Population

When humans modify the natural environment, it is usually done with good intentions so as to achieve some positive benefit. However, our activity almost always impacts one or more natural processes, generating secondary effects that ripple through different parts of the Earth system. The result is a series of unintended consequences that ultimately affect the lives of people and other living organisms that inhabit the planet. A good example of how our actions can create unintended consequences is the development of algae blooms on Lake Erie (Case Study 1.1). There are certain geologic processes though, such as earthquakes and volcanic eruptions, that humans have no ability to control.

FIGURE 1.18 Photograph of a deforested landscape in Sumatra, Indonesia. This once resource-rich landscape has been seriously degraded by deforestation. In addition to destroying the diverse ecosystem of plants and animals, deforestation typically leads to landslides and excessive soil erosion, causing streams to become choked with sediment. The filling of stream channels results in collapsed aquatic ecosystems and increased flooding during heavy rains.
Bagus Indahono/EPA/Shutterstock

CASE STUDY 1.1

Harmful Algae Blooms and Humans Interacting with the Earth System

Cyanobacteria, often called blue-green algae, have been on our planet for the past 2.7 billion years, making them some of the oldest life-forms on Earth. Interestingly, cyanobacteria along with green and brown algae were organisms responsible for oxygenating Earth's atmosphere, which then gave rise to the evolution of the terrestrial biosphere, including humans. Cyanobacteria and algae play important roles in the food chain, but when they multiple rapidly, a phenomenon referred to as an *algae bloom*, the excessive growth can create serious water-quality problems in our lakes and rivers (Chapter 15). Algae blooms typically occur when water temperatures exceed 70°F (21°C) combined with an abundant supply of sunlight and food source (nutrients). When the algae die, they are broken down by *aerobic bacteria* that remove oxygen from the water. This leads to the problem known as *oxygen depletion* or *hypoxia*, which commonly results in the death of large numbers of fish and other aquatic organisms. The excessive growth of cyanobacteria is particularly a problem because they produce compounds that are toxic to both humans and certain aquatic life.

Although algae and cyanobacteria blooms have occurred in surface waters long before humans became part of the biosphere, science has shown that modern human activity has greatly increased the frequency and severity of the blooms. This problem is worldwide and largely the result of land-use changes that have increased the amount of nutrients, namely nitrogen and phosphorous, entering our lakes and streams. An excellent example is the western end of Lake Erie (Figure B1.1), which is one of the five Great Lakes that formed after the end of the last ice age 18,000 years ago. While the eastern portion of Lake Erie reaches depths of just over 200 feet (61 m), the western part of the lake near Toledo, Ohio, averages less than 25 feet (7.6 m) deep. During the summer, the shallow depths combined with lots of sunshine can produce water temperatures up to 80°F (27°C). Under these conditions, the only thing needed for cyanobacteria and algae to grow rapidly is an abundant supply of nitrogen and phosphorous.

By the 1950s and 1960s, humans around the world were starting to release large amounts of nitrogen and phosphorous into surface waters via agricultural fertilizers, untreated sewage, and industrial plants. In the warm, shallow waters of western Lake Erie, the excessive nutrients represented an enormous food supply for bacteria and algae naturally present in the water. Extensive algae blooms began forming on the lake each summer, followed by large fish kills as the decaying algae caused the water to become depleted of oxygen. By the late 1960s, the combination of fish kills and industrial pollution resulted in the collapse of fisheries and closing of public beaches. In the press, Lake Erie was often referred to as being "dead." With passage of the Clean Water Act (1972) and improved agricultural practices, the amount of nutrients entering the lake was greatly reduced. Algae blooms soon became less common and less severe. By the

A

B

FIGURE B1.1 Satellite image (A) of the large algae and cyanobacteria plume that formed on western Lake Erie in 2017. These modern blooms are due primarily to agricultural fertilizers being carried into the lake by rivers draining the adjoining farmlands. Photo (B) showing a thick accumulation of algae at the city of Toledo's water intake on Lake Erie.

(A) *Source:* Joshua Stevens/Earth Observator/NASA; (B) The Blade, Dave Zapotosky, 2014

1980s, the beaches had reopened and fisheries had largely recovered, leading to the development of a billion dollar sport-fishing industry.

Unfortunately, Lake Erie's algae blooms started to return in the late 2000s due to the additional influx of nutrients and warmer lake temperatures. Then in 2011, a giant bloom covered the western portion of the lake (Figure B1.1). This was followed by a bloom in 2014 in which cyanobacteria produced enough toxins to literally poison the drinking water supply for more than 400,000 residents in Toledo and southeastern Michigan. Although large blooms in western Lake Erie are now common each summer, the good news is that the problem has drawn the attention of the U.S. and Canadian governments and state governments of Ohio and Michigan. A joint plan was agreed upon whose goal is to reduce the amount of nutrients entering Lake Erie by 40% by the year 2025. Since 2011, Ohio alone has spent over $3 billion in attempts to reduce the annual blooms. Researchers have now shown that the main culprit is the runoff of fertilizers from the rich farmlands surrounding Lake Erie in northwestern Ohio. To date, efforts at reducing the influx of nutrients have focused on farmers voluntarily implementing soil management practices that minimize runoff from their fields (Chapter 10). These efforts, however, have yet to lead to a reduction in nutrients entering the western end of the lake.

Some researchers are now proposing that the best solution lies in restoring parts of the once vast wetland known as the Great Black Swamp (Figure B1.2). Here, agricultural runoff would be directed into reconstructed wetlands where plants would consume the nitrogen and phosphorus before slowly releasing the water into nearly rivers (Chapter 15). Interestingly, about 20,000 years ago the Great Black Swamp was actually the bottom of a glacial lake that formed as a large ice sheet retreated into present-day Lake Erie. As the lake level lowered, the land became exposed, but was poorly drained due to the clay-rich bottom sediments and fresh glacial deposits surrounding the old lake. The resulting swamp became a large ecosystem, teaming with wildlife and filled with hardwood forests. By 1840 the Great Black Swamp found itself as Ohio's only remaining frontier. To the European settlers, the swamp was both a source of deadly mosquito-borne diseases and an impassible barrier that forced those traveling along Lake Erie to detour around to Fort Wayne, Indiana. Then in 1850, the State of Ohio supported the digging of large ditches throughout the swamp so that the water would drain into Lake Erie via the Maumee and Portage Rivers (Figure B1.2). Settlers soon harvested the valuable hardwood forests and began cultivating the exceptionally fertile soils. The entire ecosystem of the Great Black Swamp was now completely destroyed.

It is ironic that perhaps our best hope for reducing the algae blooms on Lake Erie is to restore parts of the Great Black Swamp, whose reclaimed land is the source of agricultural fertilizers that are now the primary cause of the blooms. Clearly, at the time the swamp was drained people did not understand how destroying the wetland's ecosystem would later prove to have serious consequences for society. Back in the 1800s we were simply taking a "worthless" and disease-infested swamp and transforming it into productive cropland. Today we understand how the Earth operates as a complex system, and that when people make changes to one part of the system we set in motion other changes that ripple through the system. Based on modern science, we are able to use our knowledge of wetland ecosystems to help reduce Lake Erie's algae bloom problem that our actions set in motion almost 200 years ago.

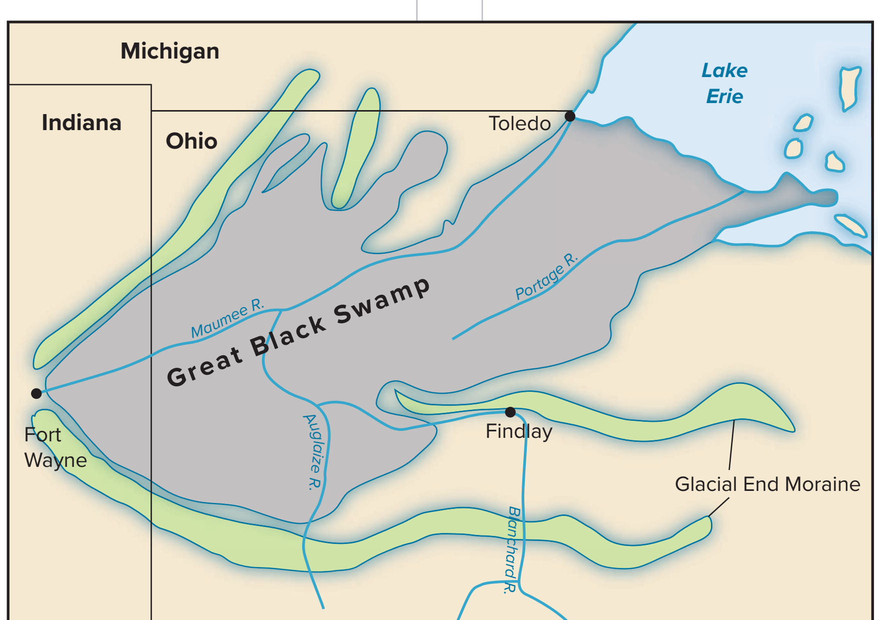


FIGURE B1.2 Map showing the extent of the Great Black Swamp prior to it being drained in the 1850s and converted into highly productive croplands.

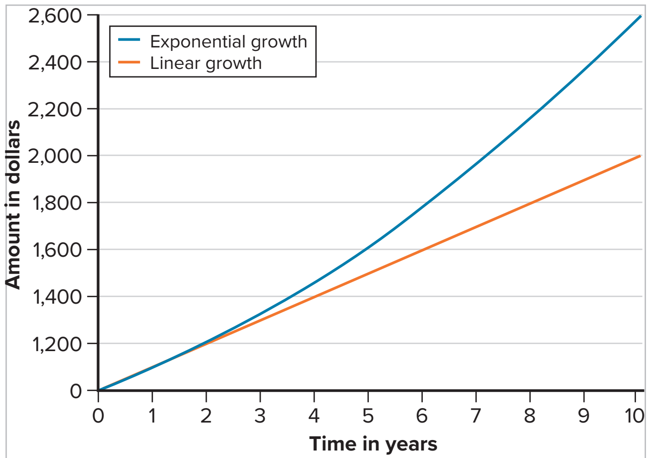


FIGURE 1.19 Plots showing how an initial sum of $1,000 responds to a linear growth rate of $100 per year versus an exponential (nonlinear) rate of 10% per year.

Regardless of whether an environmental problem results from our own actions or is a natural hazard we cannot control, the focus in this text will be on how humans are affected by our interaction with the geologic environment. It should be obvious that as human population continues to increase there will be greater interaction between people and the environment. For example, as population grows, more people will be living in areas at risk of floods, earthquakes, volcanic eruptions, landslides, and hurricanes. More people also mean greater resource depletion, pollution, and habitat destruction. Because human population plays such a key role in environmental issues, we will begin by taking a closer look at population growth.

Population Growth

We are all familiar with things that increase over time, such as gas prices, traffic congestion, and college tuition. Our interest here is in *how* things increase. Scientists classify growth rates as being either linear or nonlinear, meaning their graphs will plot as a straight line or a curve (Figure 1.19). **Linear growth** occurs when the amount added over successive time periods remains the same. In other words, if 10 is added to the total one month, then 10 more is added the next month, and so on. When you plot the growing total against time, the result is a straight line with a constant slope. Nonlinear or **exponential growth** is when the amount added over successive time increments keeps increasing. Adding 10 to the total one month, 15 the next, and then 25, would be considered exponential growth, generating a graph where the slope increases with time.

Because the slope keeps getting steeper, exponential growth leads to much greater increases over time compared to linear growth. For example, the data used in the plots shown in Figure 1.19 are listed in Table 1.3. Notice how the initial sum of $1,000 grows linearly at $100 per year. After 10 years this $1,000 would grow to $2,000. If the money grew exponentially at a fixed percentage of 10% per year, then after 10 years the total would be $2,593 rather than $2,000. Note that the difference occurs because with exponential growth you keep adding a percentage of a *growing* total. Thus as the total grows, so too does the amount you add over successive time intervals.

There are many natural processes that expand exponentially, but the most important in terms of our discussion is human population. From Figure 1.20 you can see that throughout most of history the population of the modern human species, known as *Homo sapiens,* grew quite slowly. Then, around the 1700s, population growth accelerated rapidly in response to increased industrialization and advances in medicine that brought about a decline in death rates. Notice in the graph that it took our species until 1830 to reach a population of 1 billion, which represented a time span of nearly 200,000 years. Incredibly, the population then doubled and reached 2 billion in only 100 years. It doubled again to 4 billion in just 45 years and is now projected to reach 9.8 billion by 2050. This leads to an obvious question: Can our population continue to expand exponentially, or is there a limit to how many people Earth can hold?

TABLE 1.3 **Calculations showing how an initial sum of $1,000 responds to linear and exponential growth rates. Each interval lists the beginning and ending totals as well as the yearly increase. Note how the yearly increase is constant under linear growth but keeps expanding under exponential growth.**

	Linear Growth	Exponential Growth
End of year 1	$1,000 + $100 = $1,100	$1,000 + $100 = $1,100
End of year 2	$1,100 + $100 = $1,200	$1,100 + $110 = $1,210
End of year 3	$1,200 + $100 = $1,300	$1,210 + $121 = $1,331
End of year 4	$1,300 + $100 = $1,400	$1,331 + $133 = $1,464
End of year 5	$1,400 + $100 = $1,500	$1,464 + $146 = $1,610
End of year 6	$1,500 + $100 = $1,600	$1,610 + $161 = $1,771
End of year 7	$1,600 + $100 = $1,700	$1,771 + $177 = $1,948
End of year 8	$1,700 + $100 = $1,800	$1,948 + $195 = $2,143
End of year 9	$1,800 + $100 = $1,900	$2,143 + $214 = $2,357
End of year 10	$1,900 + $100 = $2,000	$2,357 + $236 = $2,593

Limits to Growth

The idea of there being a limit to the number of humans that Earth can support was first proposed in 1687 by Antoni van Leeuwenhoek, a Dutch naturalist who estimated an upper limit of 13.4 billion.

He came up with this number by first calculating the inhabited land area of the world at the time, and then assumed that the maximum population it could support would have the population density of Holland. This upper limit seemed reasonable since Holland was importing many of its resources in order to support its high population density. Then in 1798 a British political economist named Thomas Malthus recognized that human population growth was exponential, whereas increases in food production were linear. Malthus concluded that unless population was brought under control, it would outstrip food supply and lead to a future of poverty and recurring famine. Famine, after all, was nature's way of keeping the population of animals in line with their available food supply.

Malthus's ideas on population limits have been highly influential over the years, leading to various predictions that human population would collapse in a catastrophic manner. What his population model failed to take into account, however, was the ability of people to increase food production at an exponential rate through technology and innovation. The driving force behind this modern increase in food production has been the use of fossil fuels, particularly crude oil and natural gas (Chapter 13). Oil has made the use of mechanized farm equipment possible, along with irrigation systems driven by diesel-powered pumps. Equally important has been the use of synthetic fertilizers and pesticides produced from oil and gas. In more recent years the development of genetically modified grains (rice, corn, wheat) has also helped increase agricultural yields. World population, therefore, has continued to expand, rather than collapse as Malthus's model predicted. The result has been that cities grow ever larger and spread across the landscape in a process known as *urbanization* or *urban sprawl* (Figure 1.21).

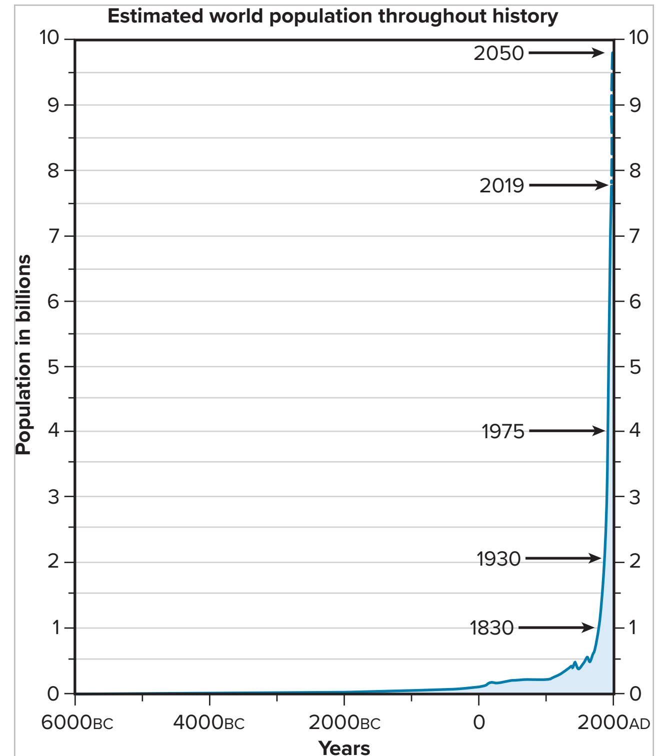


FIGURE 1.20 Graph showing exponential growth of world population throughout history. Population is projected to reach 9.8 billion by the year 2050.

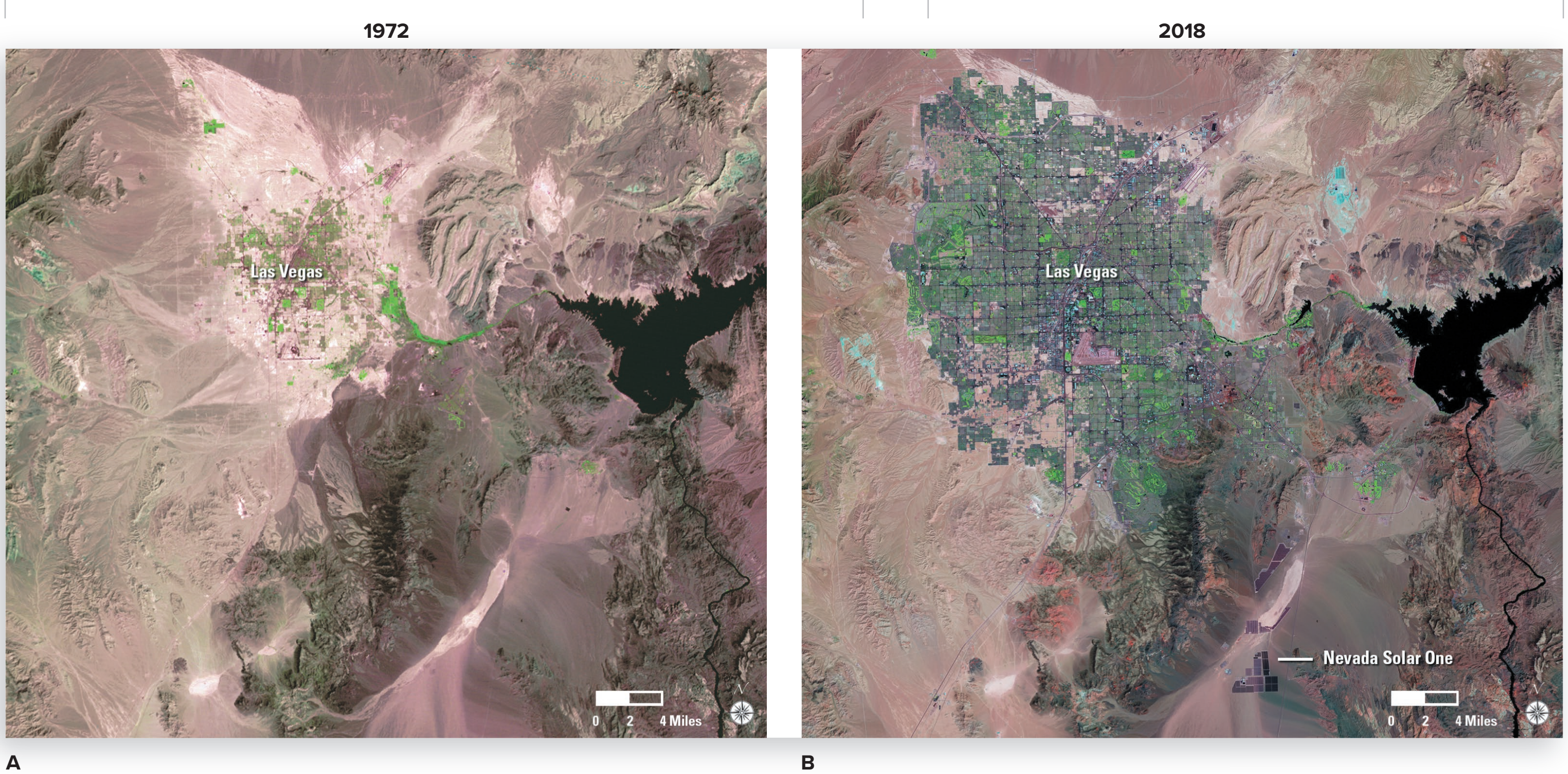


FIGURE 1.21 Satellite images showing the rapid urbanization of Las Vegas, Nevada. The population here grew from 273,000 in 1972 to over 2,204,000 by 2018, a 700 percent increase. This rapid growth has increased the demand for water from nearby Lake Mead, which is the region's principal water supply. Water levels in the lake have fallen significantly in recent years due to long-term drought and may limit Las Vegas's future growth. Note the new solar power plant in the southern part of the 2018 image.
(A) *Source:* U.S. Geological Survey; (B) National Aeronautics and Space Administration (NASA)

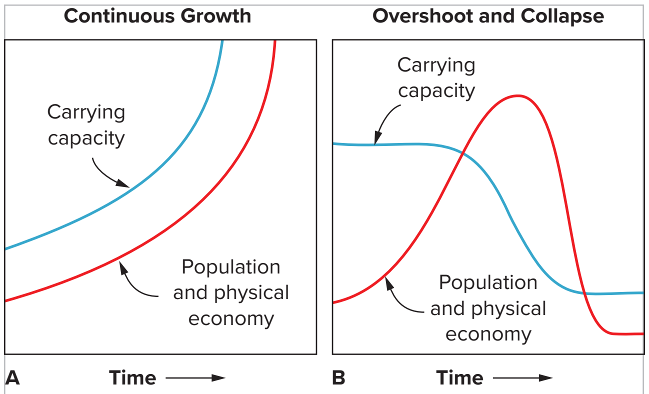


FIGURE 1.22 If Earth's carrying capacity could continue to increase (A), it would allow human population and economic activity to grow indefinitely. Since many of Earth's resources are finite, carrying capacity is fixed (B) and will begin to decline as population and economic expansion consume progressively more resources. Eventually growth exceeds the carrying capacity, causing the economy and population to crash.

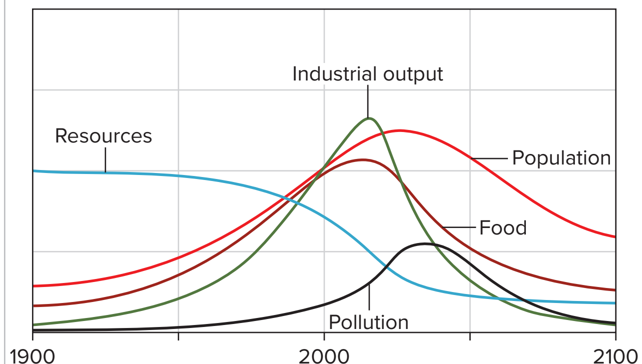


FIGURE 1.23 Modeling results showing relationships among population growth, industrial capital, food production, resource consumption, and pollution should the world continue under the policies and consumption patterns in place since 1900. Once population exceeds available resources, industrial output peaks as more and more capital is diverted to extract the remaining resources. This eventually leads to decreases in food production and population.

The idea that population growth would eventually collapse gained strength again in the early 1970s when an international group of scientists and economists examined the relationships among population growth, industrial capital, food production, resource consumption, and pollution. In this analysis they developed a computer model to study the ways in which human population and economic growth would respond as civilization approaches Earth's ability to support its inhabitants, often referred to as *carrying capacity*. For example, the scenario in Figure 1.22A shows Earth's carrying capacity continuing to increase such that it allows for infinite population and economic growth. Although humans have succeeded in increasing Earth's carrying capacity through increased food production, this has required massive amounts of investment capital and fossil fuels to produce the necessary mechanical equipment, fertilizers, irrigation systems, and so forth. Since fossil fuels are a finite resource, this infinite growth model is simply not realistic. In contrast, the scenario in Figure 1.22B has a carrying capacity that is initially fixed, but begins to decline at an accelerating rate as the expanding population consumes the finite resources. Contributing to the decline is the loss of renewable resources, such as fisheries and forests, which at some point are consumed faster than they can be replenished. Population and economic growth will then exceed or *overshoot* the planet's declining carrying capacity. Once overshoot occurs, the population and economy eventually crash and then stabilize at a level that is consistent with the system's new carrying capacity.

When running the model under different rates of resource consumption and policy changes, the researchers found that overshoot and collapse was the most likely outcome. For example, the results shown in Figure 1.23 are based on the scenario in which the world continues with the basic policies and consumption patterns that have been in place since 1900. Notice that once population exceeds the available resources, industrial output soon peaks. This occurs since population growth and economic expansion cause more and more capital to be diverted to extract the remaining resources. Keep in mind that as time progresses, the remaining resources become more expensive as they are more difficult to extract. The resulting diversion of capital makes it impossible to maintain the growth in industrial output. This means fewer factories and consumer goods, but most importantly, fewer farm machines and equipment. As food production and consumer goods decline, a decline in population and economic activity soon follows.

While many people have been skeptical over the years that population and economic growth will someday cease, there is now abundant evidence that infinite growth is not possible. For example, topsoils, which are critical for food production, are being lost worldwide at an alarming rate due to agricultural practices that leave soils exposed to erosion (Chapter 10). Another critical problem is that water supplies are being stretched to the limit in many regions, leaving little room for expanding irrigation (Chapter 11). Equally troublesome is that world production of cheap crude oil has declined, forcing us to rely on more expensive oil, which can lead to market instability and wide fluctuations in price (Chapter 13). It seems reasonable to expect that if we continue to rely on finite fossil fuels as our primary energy source, then at some point food production will begin to decline. The result would be progressively higher food prices and higher death rates as many people would be unable to afford the higher costs.

Sustainability

Since human civilization seems to be on a path toward eventual collapse, an obvious question is what can we do to avoid it? This leads us to the concept of **sustainability**, which is where a system or process is able to be maintained for an indefinite period of time. With respect to humans living within the Earth system, the term *sustainable society* is used to describe a society that lives within Earth's capacity to provide resources such that the resources remain available for future generations. The concept of sustainability is something that is readily observed in both nature and in our daily lives. Consider deer, whose population if left unchecked will quickly grow to the point where they outstrip their food supply. Starvation and disease then follow, resulting in a population crash. Another example is a person's finances. Suppose you make $50,000 a year, but spend $60,000. This deficit spending is not sustainable as it will eventually lead to a level of debt where the interest makes it impossible to pay off. To avoid bankruptcy you would have to earn more money and/or spend less by changing your lifestyle. There are no other choices. The same relationship exists between society and Earth's limited ability to provide resources. Therefore, the only options for humans are to level out population growth and change our consumption habits, or suffer the consequences of living beyond Earth's carrying capacity.

Suppose that the human race is unable to control its exploding population and ends up overwhelming the planet's capacity to provide resources. The consequences would likely vary among nations due to differences in population growth rates, level of economic development, and types of resources being consumed. From Figure 1.24 one can see that there are considerable differences in population growth rates between developing nations and those that are more developed, with higher living standards and more consumer goods. Note how the population in developing countries is presently growing very rapidly compared to that in developed countries (e.g., the United States, members of the European Union, and Japan). The difference is partly due to developing nations having high birth rates that tend to match their high death rates, thereby creating a pyramid-shaped population distribution as illustrated in Figure 1.25. Here large numbers of people are in age groups of potential child-bearing years. As these nations begin to develop, improvements in sanitation, health care, and food supply cause the death rate to decline, whereas the birth rate remains high. The result is rapid population growth. As development continues and living standards improve, couples commonly decide to have fewer children. Population growth then begins to slow. In highly developed countries, the population tends to stabilize when birth rates finally equal death rates—in some cases population actually declines because the number of births is less than the number of deaths. Geographers refer to the change in population growth rates associated with development as a *demographic transition.*

Because of the vastly different growth rates, the population of less-developed countries is projected to rise dramatically, whereas the population in more-developed nations will decline (see Figure 1.24). In fact, the population of some European countries has already started to decline, making further economic

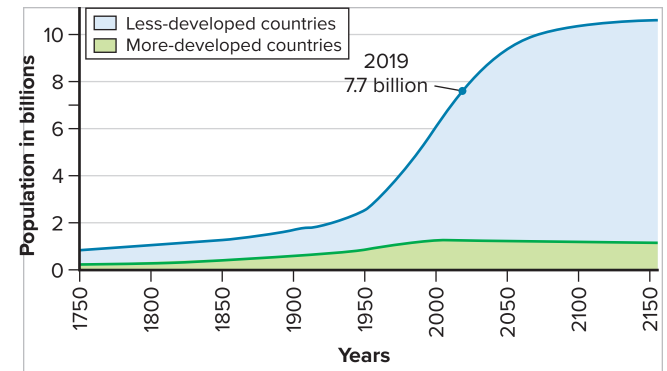


FIGURE 1.24 Graph showing world population growth and projected trends in both developed and developing countries.

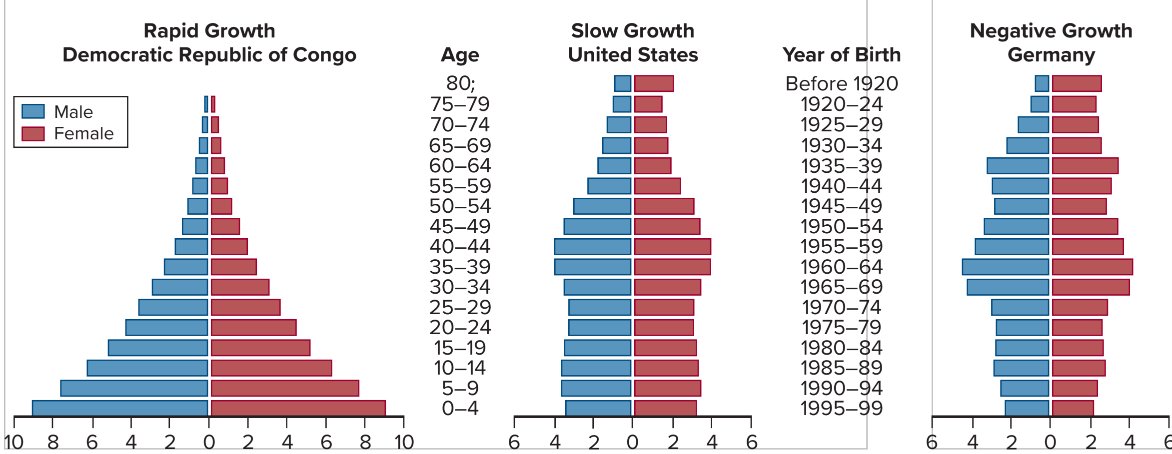


FIGURE 1.25 As nations become more developed, they usually undergo a demographic transition where death rates initially fall, followed later by declining birth rates. This results in a period of explosive population growth, gradually slowing to a point where population becomes steady, or in some cases actually declines.

expansion more difficult due to a surplus of retirees and a shortage of workers. The rapid population growth of less-developed countries, on the other hand, will make it increasingly more difficult for them to obtain adequate supplies of food and water. Even if these countries could afford to import food, world food production will still be limited by the availability of Earth's soil and water resources. To help illustrate this point, notice the uneven distribution of the world's population shown in Figure 1.26. Here we see that the areas with low population density lie in regions with desert and/or polar climates. People historically have tended to avoid living in these climatic zones due to the lack of liquid water and difficulty of growing food.

Some people believe that developing nations will be able to make it through the demographic transition by increasing food production in a similar manner as developed nations have done, namely through mechanization, irrigation, synthetic fertilizers and pesticides, and genetically modified grains. With increased economic prosperity the high birth rates in these countries should fall, at which point global population would stabilize and become sustainable. The problem is that as developing nations go through the transition and begin to modernize, they naturally increase their per capita (per person) consumption of resources. This increased consumption places additional demands on Earth's finite mineral and energy resources, threatening the living standards of the developed countries. For example, China's rapid industrialization is currently placing greater and greater

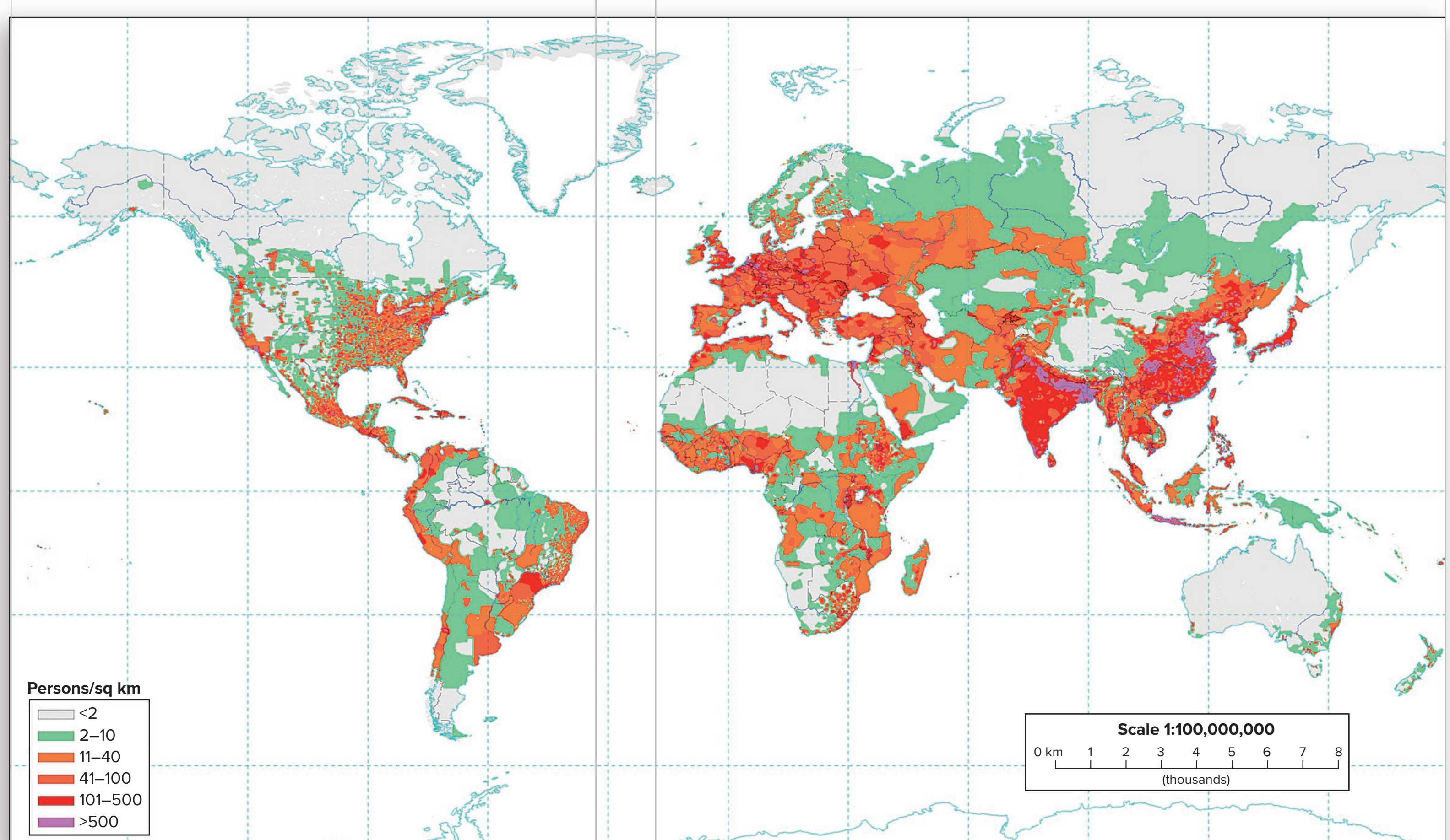


FIGURE 1.26 Map showing global population density. Note how vast regions that are sparsely populated correspond to desert and polar climates where food production is limited or nonexistent.

demand on the world's supplies of inexpensive crude oil (Chapter 13), causing market instabilities and wide fluctuations in price. This in turn could help destabilize the world economy and cause living standards to decline.

The key to sustainability, therefore, is not just Earth's total population, but also humanity's per capita consumption rate of resources. More people naturally means greater demand on Earth's resources. However, when per capita consumption rates increase along with population, the depletion of resources will follow a nonlinear downward path, as shown in Figure 1.27. Consider for a moment that if China's entire population were to achieve the present living standards of developed nations, humanity's impact on the planet would double. If all of Earth's inhabitants were to attain these higher living standards, then demand on resources would increase 14-fold. Achieving a sustainable society at this level of consumption would be virtually impossible.

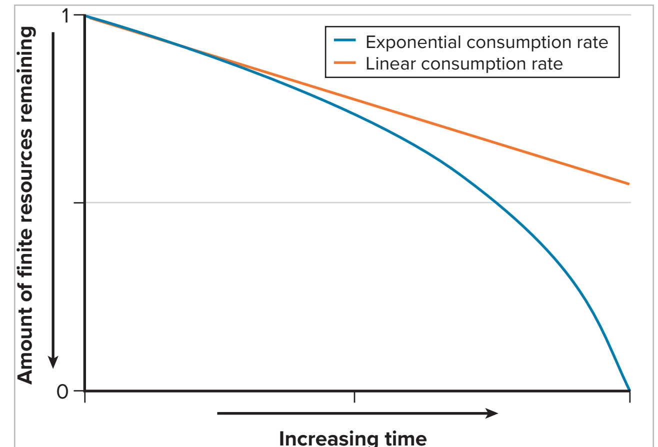


FIGURE 1.27 When an expanding population begins to increase its per capita consumption rate of a finite resource such as crude oil, resource depletion will accelerate and follow a nonlinear downward path.

Ecological Footprint

It should be apparent that one way to view sustainability is from the perspective of how many people Earth can feed with its existing water and soil resources. Another is the number of people living at developed world standards that can be supported by the planet's mineral and energy resources. We can also look at sustainability in terms of maintaining the present-day biosphere of the Earth system. A particularly useful concept here is the idea of an **ecological footprint**, which is simply the amount of *biologically productive* land/sea area needed to support the lifestyle of humans. The idea behind an ecological footprint is that every person requires a certain portion of the biosphere for extracting the resources that he or she needs and for absorbing the waste that is generated. Remember, we depend on the biosphere for its ability to purify water, provide forest resources, and regulate oxygen and carbon dioxide levels in the atmosphere. Simply put, humans could not survive without the ecosystems that make up the biosphere.

Biologists have estimated that the ecological footprint for all of humanity is currently 2.8 hectares per person (1 hectare is about the size of a soccer field). Citizens living in developed countries naturally have a much larger footprint than the global average due to their higher rates of per capita consumption. For example, the German average is 5.0 hectares per person and the British 4.8 hectares, whereas Americans require a staggering 8.4 hectares. The Chinese average only about 3.7 hectares per person, but since China is undergoing rapid industrialization, this average is expected to rise as its citizens purchase more and more consumer goods. If all the people in developing counties were to achieve the living standards of the United States, Europe, and Japan, then humanity's ecological footprint would obviously be far greater than the current average of 2.8 hectares per person. According to the Global Footprint Network, a nonprofit organization, humanity's current ecological footprint is already estimated to be about 70% larger than what the planet can support. This means humans are already consuming Earth's renewable resources faster than they can be replenished by natural ecosystems. Based on this footprint analysis, many people have concluded that we have gone beyond the ecological limits of the planet and that the present state of humanity is not sustainable. This view is consistent with the overshoot and collapse scenario illustrated in Figures 1.22 and 1.23.

Environmentalists generally believe the solution is for humanity to stabilize its population and reduce its per capita consumption of resources through conservation. Otherwise we will have to suffer the consequences of living beyond Earth's ability to support our civilization. The collapse of the society on Easter Island (Case Study 1.2) is perhaps the best example of people who lived unsustainably and eventually destroyed the very ecosystem on which they depended.

CASE STUDY 1.2

Collapse of a Society Living Unsustainably

While exploring the remote reaches of the Pacific in 1722, Dutch sailors came upon a place they named Easter Island, which was very different from all the others they had seen in the region. Here sailors found an island inhabited by approximately 2,000 people who looked very similar to the Polynesians they had encountered throughout the Pacific. However, unlike the seafaring Polynesians with their large canoes crafted from solid tree trunks, Easter Islanders came out to greet them in small, leaky crafts made from a patchwork of small planks and timbers. Even more odd was Easter Island itself. Most other islands in this subtropical climate had rich volcanic soils and lush forests teeming with birds. Instead of a rich paradise, the Dutch found a windswept and grass-covered wasteland, completely devoid of large trees and any native animals larger than insects. Equally strange were the more than 200 stone statues (Figure B1.3) lining the coastline and another 700 in various stages of development. Some statues weighed over 80 tons and were somehow transported as much as 6 miles (9.7 km) from a single quarry in which they were carved. Uncompleted statues weighed as much as 270 tons!

Several intriguing questions have been raised in the years since Easter Island was discovered. First, why was this grass-covered wasteland so unlike the surrounding islands where lush forests, abundant birds, and flowing streams are common? How could a population of only 2,000 manage to transport and erect 200 huge statues, particularly since they had no suitable trees for making heavy timbers and ropes? Moreover, why would people who were living in caves and struggling to survive by raising chickens and growing crops in thin soils expend such great effort erecting statues? Also puzzling was the islanders' oral history, in which they told of their ancestors routinely visiting a well-known reef located 260 miles (420 km) away. How could they have made such a journey in leaky canoes barely capable of sailing offshore from their own island? Finally, how in the world did these people ever come to colonize Easter Island in the first place?

The answers to these questions didn't come until modern times when scientists from various disciplines began collecting data. Here radiocarbon dates from archaeological excavations first showed that human activity began on Easter Island somewhere between 700 and 1100 AD, followed by peak statue construction from 1200 to 1600. Moreover, the density of archaeological sites indicated a population of around 7,000 during the peak period—some estimates go as high as 15,000. A population crash obviously must have occurred since only about 2,000 people were present when the Dutch arrived in 1722. Also quite revealing was the analysis of pollen spores that had fallen into wetlands and had become incorporated into the sediment record. By comparing the pollen grains found in the various sediment layers to known plant species, scientists could determine the abundance of different plants over time. This analysis proved that large palm trees (up to 6 feet in diameter and 80 feet tall) along with numerous species of shorter trees, ferns, and shrubs had blanketed Easter Island for more than 30,000 years prior to the first human inhabitants. These palm trees would have been ideally suited for constructing the large ocean-going canoes and the timbers needed to transport and erect statues. Similar palm trees today are used in other cultures for their edible nuts and sap.

By examining the bones found in old garbage dumps, scientists were able to determine that the islanders' diet initially consisted of large native birds and dolphins in addition to palm nuts. The fact that people feasted on dolphins rather than fish was explained by the relatively deep water and corresponding lack of coral reefs around Easter Island. This forced the people to sail offshore in order to harvest the only sea animal available in any abundance, namely dolphins. For this, of course, they needed large, seaworthy canoes. Easter Island's extensive forest therefore provided a direct source of food (birds, nuts, and sap) and the large trees allowed them to build

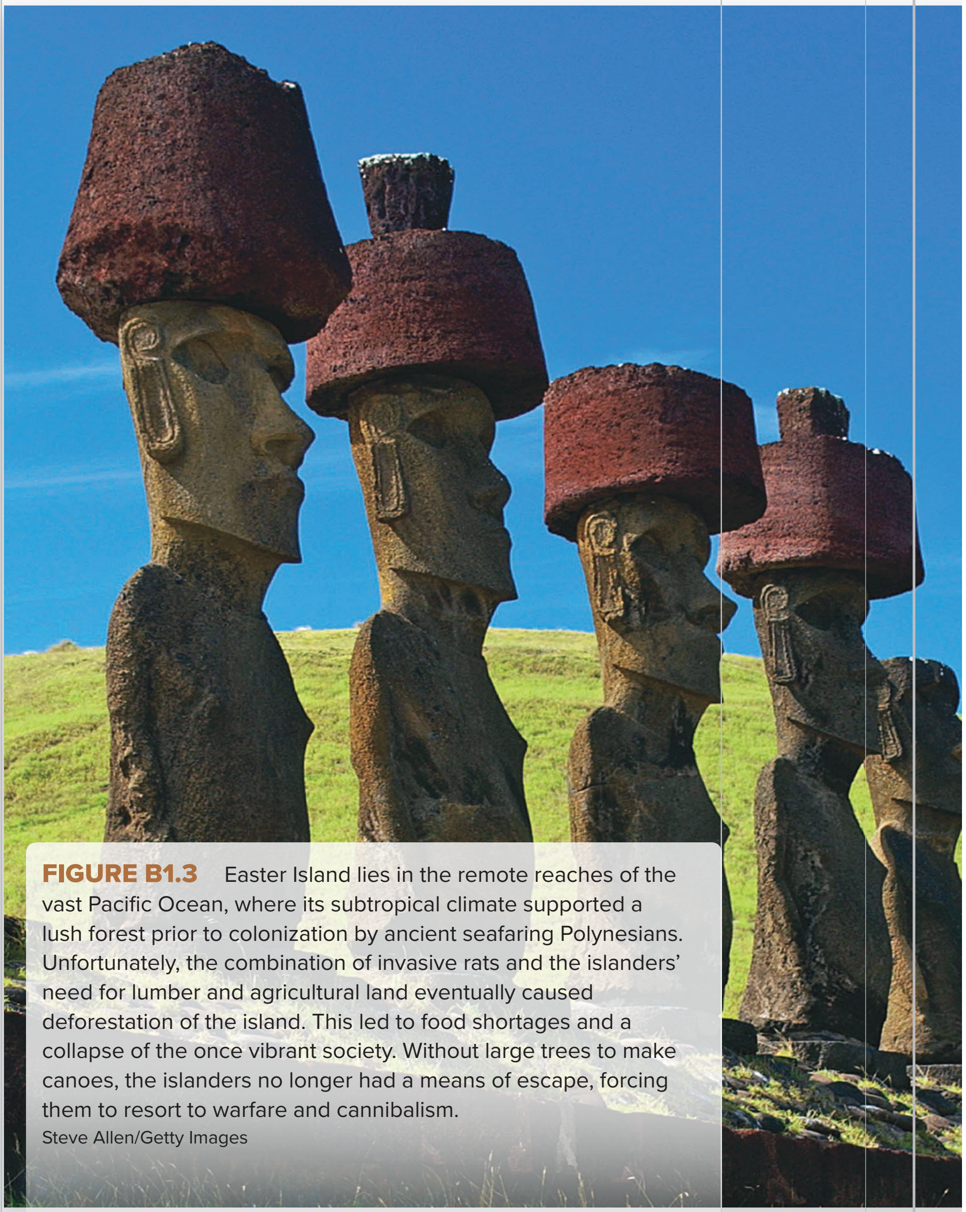
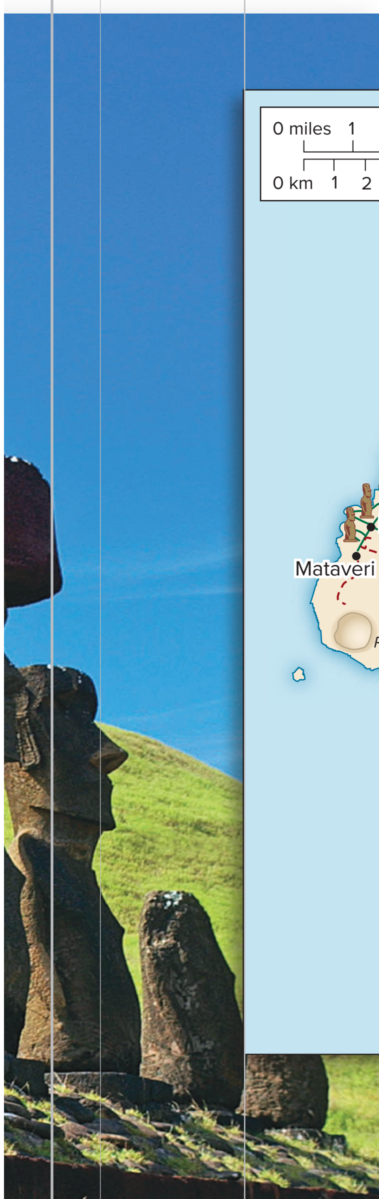
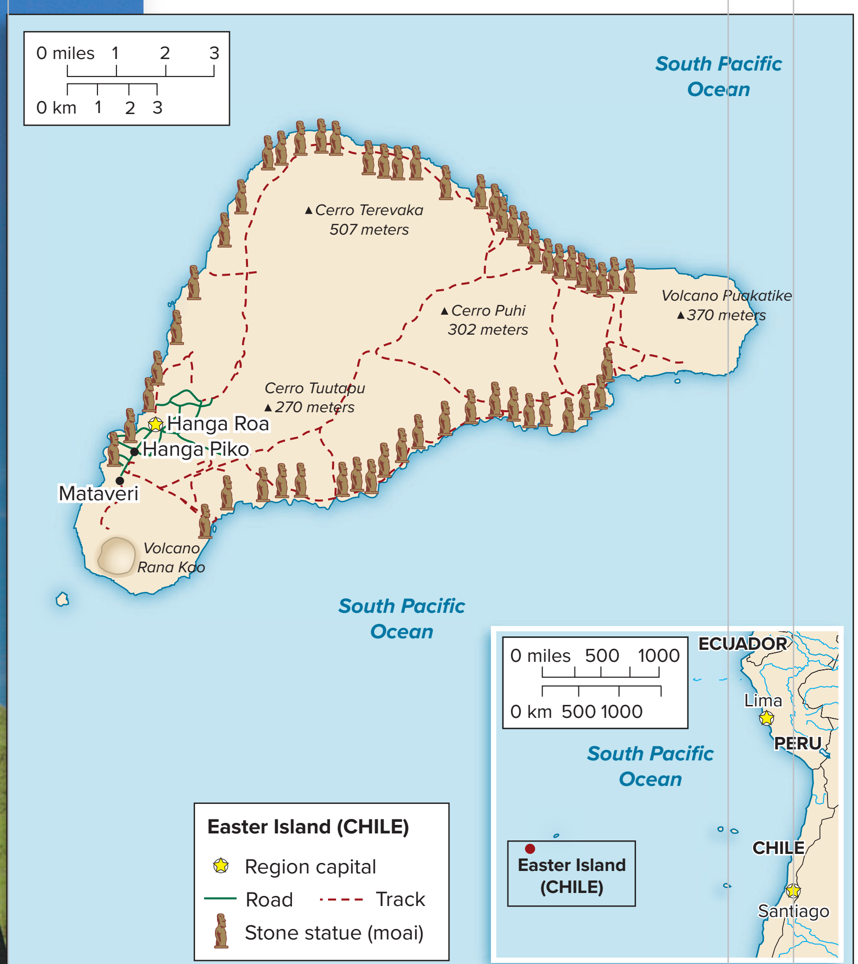


FIGURE B1.3 Easter Island lies in the remote reaches of the vast Pacific Ocean, where its subtropical climate supported a lush forest prior to colonization by ancient seafaring Polynesians. Unfortunately, the combination of invasive rats and the islanders' need for lumber and agricultural land eventually caused deforestation of the island. This led to food shortages and a collapse of the once vibrant society. Without large trees to make canoes, the islanders no longer had a means of escape, forcing them to resort to warfare and cannibalism.
Steve Allen/Getty Images

canoes for hunting dolphins and traveling to distant islands. It was this abundance of natural resources that enabled the population to expand and develop into a highly organized society. Clearly, erecting monuments around the entire island, all from a single quarry, must have required the organization and cooperation of a large number of people.

The obvious question now is why did this complex society collapse? Here again the pollen grains and bones provide the answer. By around 1200 AD the sediment record started showing greater amounts of charcoal from wood fires, but far fewer pollen grains from the palm trees. After inhabiting the island for only a few centuries, the people had begun the process of clearing the forest to grow crops and provide wood for building canoes, fueling fires, and transporting statues. Moreover, recent data also indicate that the early settlers brought rats with them to the island. The rats survived largely by eating the hulls from the seeds of the palm trees. Having no natural predators, the rat population exploded. Due to the combination of rats eating the seeds and humans clearing the forest, the palm trees went extinct shortly after 1400 AD. During this period of deforestation the analysis of bones in the islanders' garbage dumps showed that the number of birds in their diet had decreased dramatically. By around 1500 AD the bones of native birds as well as dolphins were completely lacking. As the forest was being lost, birds and palm nuts were also being lost from the islanders' food supply. Dolphins were soon removed from their diet as well once there were no more large trees for making seaworthy canoes. Deforestation also led to severe soil loss and decreased the ability of rainwater to infiltrate the soils. This resulted in thinner and dryer soils, reducing crop production and altering the island's hydrology such that many of its streams stopped flowing. Not surprisingly, the islanders slowly began to experience both food and water shortages.





By the time the Dutch arrived in 1722, the once-vibrant society was on the verge of collapse. Researchers now believe that this society eventually collapsed due to a combination of environmental degradation, warfare, and disease introduced by the Europeans. Moreover, without the large palm trees for making seaworthy canoes, the islanders had no means of escape. They were stuck.

In the book *Collapse* by Jared Diamond, the author asks questions as to why the islanders didn't try to save themselves: "Why didn't they look around, realize what they were doing, and stop before it was too late? What were they thinking when they cut down the last palm tree?" Diamond concludes that the islanders didn't see the problem because of what he refers to as *creeping normalcy.* As the years slowly passed, generations of islanders saw only small changes in the amount of forest; hence it looked "normal." Islanders who understood and warned of the dangers of deforestation likely would have been drowned out by those in society whose jobs depended upon harvesting the trees. Diamond argues that by the time the last palm tree was cut, the large old-growth trees were a distant memory.

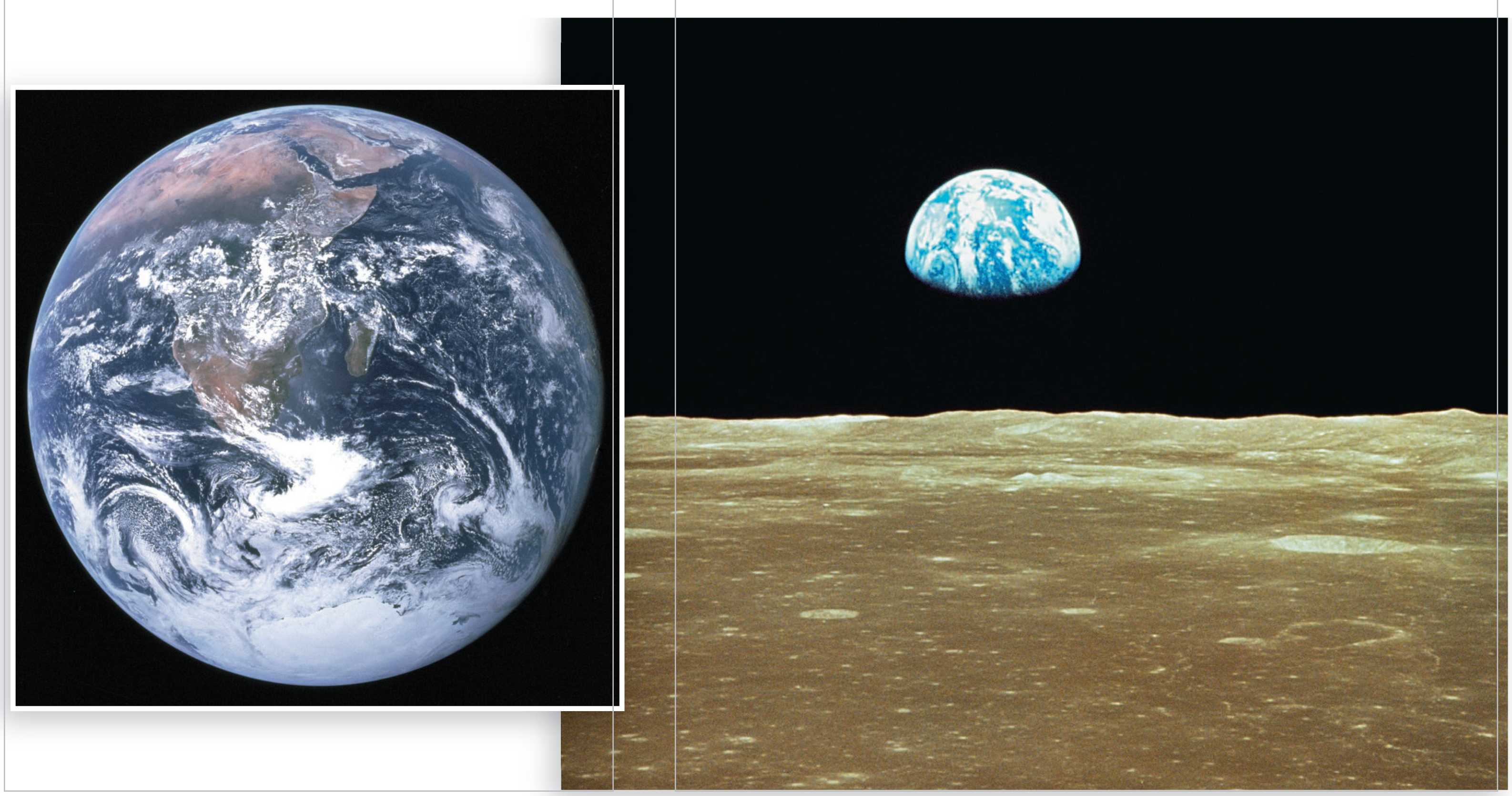
Although the demise of Easter Island's society was likely due to multiple factors, many environmentalists view it as a small-scale example of what is currently happening worldwide. As Earth's expanding population continues to degrade the environment and consume key resources such as petroleum, water, and soil at an unsustainable rate, we are putting our global society at risk of collapse. Moreover, the burning of vast amounts of fossil fuels is having the unintended consequence of accelerated global warming, which may in turn threaten the very survival of humans. Similar to Easter Island in the middle of the vast Pacific, Earth is a blue speck in the vastness of space whose people have nowhere to go should they overexploit their natural resources. Unlike Easter Islanders, however, we have history from which to learn the mistakes of others. The question is, will enough of us learn the lessons from history before it is too late?

Environmentalism

Environmental awareness in the United States really began in the 1960s and 1970s as a grassroots movement, driven in large part by widespread water and air pollution. One of the sparks for this environmental movement was Rachel Carson's classic 1962 book, *Silent Spring*. Her book helped awaken both the public and scientists to the fact that Earth's complex web of life is sensitive to environmental change, particularly pollution. The basic problem in the United States was that industries had historically been free to discharge their waste by-products into the atmosphere and nearby water bodies. However, as people recognized that pollution was fouling their air and drinking water as well as their beaches, fishing holes, and other recreational sites, they began to demand change. Eventually federal laws, such as the Clean Air Act (1970) and Clean Water Act (1972), were enacted and forced industries to properly dispose of their waste (Chapter 15). Businesses could no longer freely dump waste into the environment and pass the cleanup and health costs on to society. Proper waste disposal now had to be treated as a business expense.

Another defining event in the environmental movement came in 1968 when Apollo astronauts heading to the Moon provided humans with views of the Earth no one had ever seen before (Figure 1.28). People around the globe were struck by both the beauty and isolation of our planet in the darkness of space. It also caused many to start thinking of humanity as a single race, surviving on a fragile oasis in space, rather than as different nationalities all in competition with one another. This new perspective helped us see how Earth operates as a system, providing the necessary resources that make our lives possible. Moreover, it helped us understand how we could damage this system and overuse its limited resources to the

FIGURE 1.28 Photographs of planet Earth taken by Apollo astronauts helped humans understand that Earth behaves as a system and that we depend on the system for survival.
(left) *Source:* NASA; (right) Brand X/PunchStock/Getty Images



point where the planet would become less hospitable for humans. Should this occur, we would be stuck on this island in space with nowhere else to go, similar to the Easter Islanders in the vast Pacific (Case Study 1.2).

The environmental regulations passed in the United States since the 1970s succeeded in eliminating the most visible and obvious forms of pollution, leading many people to think pollution is no longer a problem. More subtle forms of pollution, however, still exist and pose a threat to the health of both humans and Earth's ecosystems. Another consequence of the environmental regulations was that the federal government began exercising its authority over individual and state property rights in order to protect the health of society as a whole. This issue of personal property rights, combined with the perception that pollution is no longer a problem, has contributed to a backlash against the environmental movement in recent years. Today various groups and individuals portray environmentalists as "wackos," "tree huggers," or "ecoterrorists" who feel that plants and animals are more important than people. This is simply not true. Environmentalism is not just about saving owls in a forest or fish in a river; it is about saving humans from themselves. Forests and wetlands, for example, are important not simply because they contain interesting plants and animals, but because they provide people with clean water and help regulate our climate. If we end up destroying Earth's ecosystems, then humans would find it difficult to survive.

The biggest environmental issue facing the human race is sustainability. The question is whether we will be able to use Earth's limited resources in a sustainable manner, or will population growth outstrip the planet's ability to support us? The answer to this question will depend on whether we can control our population and reduce per capita consumption of resources through conservation. Achieving sustainability will also require many societies to change from constant economic growth to nongrowth, similar to what is taking place today in some developed countries with stable populations. The problem is that many nations define economic success in terms of increased numbers of new homes and jobs and expanded factory production and trade. These economic indicators all depend on greater numbers of people consuming greater amounts of Earth's resources. Both science and common sense tell us that it is not possible to have permanent economic growth on a planet whose resources are finite. David Brower, a leading environmentalist for over 50 years, often spoke on the subject of sustainability and the rapid pace at which we have been consuming Earth's resources since the Industrial Revolution. John McPhee described Brower's thoughts on this subject in the 1971 book *Encounters with the Archdruid:*

> Sooner or later in every talk, Brower describes the creation of the world. He invites his listeners to consider the six days of Genesis as a figure of speech for what has in fact been four billion years. On this scale, a day equals something like six hundred and sixty-six million years, and thus "all day Monday and until Tuesday noon, creation was busy getting the earth going." Life began Tuesday noon, and "the beautiful organic wholeness of it" developed over the next four days. "At 4 p.m. Saturday, the big reptiles came on. Five hours later, when the redwoods appeared, there were no more big reptiles. At three minutes before midnight, man appeared. At one-fourth of a second before midnight, Christ arrived. At one-fortieth of a second before midnight, the Industrial Revolution began. We are surrounded with people who think that what we have been doing for that one-fortieth of a second can go on indefinitely. They are considered normal, but they are stark, raving mad. . . . We've got to kick this addiction. It won't work on a finite planet. When rapid growth happens in an individual, we call it cancer."

It is certainly not pleasant to think of the human race as being some type of disease on the planet, but we are most definitely having an enormous impact on