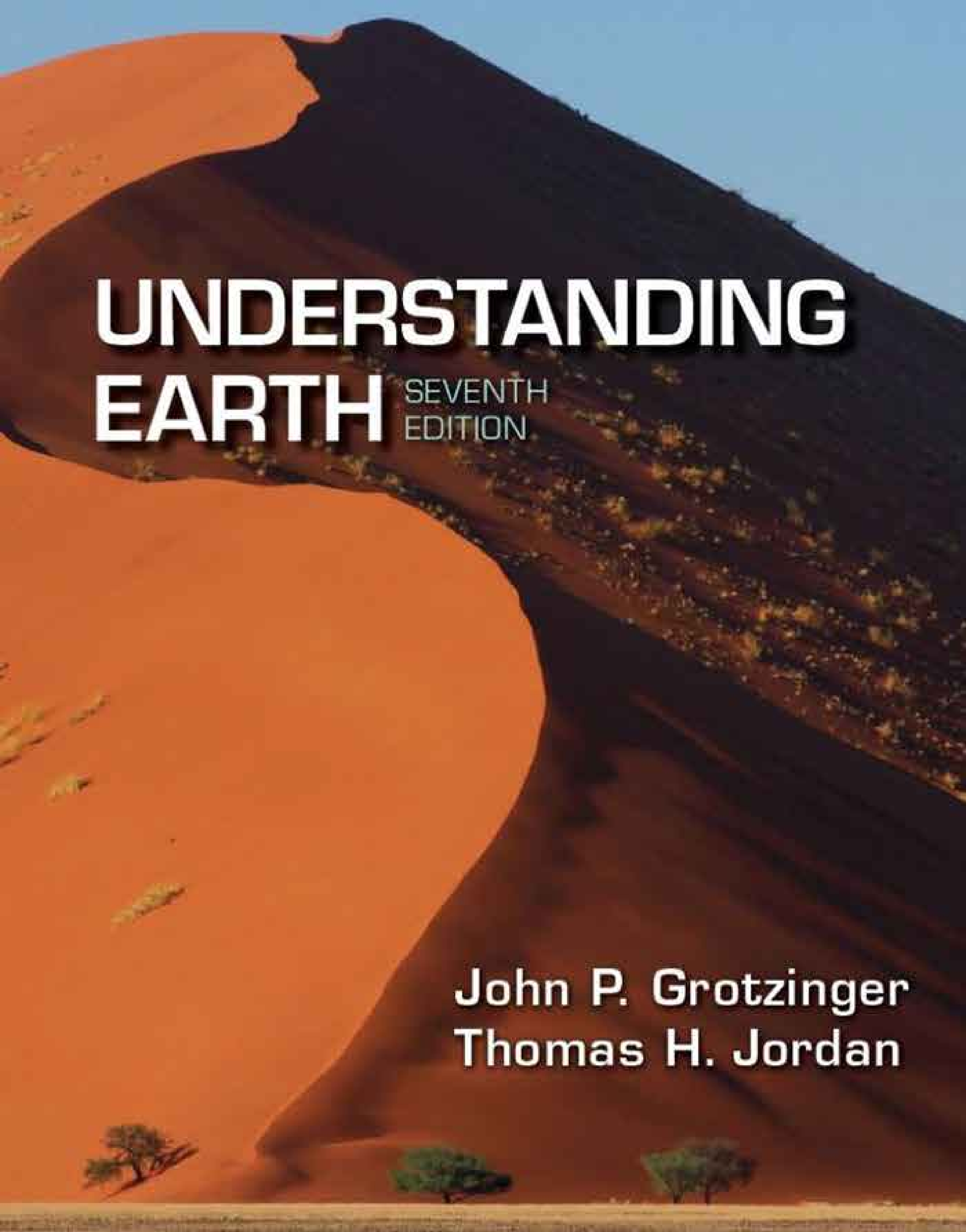
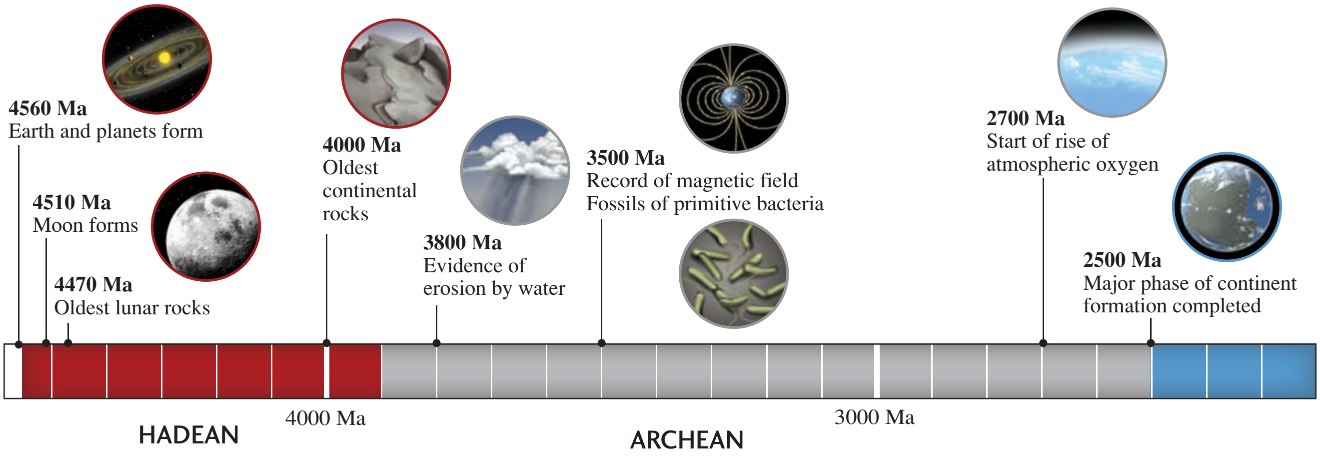
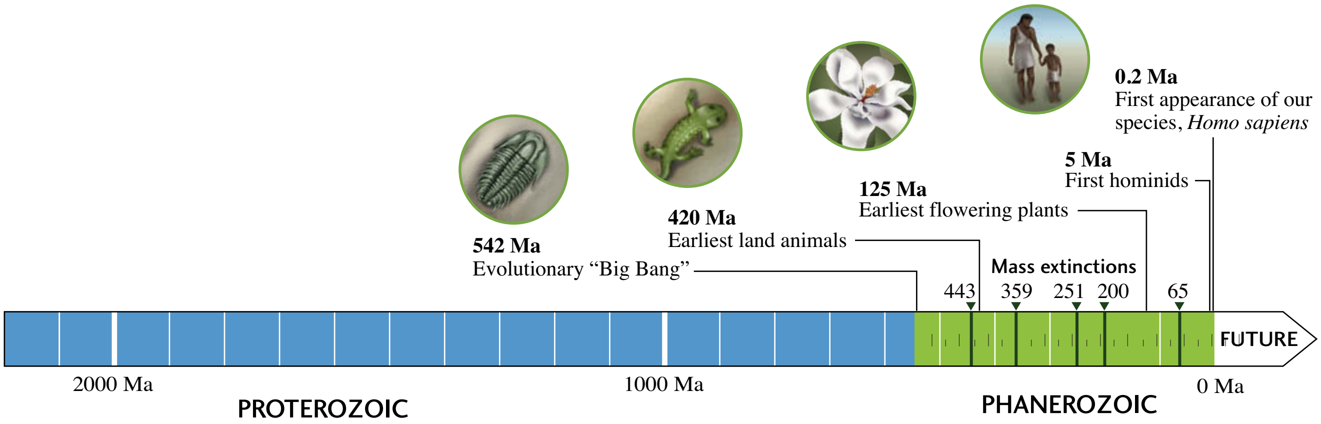


UNDERSTANDING EARTH

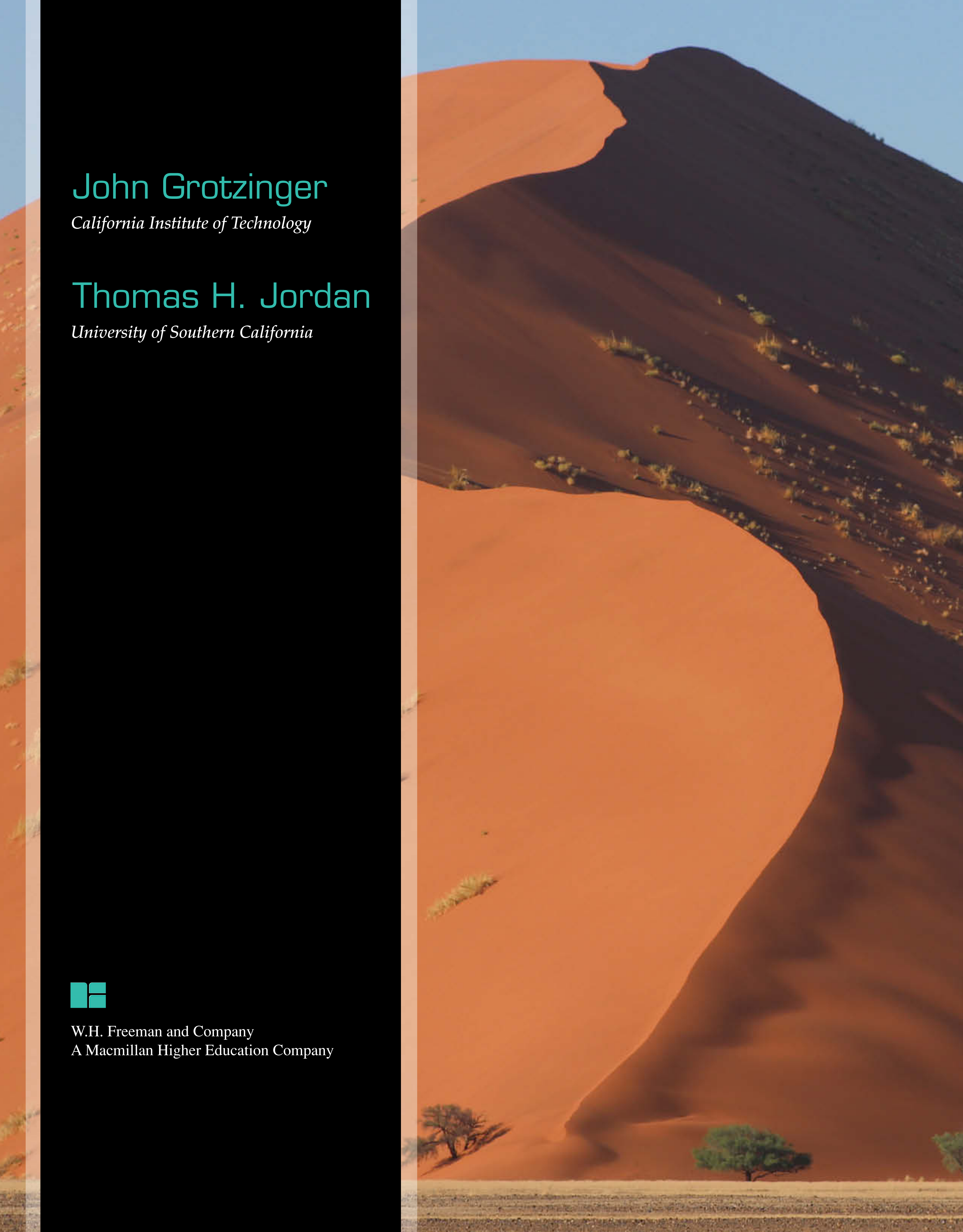
SEVENTH EDITION

John P. Grotzinger
Thomas H. Jordan


4560 Ma
Earth and planets form
4510 Ma
Moon forms
4470 Ma
Oldest lunar rocks
4000 Ma
Oldest continental rocks
3800 Ma
Evidence of erosion by water
3500 Ma
Record of magnetic field
Fossils of primitive bacteria
2700 Ma
Start of rise of atmospheric oxygen
2500 Ma
Major phase of continent formation completed
4000 Ma
3000 Ma
HADEAN
ARCHEAN



0.2 Ma
First appearance of our species, *Homo sapiens*
5 Ma
First hominids
125 Ma
Earliest flowering plants
420 Ma
Earliest land animals
542 Ma
Evolutionary “Big Bang”
Mass extinctions
443
359
251
200
65
FUTURE
2000 Ma
1000 Ma
0 Ma
PROTEROZOIC
PHANEROZOIC



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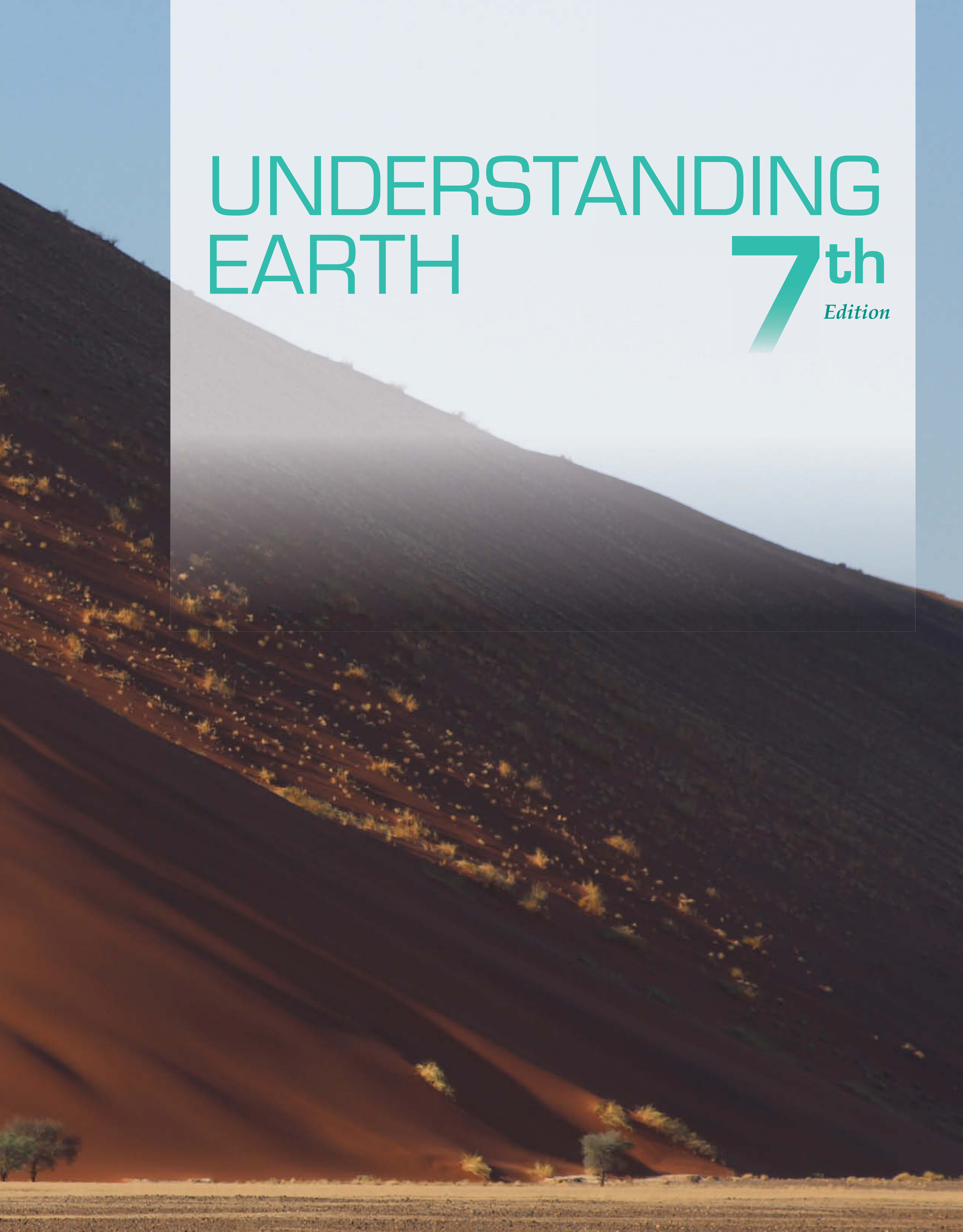

UNDERSTANDING EARTH

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We dedicate this book to Frank Press and Ray Siever, pioneering educators in the era of modern geology. This book was possibly only because they led the way.

MEET THE AUTHORS

John Grotzinger is a field geologist interested in the evolution of Earth's surface environments and biosphere. He also works on the early environmental evolution of Mars and on assessing its potential habitability. His research addresses the chemical development of the early oceans and atmosphere, the environmental context of early animal evolution, and the geologic factors that regulate sedimentary basins. His fieldwork has taken him to northwestern Canada, northern Siberia, southern Africa, the western United States, and via robot, to Mars. He received a B.S. in geoscience from Hobart College in 1979, an M.S. in geology from the University of Montana in 1981, and a Ph.D. in geology from Virginia Polytechnic Institute and State University in 1985. He spent three years as a research scientist at the Lamont-Doherty Geological Observatory before joining the MIT faculty in 1988. From 1979 to 1990, he was engaged in regional mapping for the Geological Survey of Canada. He currently works as the Chief Scientist for the Mars Curiosity Rover team, the first mission to assess the habitability of the ancient environments of another planet.

In 1998, Dr. Grotzinger was named the Waldemar Lindgren Distinguished Scholar at MIT, and in 2000, he became the Robert R. Shrock Professor of Earth and Planetary Sciences. In 2005, he moved from MIT to Caltech, where he is the Fletcher Jones Professor of Geology. He received the Presidential Young Investigator Award of the National Science Foundation in 1990, the Donath Medal of the Geological Society of America in 1992, the Charles Doolittle Walcott Medal of the National Academy of Sciences in 2007, and NASA's Outstanding Public Leadership Medal in 2013. He is a member of the American Academy of Arts and Sciences and the U.S. National Academy of Sciences.

Tom Jordan is a geophysicist interested in the composition, dynamics, and evolution of the solid Earth. He has conducted research into the nature of deep subduction, the formation of thickened keels beneath ancient continental cratons, and the question of mantle stratification. He has developed a number of seismological techniques for investigating Earth's interior that bear on geodynamic problems. He has also worked on modeling plate movements, measuring tectonic deformation, quantifying seafloor morphology, and characterizing large earthquakes. He received his Ph.D. in geophysics and applied mathematics at the California Institute of Technology (Caltech) in 1972 and taught at Princeton University and the Scripps Institution of Oceanography before joining the Massachusetts Institute of Technology (MIT) faculty as the Robert R. Shrock Professor of Earth and Planetary Sciences in 1984. He served as the head of MIT's Department of Earth, Atmospheric and Planetary Sciences for the decade 1988–1998. He moved from MIT to the University of Southern California (USC) in 2000, where he is University Professor and W. M. Keck Professor of Earth Sciences. He is currently the director of the Southern California Earthquake Center, where he coordinates an international research program in earthquake system science that involves over 600 scientists at more than 60 universities and research organizations.

Dr. Jordan received the Macelwane Medal of the American Geophysical Union in 1983, the Woollard Award of the Geological Society of America in 1998, and the Lehmann Medal of the American Geophysical Union in 2005. He is a member of the American Academy of Arts and Sciences, the U.S. National Academy of Sciences, and the American Philosophical Society.

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PREFACE

Our Vision

Geology is everywhere in our daily lives. We are surrounded by materials and resources extracted from the Earth, from jewelry to the gasoline we use to fuel our cars, to the water we drink. Geological science routinely informs the decisions of public policy leaders in government, industry, and community organizations. Understanding our Earth has never been more important.

Because Earth science is so intertwined with our daily lives, our discipline evolves as the years go by, responding to the needs of what society compels us to understand. Decades ago most geologists worked in oil and mining companies, but today there is an exploding need for environmental specialists. As our world population grows we see the increased impact of hurricanes, tornadoes, and other environmental forces such as landslides. Even in the search for life on other planets we increasingly see the need for geological expertise in helping to reconstruct the environments on planets like Mars. There, geologists are exploring for traces of past life in rocks that are billions of years old, with robots that are hundreds of millions of miles away.

These diverse needs require a strong understanding of the basic concepts and principles of Earth science. Although the times change and the applications vary, understanding the basic composition of geologic materials, their origins, and how the planet acts as a system is imperative to understanding Earth. Everything from climate change, to the abundance of groundwater, to the frequency of large storms and volcanic eruptions, to the location and cost of extracting rare elements from Earth is relevant. It is a simple fact that as the complexity of these challenges increases, the need for well-educated geologists to make wise decisions will increase as well. We bring that conviction to this book.

Content Updates and Revisions

Since the publication of the sixth edition, we have witnessed some major geologic events, seen new data on climate trends and global climate change, discovered new sources of natural resources and more modern methods of retrieving them, and have new policies that address how we impact and are impacted by geologic events. Some of the updated topics, as well as topics new to the seventh edition, are listed below:

Interactions among geosystems support life (Chapter 1)

Past climate changes (Chapter 2)

Ages of petroleum-source rocks (Chapter 8)

Current status and findings of Mars Mission (Chapters 9 and 11)

Iceland volcano, eruption clouds, and air traffic (Chapter 12)

Christchurch, New Zealand, earthquake of September 2010 (Chapter 13)

- Tohoku, Japan, earthquake and tsunami of March 2011 (Chapter 13)
- Earth Issues essay on the L'Aquila, Italy, earthquake and subsequent trial (Chapter 13)
- Haiti earthquake of January 2010 (Chapter 13)
- Current global seismicity maps (Chapter 13)
- Land use policies, including the construction of nuclear power facilities (Chapter 13)
- Earthquake and tsunami early warning systems (Chapter 13)
- Current seismic tomography models of Earth's mantle (Chapter 14)
- Twentieth-century warming (Chapter 15)
- Recent drought in New Zealand (Chapter 17)
- Discovery of Kenya aquifers and ancient aquifers (Chapter 17)
- Hurricane Sandy (Chapter 20)
- New IPCC data about the state of the East Antarctic ice sheet and changes in sea level (Chapter 21)
- New trends in energy use (Chapter 23)
- Hydraulic fracturing (fracking) as a method for extracting oil and gas (Chapters 5 and 23)
- New IPCC scenarios for climate change (Chapter 23)

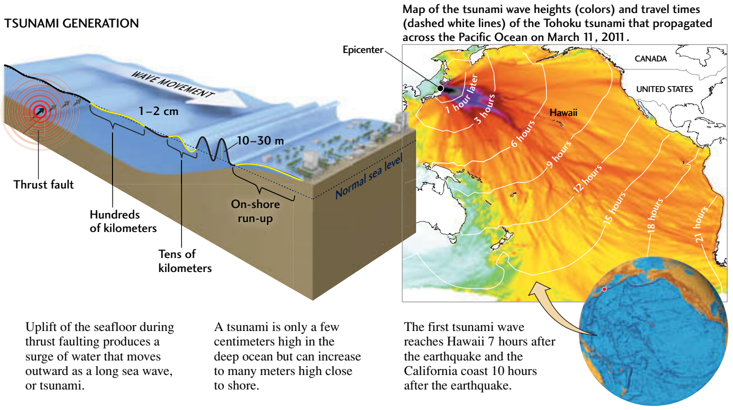
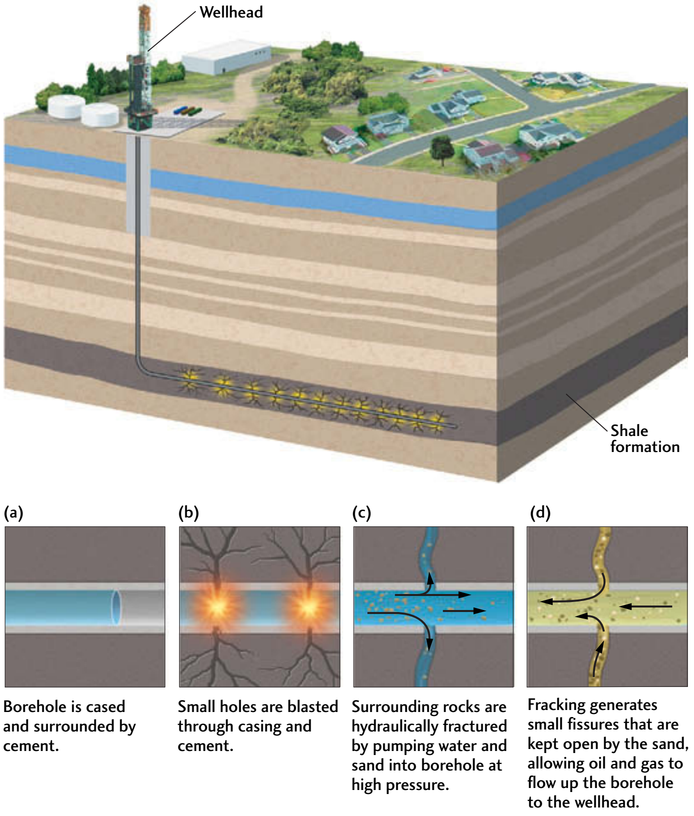


FIGURE 13.22 ■ Earthquakes on megathrusts may generate tsunamis that can propagate across ocean basins. [Map by NOAA, Pacific Marine Environmental Laboratory.]



(a) Borehole is cased and surrounded by cement.

(b) Small holes are blasted through casing and cement.

(c) Surrounding rocks are hydraulically fractured by pumping water and sand into borehole at high pressure.

(d) Fracking generates small fissures that are kept open by the sand, allowing oil and gas to flow up the borehole to the wellhead.

FIGURE 23.15 ■ Hydraulic fracturing or "fracking" is a technique for withdrawing oil and gas from shale and other tight formations by first pumping water and sand into a borehole at high pressures to create fractures through which the oil and gas can more readily flow. The boreholes are commonly drilled horizontally through nearly flat-lying shale formations.

Emphasizing What Geologists Do

If you ask the question, "What do geologists do?" the answer will most likely be something about the study of rocks, volcanoes, or earthquakes. As with many sciences, a more complete understanding of the field of geology is obtained only through its study. It is up to us as instructors to teach our students that the price of gasoline depends partly on the work of geologists who study oil deposits; that geologists help to determine the safety of building locations; and that the water emerging from their faucets is brought to them with the help of geologists. The introductory geology course presents us with an extraordinary opportunity not only to share with students the beauty and power of geology, but also to cultivate greater appreciation for the work of all scientists and a better understanding of the world around us. Several features contribute to our effort to engage students in what geologists do.

Practicing Geology Exercises help students connect to important work currently under way in the field, making cutting-edge research and problem solving accessible to students at all levels. These exercises provide enough background for an informed discussion or activity based on the topic. Each essay includes detailed visualizations of the issue at hand, as well as a question that asks students to apply their knowledge independently. Practicing Geology exercises address questions such as:

- How Big Is Our Planet?
- What Happened in Baja? How Geologists Reconstruct Plate Movements
- Is It Worth Mining?
- How Do Valuable Metallic Ores Form?
- Organic-Rich Shales: Where Do We Look for Oil and Gas?
- How Do We Read Geologic History in Crystals?
- How Do We Use Geologic Maps to Find Oil?
- How Do Isotopes Tell Us the Ages of Earth Materials?
- How Do We Land a Spacecraft on Mars? Seven Minutes of Terror
- How Fast Are the Himalaya Rising and How Quickly Are They Eroding?
- How Do Geobiologists Find Evidence of Early Life in Rocks?
- Are the Siberian Traps a Smoking Gun of Mass Extinction?
- Can Earthquakes Be Controlled?
- The Principle of Isostasy: Why Are Oceans Deep and Mountains High?
- Where's the Missing Carbon?
- What Makes a Slope Too Unstable to Build On?
- How Much Water Can Our Well Produce?
- Can We Paddle Today? Using Streamgauge Data to Plan a Safe and Enjoyable River Trip
- Can We Predict the Extent of Desertification?
- Does Beach Restoration Work?
- Why Is Sea Level Rising?
- How Fast Do Streams Erode Bedrock?

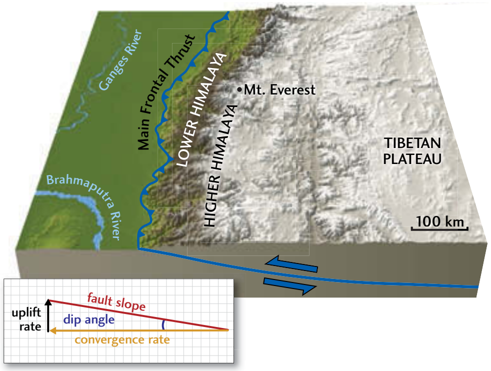
PRACTICING GEOLOGY EXERCISE

How Fast Are the Himalaya Rising, and How Quickly Are They Eroding?

The Himalaya, the world's highest and most rugged mountains, are being raised by thrust faulting caused by the collision of India with Asia (see Figure 10.15). How rapidly are they rising, and how quickly are they being eroded away? The answers to these questions depend on accurate topographic mapping.

On February 6, 1800, Colonel William Lambton, of the 33rd Regiment of Foot of the British Army, received orders to begin the Great Trigonometrical Survey of India, the most ambitious scientific project of the nineteenth century. Over the next several decades, intrepid British explorers led by Lambton and his successor, George Everest, hauled bulky telescopes and heavy surveying equipment through the jungles of the Indian subcontinent, triangulating the positions of reference monuments established at high points in the terrain, from which they could accurately establish Earth's size and shape. Along the way, in 1852, the surveyors discovered that an obscure Himalayan peak, known on their maps only as "Peak XV," was the highest mountain on Earth. They promptly named it Mount Everest, in honor of their former boss. Its official Tibetan name, Chomolungma, means "Mother of the Universe."

On February 11, 2000, almost exactly 200 years after Lambton commenced his exploration, NASA launched another great survey, the Shuttle Radar Topography Mission (SRTM). The space shuttle *Endeavour* carried two large radar antennas into low Earth orbit, one in the cargo bay and the second mounted on a mast that could extend up to 60 m outward. Working together like a pair of eyes, these antennas mapped the height of the land



Cross section of the Himalaya, showing the approximate location of the thrust fault that is uplifting the mountains. The dip angle is about 10°.

Google Earth Projects. Satellite views of Earth are commonplace on news programs, on mapping Web sites, and in other aspects of popular media. Google Earth is by far the most widely used virtual globe browser. Taking advantage of student familiarity with these images and software, the Google Earth Projects guide students through focused explorations of key geologic locations. Balancing observation, core geologic concepts, geographic awareness, guided inquiry, and active learning, the students work through a series of questions aimed at producing a unique and insightful experience. After navigating to the appropriate location and checking their position with the image provided, students may answer the questions in a free-response format or within the text's accompanying learning system, GeologyPortal, which can automatically store and grade student responses.

Google Earth Project

Water, one of the most prolific weathering and transport agents on Earth, is constantly moving material from one location to another. Google Earth is an ideal tool for interpreting and appreciating this uniquely surficial process. Large rivers such as the Mississippi illustrate how efficiently river systems can gather sediment from mountainous regions of a continent (a source area) and transport it to the ocean, where deltas form (a sink area). What kinds of drainage and channel patterns do you find in the Mississippi drainage basin? How does the slope of the river channel change as one moves downstream? These questions and many more can be explored though the GE interface.

Image © USDA Farm Service Agency Image © 2009 TerraMetrics Data SIO, NOAA, U.S. Navy, GEBCO

This image shows the continental scale of the Mississippi River, from near its point of origin (Ft. Benton) to where it enters the Gulf of Mexico near New Orleans.

LOCATION	Missouri-Mississippi drainage basin, United States
GOAL	Understand source-to-sink transportation of sediment by river systems; observe meandering rivers with point bars, eroded outside banks, and oxbow lakes
LINKED	Figure 18.20

1. Type "Ft. Benton, Montana, United States" into the GE search window. Once you arrive there, zoom out to an eye altitude of 35 km. You will be looking down on the Missouri River, the longest tributary of the Mississippi River. Examine the stretch of river that flows from the southwest to the northeast through town and describe the channel pattern you see.

- ***a.*** distributary
- ***b.*** braided
- ***c.*** meandering
- ***d.*** artificially straightened

2. Using the cursor, determine the change in the elevation of the Missouri River channel over the 525 km between Ft. Benton, Montana, and Williston, North Dakota. Now compare that value with the change in the elevation of the Mississippi River channel over the same distance between Memphis, Tennessee, and Baton Rouge, Louisiana, to the south. Which relationship is most accurate?

- ***a.*** The slope of the Missouri River is steeper than that of the Mississippi River.
- ***b.*** The slope of the Mississippi River is steeper than that of the Missouri River.

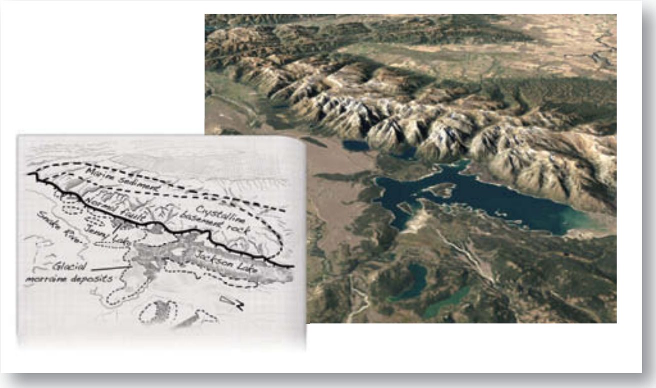


FIGURE 10.7 ■ Image synthesized from satellite data of the Teton Range, Wyoming. The sharp eastern face of the mountain range, which has a vertical relief of more than 2000 m, is the result of normal faulting along the northeastern edge of the Basin and Range province. The view is from the northeast looking to the southwest. Grand Teton Mountain, near the center of the image, rises to an altitude of 4200 meters. [NASA/Goddard Space Flight Center, Landsat 7 Team.]

Field Sketches Introductory geology is widely known for being a particularly visual course. We are fortunate to display stunning vistas and spectacular natural phenomena in our courses and textbooks. A number of photos are accompanied by realistic field sketches, bridging the gap between what students see and what geologists see when they look at a geologic formation. The use of the field sketch style provides students with a sense of the hands-on way geologists work and enables them to develop a greater appreciation for the geologic structures they may see every day.

■ Multimedia and Supplements

The teaching and learning resources that accompany the seventh edition of *Understanding Earth* constitute a comprehensive and flexible ancillary package. They provide opportunities for active learning, student self-study, and automatic grading of homework, and they emphasize the visual aspects of the concepts presented in the text.

LAUNCHPAD UNITS make class prep a whole lot easier

At W. H. Freeman, we are committed to providing online instructional materials that meet the needs of instructors and students in powerful, yet simple ways—powerful enough to dramatically enhance teaching and learning, yet simple enough to use right away.

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Combining a curated collection of video, tutorials, animations, projects, multimedia activities and exercises, and e-Book content, LaunchPad's interactive units give you a building block to use as-is, or as a starting point for your own learning units. An entire unit's worth of work can be assigned in seconds, drastically saving the amount of time it takes for you to have your course up and running.

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  - Powerful adaptive quizzing, a game-like format, direct links to the e-Book, instant feedback, and the promise of better grades make using LearningCurve a no-brainer.
  - Customized quizzing tailored to each text adapts to students' responses and provides material at different difficulty levels and topics based on students' performance. Students love the simple yet powerful system, and instructors can access class reports to help refine lecture content.
- **Interactive e-Book.** The **Interactive e-Book** is a complete online version of the textbook with easy access to rich multimedia resources that complete students' understanding.
  - All text, graphics, tables, boxes, and end-of-chapter resources are included in the e-Book, and the e-Book provides instructors and students with powerful functionality to tailor their course resources to fit their needs.
  - Quick, intuitive navigation to any section or subsection
  - Full-text search, including the Glossary and Index
  - Sticky-note feature allows users to place notes anywhere on the screen and choose the note color for easy categorization.
  - "Top-note" feature allows users to place a prominent note at the top of the page to provide a more significant alert or reminder.
  - Text highlighting in a variety of colors
- **Video Exercises.** Students complete quizzes and do matching activities after viewing 2–5-minute Expeditions in Geology video tutorials shot around the world by Jerry Magloughlin of Colorado State University. Over two dozen videos are available, including
  - *Natural Arches and Bridges.* Topics: Desert processes, erosion, stress. Filmed in the western United States and New Zealand.

  - *Gneiss: The Lewisian Complex of Scotland.* Topics: Metamorphism, cratons, and crystalline basement. Filmed in the Outer Hebrides, Scotland.
  - *Mount Vesuvius and the Plinian Eruption of 79 A.D.* Topics: Stratovolcanoes, Plinian eruptions, and effects on humans. Filmed in Pompeii and on Mount Vesuvius, Italy.
  - *Cinder Cones of Northern Arizona: Sunset and SP Craters.* Topics: Volcanism, cinder cones, and hot spots. Filmed in northern Arizona.

- **Image Map Activities.** These activities use figures from the text to assess key ideas, helping students to develop their visual literacy skills. Students must click the appropriate section(s) of the image and answer corresponding questions.
- **Animations, Flashcards, and other resources** highlight key concepts in introductory geology.
- **Assignments for Online Quizzing, Homework, and Self-Study.** Instructors can create and assign automatically graded homework and quizzes from the complete test bank, which is preloaded in LaunchPad. All quiz results feed directly into the instructor's gradebook.
- ***Scientific American* Newsfeed:** To demonstrate the continued process of science and the exciting new developments in the field, the *Scientific American* Newsfeed delivers regularly updated material from the well-known magazine. Articles, podcasts, news briefs, and videos on subjects related to geology are selected for inclusion by *Scientific American's* editors. The newsfeed provides several updates per week, and instructors can archive or assign the content they find most valuable.
- The **Gradebook** quickly and easily allows you to look up performance metrics for your whole class, for individual students, and for individual assignments. Having ready access to this information can help in both lecture prep and in making office hours more productive and efficient.

e-Books

The seventh edition of *Understanding Earth* is offered in two electronic versions: one is an interactive e-Book, available in the LaunchPad as described above, and the other is a PDF-based e-Book from CourseSmart. These options are provided to offer students and instructors flexibility in their use of course materials.

The CourseSmart e-Book offers the complete text in an easy-to-use, flexible format. Students can choose to view the CourseSmart e-Book online or to download it to a personal computer or a portable media player, such as an iPhone. To help students study and to mirror the experience of a printed textbook, the CourseSmart e-Book incorporates note taking, highlighting, and bookmark features.

Additional Resources for Instructors

The computerized test bank [ISBN 1-4641-7474-1] includes approximately 60 multiple-choice questions for each chapter (over 1300 questions in total) in an electronic format that allows instructors to edit, resequence, and add questions as they create tests.

Instructor's Resources

Images from the text, Image and Lecture PowerPoint presentations, clicker questions, and answers to end-of-chapter questions are available to instructors on the Book Companion Site at www.whfreeman.com/understandingearth7e.

Additional Resources for Students

Student Study Guide

The Student Study Guide includes tips on studying geology, chapter summaries, practice exams, and practice exercises.

Book Companion Site

The Book Companion Site, accessible at www.whfreeman.com/understandingearth7e, provides study tools aimed at helping students:

- Student Self-Quizzes, which can report to the instructor's gradebook
- Flashcards on key vocabulary

Lecture Tutorials in Introductory Geoscience, Second Edition
(ISBN: 1-4641-0105-1)

Karen Kortz, Community College of Rhode Island
Jessica Smay, San Jose City College

A set of brief worksheets designed to be completed by students working alone or in groups, *Lecture Tutorials in Introductory Geoscience* engages students in the learning process and makes abstract concepts real. The tutorials are designed specifically to address misconceptions and difficult topics. Through the use of effective questioning, scaffolded learning, and a progression from simple to complex visuals, they help students construct correct scientific ideas and foster a meaningful and memorable learning experience. Research based on extensive classroom use shows that these Lecture Tutorials increase student learning more than lectures alone.

Research indicates that students learn more when they are actively engaged while learning. Lecture Tutorials are worksheets of carefully designed questions that require students to think about challenging subjects.

They are designed to be used after a brief lecture or introduction to the topic. Working in small groups, students are encouraged to "talk science," ask questions, and teach one another.

A geologist looking at terrain or a rock formation can often identify its structure and attempt to draw conclusions about its history; most introductory geoscience students cannot make the same connections. Lecture Tutorials use simplified images and questions to help students build a fundamental understanding of a concept, then move them into more complex interpretations of that concept. In the process, the activities create an environment in which students must confront their misconceptions. Those misconceptions were identified through literature searches of published misconceptions and through the classroom experience of the authors.

Lecture Tutorials scaffold student learning. Early questions are designed to introduce the students to the topic and help them consider what they do and do not know. The tutorial then focuses on underdeveloped or misunderstood concepts and slowly steps students through more difficult questions, helping them construct a new understanding. The final questions are higher-level questions, both scientifically and cognitively, that indicate whether students understand the material.

Lecture Tutorials do not need to stand alone in the classroom and can be used with other interactive teaching methods. They are designed to be used to complement lectures, laboratory exercises, textbook use, and online resources. While research shows they are most effective when used frequently in the lecture component of a course, instructors from around the country have successfully used them in laboratory settings or as homework.

Instructors can order *Lecture Tutorials in Introductory Geoscience* as a stand-alone item or packaged with a W. H. Freeman textbook.

- *Lecture Tutorials in Introductory Geoscience*
- *Lecture Tutorials in Introductory Geoscience and Understanding Earth,* Seventh Edition
- *Lecture Tutorials in Introductory Geoscience* and *The Essential Earth*

Students can also purchase *Lecture Tutorials in Introductory Geoscience* directly at www .whfreeman.com/lecturetutorials.

Acknowledgments

It is a challenge both to geology instructors and to authors of geology textbooks to compress the many important aspects of geology into a single course and to inspire interest and enthusiasm in their students. To meet this challenge, we have called on the advice of many colleagues who teach in all kinds of college and university settings.

From the earliest planning stages of each edition of this book, we have relied on a consensus of views in designing an organization for the text and in choosing which topics to include. As we wrote and rewrote the chapters, we again relied on our colleagues to guide us in making the presentation pedagogically sound, accurate, accessible, and stimulating to students. To each one we are grateful.

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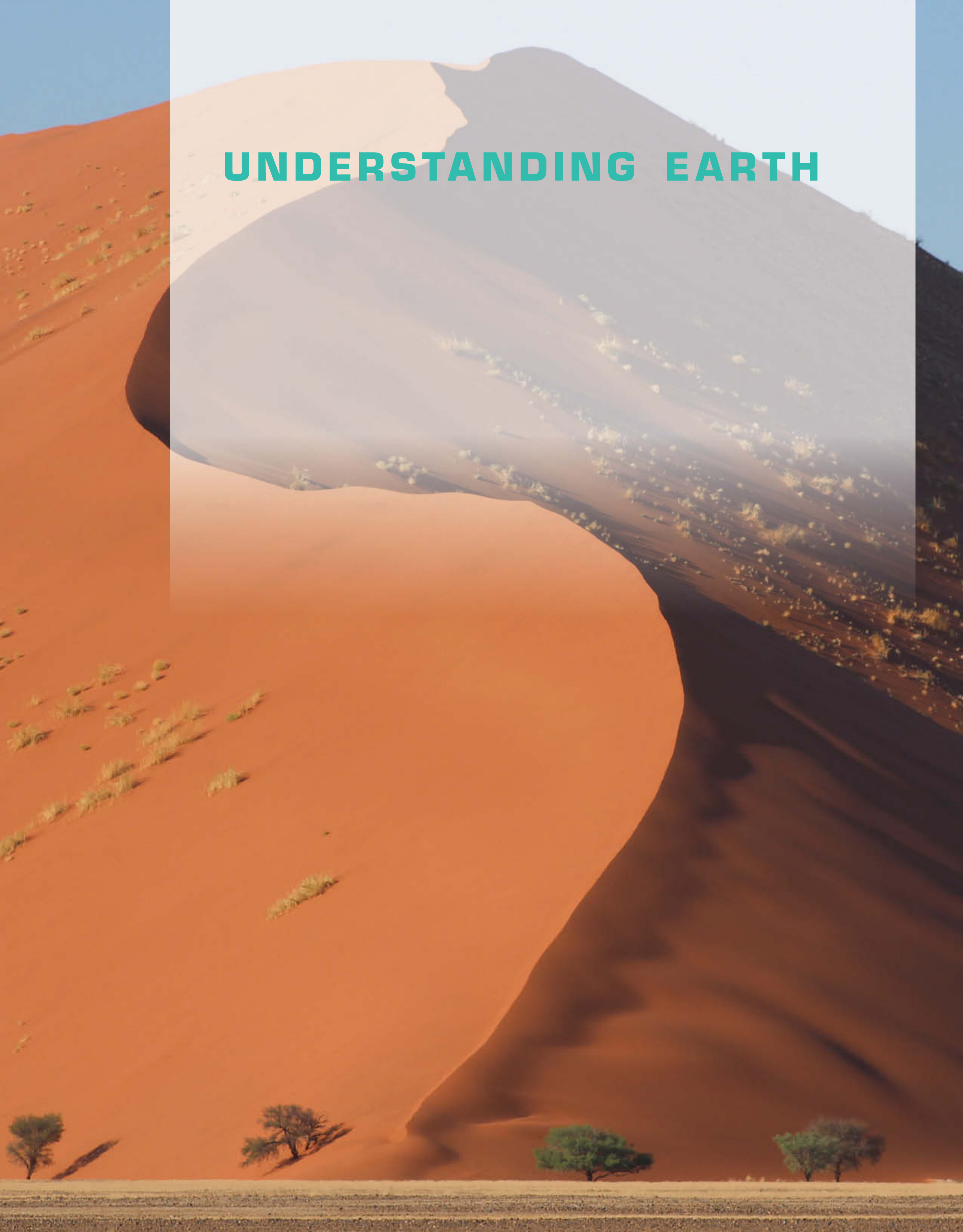
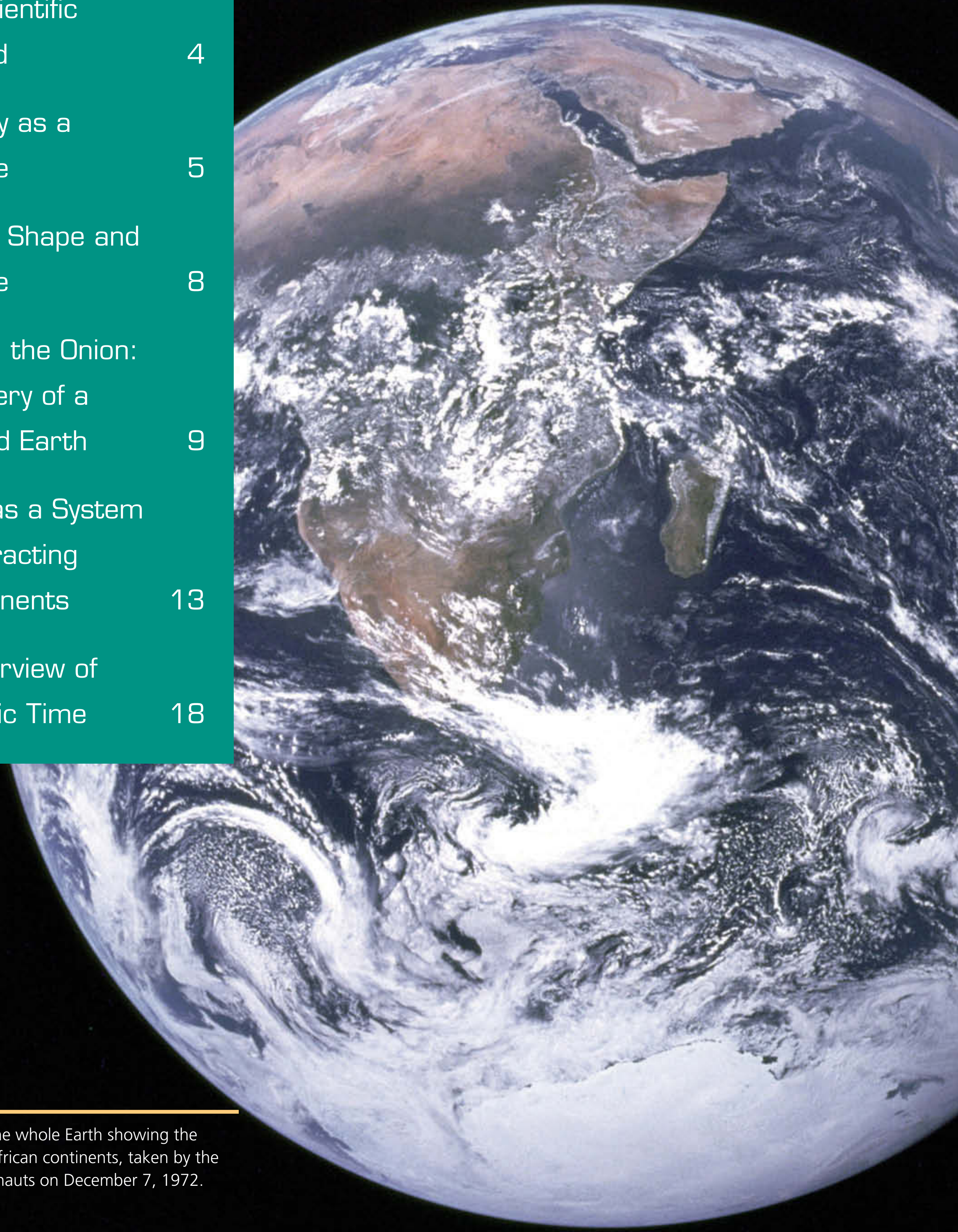
Others have worked with us more directly in writing and preparing the manuscript for publication. At our side always was our Science Editor at W. H. Freeman and Company: Randi Rossignol. Randi has worked with us for the past 12 years, and through four revisions of the text. It has been a pleasure for us to work with her every time! Bill Minick, Senior Editor, was very helpful in shepherding the process through to completion. Jen Griffes helped us with the simultaneous challenge of text revision and Mars Rover operations. Amy Thorne coordinated the media supplements, Blake Logan designed the text, Jennifer Atkins obtained many beautiful photographs, and Paul Rohloff managed the production of the text. Nick Ciani coordinated the transmittal process. We thank Dennis Free and Sheryl Rose from Aptara Corporation for creating the printed text from final manuscript. We are grateful to Jake Armour, University of North Carolina, Charlotte, who worked with us to create the Google Earth Projects. And our heartfelt thanks go to Emily Cooper, who created so many beautiful illustrations.

UNDERSTANDING EARTH





First image of the whole Earth showing the Antarctic and African continents, taken by the *Apollo 17* astronauts on December 7, 1972. [NASA.]

THE EARTH SYSTEM

1

EARTH IS A UNIQUE place, home to millions of organisms, including ourselves. No other planet we have yet discovered has the same delicate balance of conditions necessary to sustain life. Geology is the science that studies Earth: how it was born, how it evolved, how it works, and how we can help preserve its habitats for life. Geologists seek answers to many basic questions: Of what material is the planet composed? Why are there continents and oceans? How did the Himalaya, Alps, and Rocky Mountains rise to their great heights? Why are some regions subject to earthquakes and volcanic eruptions while others are not? How did Earth's surface environment and the life it contains evolve over billions of years? What changes are likely in the future? We think you will find the answers to such questions fascinating. Welcome to the science of geology!

We have organized the discussion of geology in this textbook around three basic concepts that will appear in almost every chapter: (1) Earth as a system of interacting components, (2) plate tectonics as a unifying theory of geology, and (3) changes in the Earth system through geologic time.

This chapter gives a broad picture of how geologists think. It starts with the scientific method, the observational approach to the physical universe on which all scientific inquiry is based. Throughout this textbook, you will see the scientific method in action as we describe how Earth scientists gather and interpret information about our planet. In this first chapter, we will illustrate how the scientific method has been applied to discover some of Earth's basic features—its shape and its internal layering.

To explain features that are millions or even billions of years old, Earth scientists look at what is happening on Earth today. We will introduce the study of our complex natural world as an *Earth* system involving many interrelated components. Some of these components, such as the atmosphere and oceans, are clearly visible above Earth's solid surface; others lie hidden deep within its interior. By observing the ways in which these components interact, scientists have built up an understanding of how the Earth system has changed through geologic time.

We will also introduce you to a geologist's view of time. You will think about time differently as you begin to comprehend the immense span of geologic history. Earth and the other planets in our solar system formed about 4.5 billion years ago. More than 3 billion years ago, living cells developed on Earth's surface, and life has been evolving ever since. Yet our human origins date back only a few million years—less than a tenth of a percent of Earth's existence. The decades of individual lives or even the thousands of years of recorded human history are inadequate to study Earth's long existence.

The Scientific Method

The term *geology* (from the Greek words for "Earth" and "knowledge") was coined by scientific philosophers more than 200 years ago to describe the study of rock formations and fossils. Through careful observations and reasoning, their successors developed the theories of biological evolution, continental drift, and plate tectonics—major topics of this textbook. Today, **geology** identifies the branch of Earth science that studies all aspects of the planet: its history, its composition and internal structure, and its surface features.

The goal of geology—and of science in general—is to explain the physical universe. Scientists believe that physical events have physical explanations, even if they may be beyond our present capacity to understand them. The **scientific method,** on which all scientists rely, is the general procedure for discovering how the universe works through systematic observations and experiments. Using the scientific method to make new discoveries and to confirm old ones is the process of *scientific research* (**Figure 1.1**).

When scientists propose a *hypothesis*—a tentative explanation based on data collected through observations and experiments—they present it to the community of scientists for criticism and repeated testing. A hypothesis is supported if it explains new data or predicts the outcome of new experiments. A hypothesis that is confirmed by other scientists gains credibility.

Here are four interesting scientific hypotheses we will encounter in this textbook:

- Earth is billions of years old.
- Coal is a rock formed from dead plants.
- Earthquakes are caused by the breaking of rocks along geologic faults.
- The burning of fossil fuels is causing global warming.

The first hypothesis agrees with the ages of thousands of ancient rocks as measured by precise laboratory techniques, and the next two hypotheses have also been confirmed by many independent observations. The fourth hypothesis has been more controversial, though so many new data support it that most scientists now accept it as true (see Chapters 15 and 23).

FIGURE 1.1 ■ Scientific research is the process of discovery and confirmation through observations of the real world. These geologists are researching soil samples near a lake in Minnesota. [USGS.]

A coherent set of hypotheses that explains some aspect of nature constitutes a *theory.* Good theories are supported by substantial bodies of data and have survived repeated challenges. They usually obey *physical laws,* general principles about how the universe works that can be applied in almost every situation, such as Newton's law of gravity.

Some hypotheses and theories have been so extensively tested that all scientists accept them as true, at least to a good approximation. For instance, the theory that Earth is nearly spherical, which follows from Newton's law of gravity, is supported by so much experience and direct evidence (ask any astronaut) that we take it to be a fact. The longer a theory holds up to all scientific challenges, the more confidently it is held.

Yet theories can never be considered completely proved. The essence of science is that no explanation, no matter how believable or appealing, is closed to questioning. If convincing new evidence indicates that a theory is wrong, scientists will discard it or modify it to account for the data. A theory, like a hypothesis, must always be testable; any proposal about the universe that cannot be evaluated by observing the natural world should not be called a scientific theory.

For scientists engaged in research, the most interesting hypotheses are often the most controversial, rather than the most widely accepted. The hypothesis that fossil-fuel burning causes global warming has been widely debated. Because the long-term predictions of this hypothesis are so important, many Earth scientists are now vigorously testing it.

Knowledge based on many hypotheses and theories can be used to create a *scientific model*—a precise representation of how a natural process operates or how a natural system behaves. Scientists combine related ideas in a model to test the consistency of their knowledge and to make predictions. Like a good hypothesis or theory, a good model makes predictions that agree with observations.

A scientific model is often formulated as a computer program that simulates the behavior of a natural system through numerical calculations. The forecast of rain or sunshine you may see on TV tonight comes from a computer model of the weather. A computer can be programmed to simulate geologic phenomena that are too big to replicate in a laboratory or that operate over periods of time that are too long for humans to observe. For example, models used for predicting weather have been extended to predict climate changes decades into the future.

To encourage discussion of their ideas, scientists share those ideas and the data on which they are based. They present their findings at professional meetings, publish them in professional journals, and explain them in informal conversations with colleagues. Scientists learn from one another's work as well as from the discoveries of the past. Most of the great concepts of science, whether they emerge as a flash of insight or in the course of painstaking analysis, result from untold numbers of such interactions. Albert Einstein put it this way: "In science . . . the work of the individual is so bound up with that of his scientific predecessors and contemporaries that it appears almost as an impersonal product of his generation."

Because such free intellectual exchange can be subject to abuses, a code of ethics has evolved among scientists. Scientists must acknowledge the contributions of all others on whose work they have drawn. They must not falsify data, use the work of others without recognizing them, or be otherwise deceitful in their work. They must also accept responsibility for training the next generation of researchers and teachers. These principles are supported by the basic values of scientific cooperation, which a president of the National Academy of Sciences, Bruce Alberts, has aptly described as "honesty, generosity, a respect for evidence, openness to all ideas and opinions."

■ Geology as a Science

In the popular media, scientists are often portrayed as people who do experiments wearing white coats. That stereotype is not inappropriate: many scientific problems are best investigated in the laboratory. What forces keep atoms together? How do chemicals react with one another? Can viruses cause cancer? The phenomena that scientists observe to answer such questions are sufficiently small and happen quickly enough to be studied in the controlled environment of the laboratory.

The major questions of geology, however, involve processes that operate on much larger and longer scales. Controlled laboratory measurements yield critical data for testing geologic hypotheses and theories—the ages and properties of rocks, for instance—but they are usually insufficient to solve major geologic problems. Almost all of the great discoveries described in this textbook were made by observing Earth processes in their uncontrolled, natural environment.

For this reason, geology is an outdoor science with its own particular style and outlook. Geologists "go into the field" to observe nature directly (**Figure 1.2**). They learn how mountains were formed by climbing up steep slopes and examining the exposed rocks, and they deploy sensitive instruments to collect data on earthquakes, volcanic eruptions, and other activity within the solid Earth. They discover how ocean basins have evolved by sailing rough seas to map the ocean floor (**Figure 1.3**).

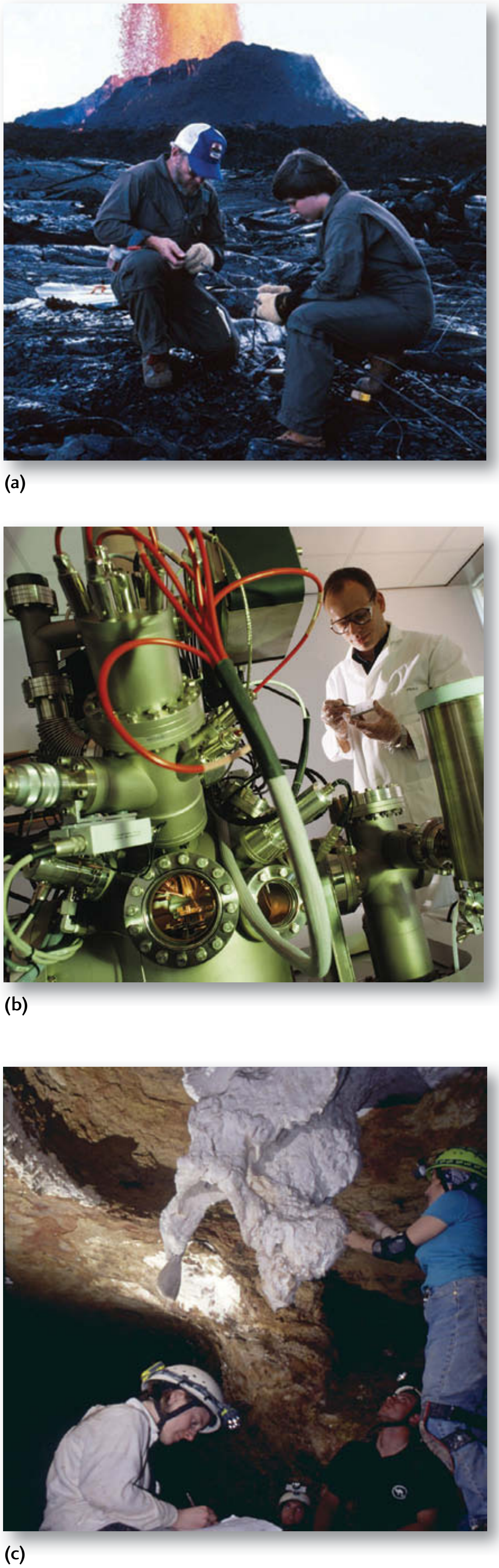
FIGURE 1.2 ■ Geology is principally an outdoor science. Here, Peter Gray welds one of the five Global Positioning System stations placed on the flanks of Mount St. Helens. The stations will monitor the changing shape of the land surface as molten rock moves upward within the volcano. [USGS/Lyn Topinka.]

FIGURE 1.3 ■ The research crew from the icebreaker Louis S. St-Laurent, lowers a corer that will gather mud and sediment from the ocean floor. [AP Photo/The Canadian Press, Jonathan Hayward.]

Geology is closely related to other areas of Earth science, including *oceanography,* the study of the oceans; *meteorology,* the study of the atmosphere; and *ecology,* which concerns the abundance and distribution of life. *Geophysics, geochemistry,* and *geobiology* are subfields of geology that apply the methods of physics, chemistry, and biology to geologic problems (**Figure 1.4**).

Geology is a *planetary science* that uses remote sensing devices, such as instruments mounted on Earth-orbiting spacecraft, to scan the entire globe (**Figure 1.5**). Geologists develop computer models that can analyze the huge quantities of data amassed by satellites to map the continents, chart the motions of the atmosphere and oceans, and monitor how our environment is changing.

A special aspect of geology is its ability to probe Earth's long history by reading what has been "written in stone." The **geologic record** is the information preserved in the rocks that have been formed at various times throughout Earth's history (**Figure 1.6**). Geologists decipher the geologic record by combining information from many kinds of work: examination of rocks in the field; careful mapping of their positions relative to older and younger rock formations; collection of representative samples; and determination of their ages using sensitive laboratory instruments (Figure 1.4b).



(a)

(b)

(c)

FIGURE 1.4 ■ A number of subfields contribute to the study of geology. (a) Geophysicists deploy instruments to measure the underground activity of a volcano. (b) A geochemist readies a rock sample for analysis by a mass spectrometer. (c) Geobiologists investigate underground life inside Spider Cave at Carlsbad Caverns, New Mexico. [(a) Hawaiian Volcano Observatory/USGS; (b) John McLean/Science Source; (c) AP Photo/Val Hildreth-Werker.]

FIGURE 1.5 ■ An astronaut checks out instrumentation for monitoring Earth's surface. [StockTrek/SuperStock.]

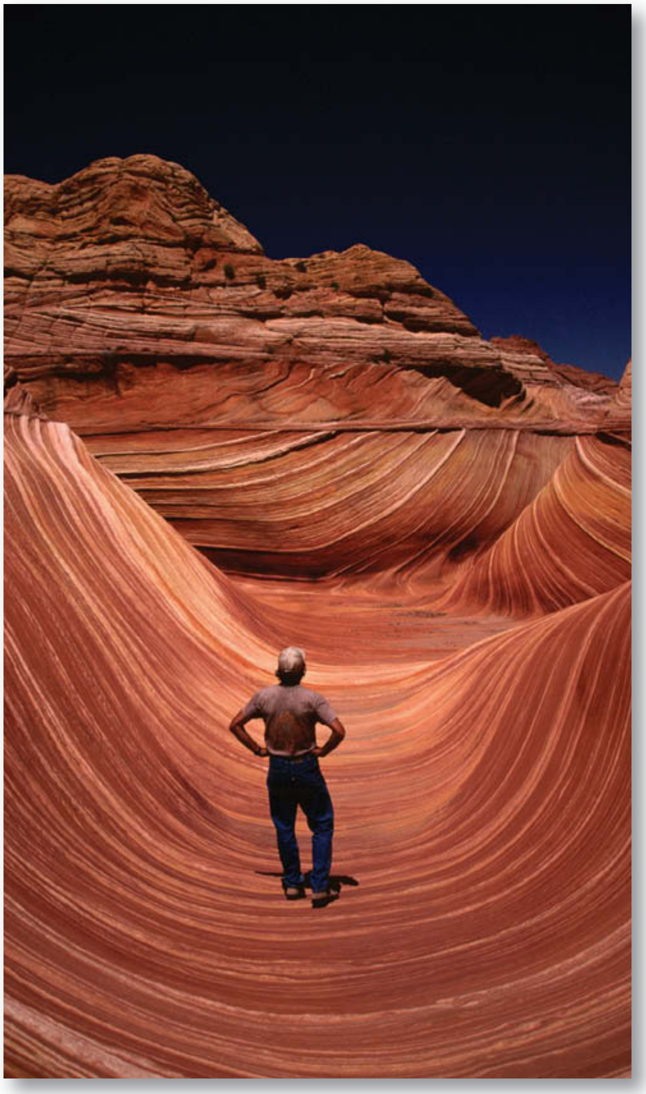


FIGURE 1.6 ■ The geologic record preserves evidence of Earth's long history. These multicolored layers of sand at Colorado National Monument were deposited more than 200 million years ago, when this part of the western United States was a vast Sahara-like desert. They were subsequently overlain by other rocks, welded by pressure into sandstone, uplifted by mountain-building events, and eroded by wind and water into today's stunning landforms. [Mark Newman/Lonely Planet Images/Getty Images, Inc.]

In *Annals of the Former World*, a compendium of colorful stories about geologists, the popular writer John McPhee offers his view of how geologists bring field and laboratory observations together to visualize the big picture:

> *They look at mud and see mountains, in mountains oceans, in oceans mountains to be. They go up to some rock and figure out a story, another rock, another story, and as the stories compile through time they connect—and long case histories are constructed and written from interpreted patterns of clues. This is detective work on a scale unimaginable to most detectives, with the notable exception of Sherlock Holmes.*

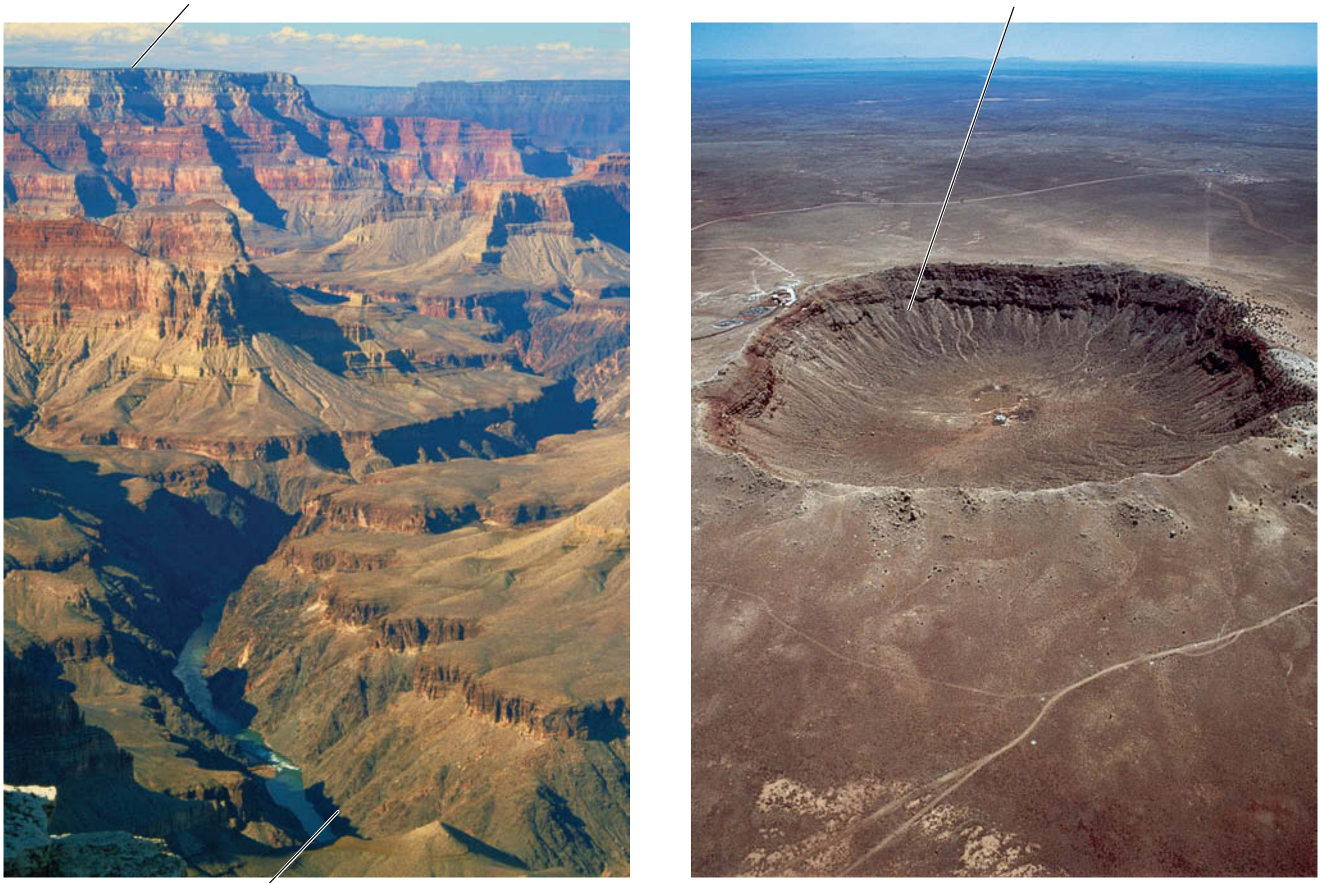
The geologic record tells us that, for the most part, the processes we see in action on Earth today have worked in much the same way throughout the geologic past. This important concept is known as the **principle of uniformitarianism.** It was stated as a scientific hypothesis in the eighteenth century by a Scottish physician and geologist, James Hutton. In 1830, the British geologist Charles Lyell summarized the concept in a memorable line: "The present is the key to the past."

The principle of uniformitarianism does not mean that all geologic phenomena proceed at the same gradual pace. Some of the most important geologic processes happen as sudden events. A large meteorite that impacts Earth can gouge out a vast crater in a matter of seconds. A volcano can blow its top, and a fault can rupture the ground in an earthquake, almost as quickly. Other processes do occur much more slowly. Millions of years are required for continents to drift apart, for mountains to be raised and eroded, and for river systems to deposit thick layers of sediments. Geologic processes take place over a tremendous range of scales in both space and time (**Figure 1.7**).

Nor does the principle of uniformitarianism mean that we have to observe a geologic event to know that it is important in the current Earth system. Humans have not witnessed a large meteorite impact in recorded history, but we know these impacts have occurred many times in the geologic past and will certainly happen again. The same

Over millions of years, layers of sediments built up over the oldest rocks. The most recent layer—the top—is about 250 million years old.

About 50,000 years ago, the explosive impact of a meteorite (perhaps weighing 300,000 tons) created this 1.2-km-wide crater in just a few seconds.



(a) The rocks at the bottom of the Grand Canyon are 1.7–2.0 billion years old.

(b)

FIGURE 1.7 ■ Some geologic processes take place over thousands of centuries, while others occur with dazzling speed. (a) The Grand Canyon, Arizona. (b) Meteor Crater, Arizona. [(a) John Wang/PhotoDisc/Getty Images; (b) John Sanford/Science Source.]

can be said of the vast volcanic outpourings that have covered areas bigger than Texas with lava and poisoned the global atmosphere with volcanic gases. The long history of Earth is punctuated by many such extreme, though infrequent, events that result in rapid changes in the Earth system. Geology is the study of *extreme events* as well as gradual change.

From Hutton's day onward, geologists have observed nature at work and used the principle of uniformitarianism to interpret features found in rock formations. This approach has been very successful. However, Hutton's principle is too confining for geologic science as it is now practiced. Modern geology must deal with the entire range of Earth's history, which began more than 4.5 billion years ago. As we will see in Chapter 9, the violent processes that shaped Earth's early history were distinctly different from those that operate today. To understand that history, we will need some information about Earth's shape and surface, as well as its deep interior.

■ Earth's Shape and Surface

The scientific method has its roots in **geodesy,** a very old branch of Earth science that studies Earth's shape and surface. The concept that Earth is spherical rather than flat was advanced by Greek and Indian philosophers around the sixth century B.C., and it was the basis of Aristotle's theory of Earth put forward in his famous treatise, *Meteorologica,* published around 330 B.C. (the first Earth science

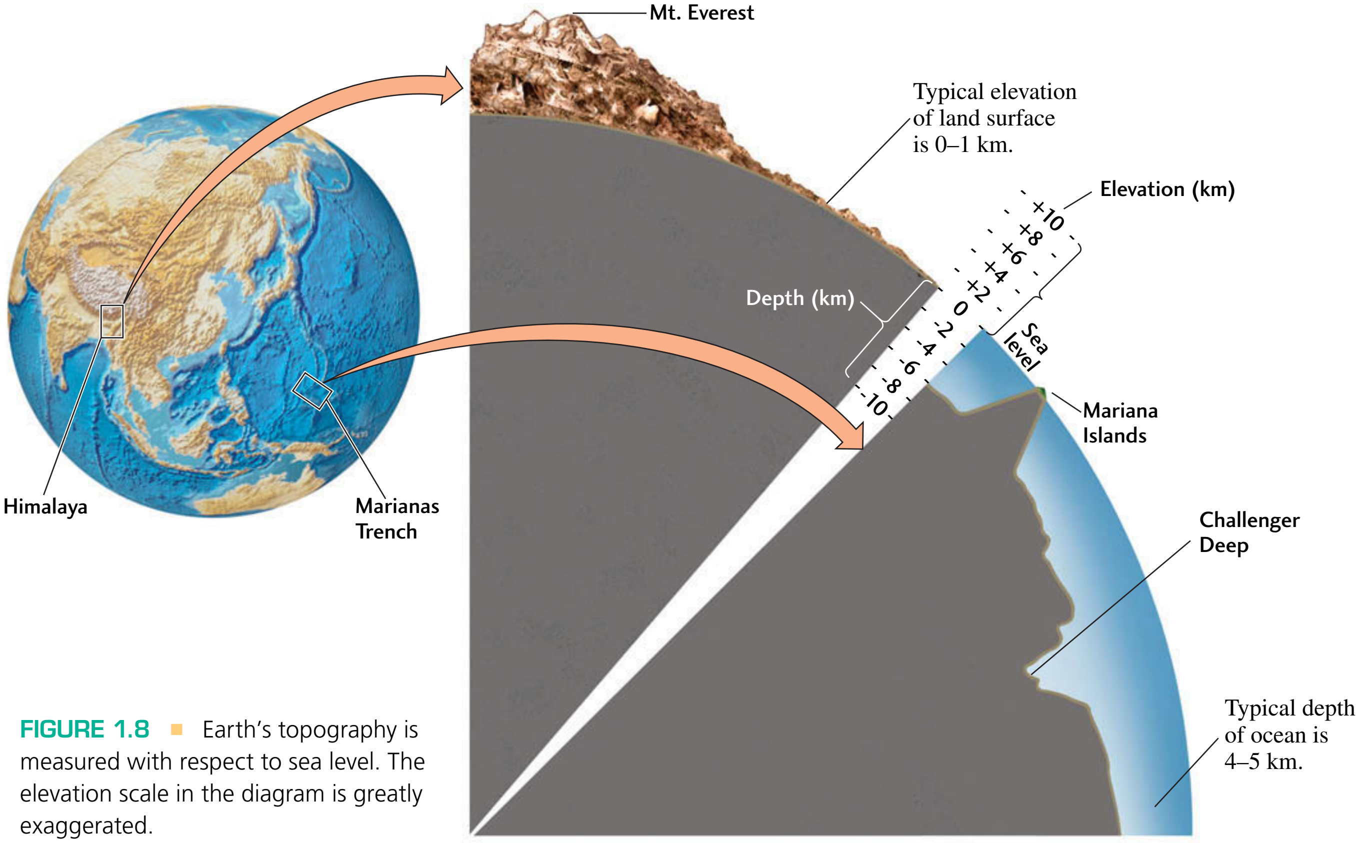


FIGURE 1.8 ▪ Earth's topography is measured with respect to sea level. The elevation scale in the diagram is greatly exaggerated.

textbook!). In the third century B.C., Eratosthenes used a clever experiment to measure Earth's radius, which turned out to be 6370 km (see the Practicing Geology exercise at the end of the chapter).

Much more precise measurements have shown that Earth is not a perfect sphere. Because of its daily rotation, it bulges out slightly at its equator and is slightly squashed at its poles. In addition, the smooth curvature of Earth's surface is broken by mountains and valleys and other ups and downs. This **topography** is measured with respect to *sea level,* a smooth surface set at the average level of ocean water that conforms closely to the squashed spherical shape expected for the rotating Earth. Many features of geologic significance stand out in Earth's topography (**Figure 1.8**). Its two largest features are continents, which have typical elevations of 0 to 1 km above sea level, and ocean basins, which have typical depths of 4 to 5 km below sea level. The elevation of Earth's surface varies by nearly 20 km from its highest point (Mount Everest in the Himalaya at 8850 m above sea level) to its lowest point (Challenger Deep in the Marianas Trench in the Pacific Ocean at 11,030 m below sea level). Although the Himalaya may loom large to us, their elevation is a small fraction of Earth's radius, only about one part in a thousand, which is why the globe looks like a smooth sphere when seen from outer space.

▪ Peeling the Onion: Discovery of a Layered Earth

Ancient thinkers divided the universe into two parts, the heavens above and Hades below. The sky was transparent and full of light, and they could directly observe its stars and track its wandering planets. But Earth's interior was dark and closed to human view. In some places, the ground quaked and erupted hot lava. Surely something terrible was going on down there!

So it remained until about a century ago, when geologists began to peer downward into Earth's interior, not with waves of light (which cannot penetrate rock), but with waves produced by earthquakes. An earthquake occurs when geologic forces cause brittle rocks to fracture, sending out vibrations like the cracking of ice on a river. These **seismic waves** (from the Greek word for earthquake, *seismos*), when recorded on sensitive instruments called *seismometers,* allow geologists to locate earthquakes and also to make pictures of Earth's inner workings, much as doctors use ultrasound and CAT scans to image the inside of your body. When the first networks of seismographs were installed around the world at the end of the nineteenth century, geologists began to discover that