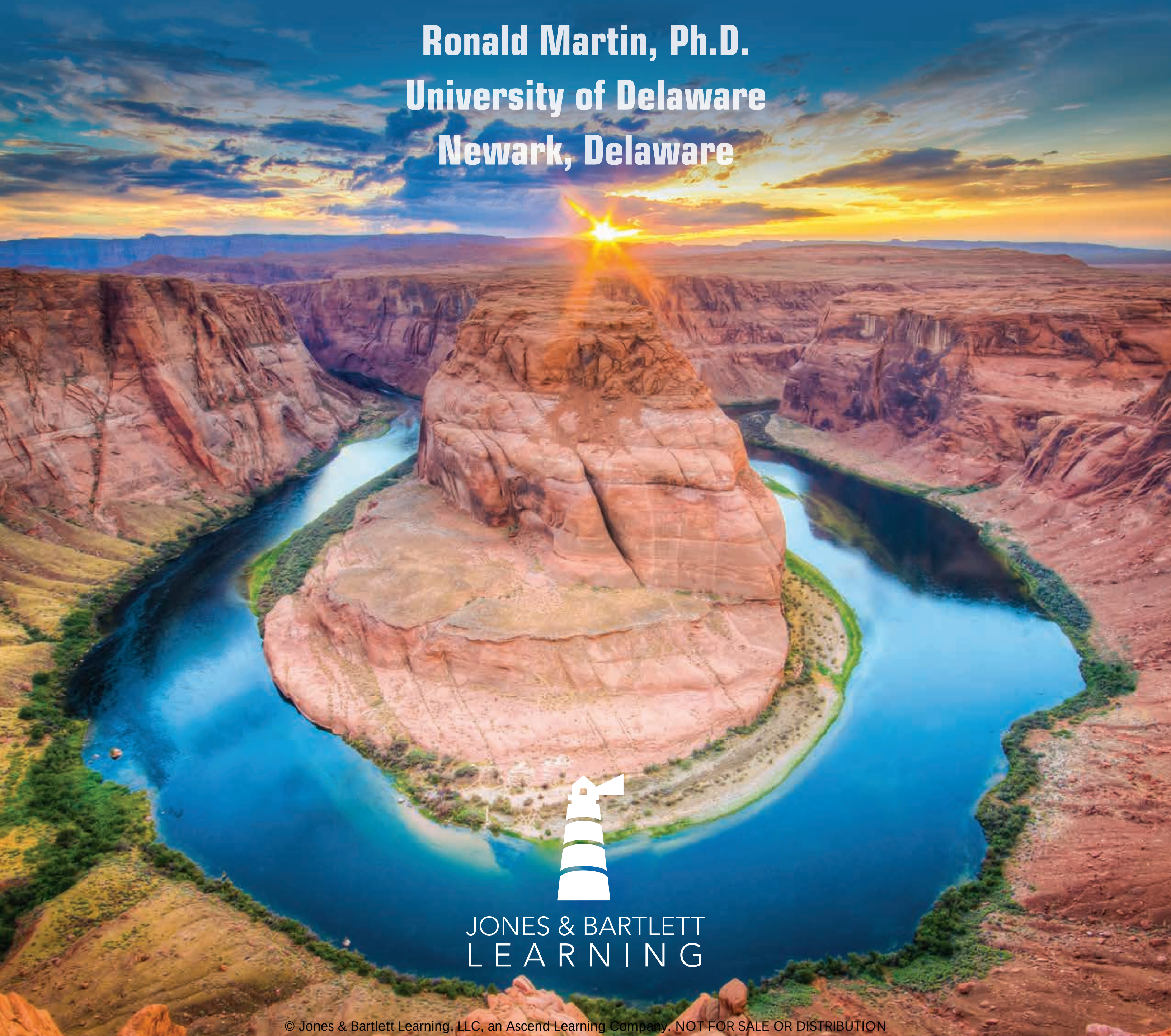
SECOND EDITION

Earth's Evolving Systems

The History of Planet Earth

Ronald Martin, Ph.D.
University of Delaware
Newark, Delaware



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Jones & Bartlett Learning
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Burlington, MA 01803
978-443-5000
info@jblearning.com
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DEDICATION

This book is again dedicated to the late Dr. Allan Thompson (Department of Geological Sciences, University of Delaware), who did not shrink from learning something new and then teaching it. And to all those instructors who, like Al did, teach about the importance of the science of geology by transporting students to the other-worlds of Earth recorded in the rocks of geologic time.

BRIEF CONTENTS

CONTENTS

PREFACE TO THE SECOND EDITION: FOR THE INSTRUCTOR AND STUDENT

As the title indicates, *Earth's Evolving Systems* attempts to bridge the gap between traditional historical geology texts and the study of Earth's systems. The response to the first edition of *Earth's Evolving Systems* has been quite gratifying, especially given the recent emphasis by a National Science Foundation–sponsored webinar by the American Geophysical Union and American Geological Institute in October 2015 entitled "Geoscience Workforce and the Future of Undergraduate Geoscience Education." The respondents to this webinar emphasized at the outset the complex, dynamic linkages among Earth's systems, the role of "deep time" (and thus the role of the scale of time in understanding process), the origin and evolution of life, climate change, and energy resources. All of these topics were emphasized in the first edition of *Earth's Evolving Systems* and continue to be emphasized in the second.

Nevertheless, there is always room for improvement, and I have attempted to respond positively to reviewers' comments on the first edition. This has of course involved some compromises, given each instructor's approach to his or her particular course and research and teaching interests. Chapters have been updated with information on significant advances that have been reported in the literature over the past several years. Themes stated at the beginning of each chapter are now restated or rephrased, in some cases as "big concept" questions, which are highlighted at relevant points in the text margins of the chapters. As before, each chapter is followed by a summary that provides a detailed overview of the chapter.

The following key points about the second edition are applicable to all chapters:

- As in the first edition, a major theme of the text is the method of multiple working hypotheses and debates, among them the origin of the theory of plate tectonics, the origins of the atmosphere and life, the tectonics of the western United States, human evolution, and the recognition of Milankovitch cycles.
- Discussion and contributions and photos of some major women scientists to the earth sciences, such as Marie Tharp and Lynn Margulis, have been included in the relevant chapters.
- An extensive list of references is provided at the end of each chapter, along with a list of key terms and review questions. In addition, a second set of questions, called "Food for Thought," is provided to stimulate students to think beyond the chapter material.

Part I: Earth Systems: Their Nature and Their Study

Major changes were made to Chapters 1–6 to improve the flow of the material in Part I:

- **Chapter 1**: A brief discussion of Vladimir Vernadsky, the founder of Earth systems science, has been added. The discussion on the nature of historical sciences such as geology has been improved by eliminating Chapter 18 from the first edition and incorporating certain elements of that chapter into Chapter 1.
- **Chapter 2**: As before, much of the discussion of Earth's history revolves around the framework of the tectonic cycle. Plate tectonics has therefore been moved from Chapter 6 to Chapter 2.
- **Chapter 3**: The discussion of the interactions among Earth's systems has been simplified, and the introduction and discussion of specific stable isotopes have been pushed back to the chapters where they are explicitly tied to the geologic record. A new section has been added to this chapter, "How Does the Tectonic Cycle Affect Other Earth Systems?" which describes the effects of the tectonic cycle on sea level, ocean circulation, the hydrologic cycle, and major lithologies.
- **Chapters 5 and 6**: Chapter 5, which presents evolution, remains largely unchanged, but it now precedes Chapter 6, which deals with geologic time and stratigraphy. Discussion of iterative evolution has been moved from Chapter 14 to the section on marine organisms during the Paleogene.

Part II: The Precambrian: Origin and Early Evolution of Earth's Systems

- **Chapter 7**: Chapter content has been updated to reflect the most recent research.
- **Chapter 8**: A few reviewers questioned the relevance of a chapter on the origins of life in an Earth science text. However, I believe that life's origins are among the most fascinating chapters in Earth's history and that this is when the initial, fundamental interactions among all of Earth's systems began to occur. Life has been a geologic force throughout much of Earth's history, as emphasized throughout the text. The study of the interactions between life and Earth therefore serves as a bridge

between the biologic and inorganic worlds. Furthermore, like evolutionary theory, origin of life studies present viable alternatives to Creationism. A new paragraph at the beginning of the chapter now reiterates the rationale for retaining Chapter 8.

- **Chapter 9**: Chapter content has been updated to reflect the most recent research.
- **Chapter 10**: The discussion of the origins of various important fossil phyla has been augmented.

Part III: The Phanerozoic: Toward the Modern World

- **Chapters 11–15**: Chapters on the Phanerozoic continue to use the tectonic cycle as a basic framework for understanding the history of the Earth. Many figures in these chapters have been replaced and sections on various taxa augmented with multiple photos and new artwork.
- **Chapter 15**: The section on human evolution in Chapter 15 has been completely revised and reviewed by two professional paleoanthropologists.

Part IV: Humans and the Environment

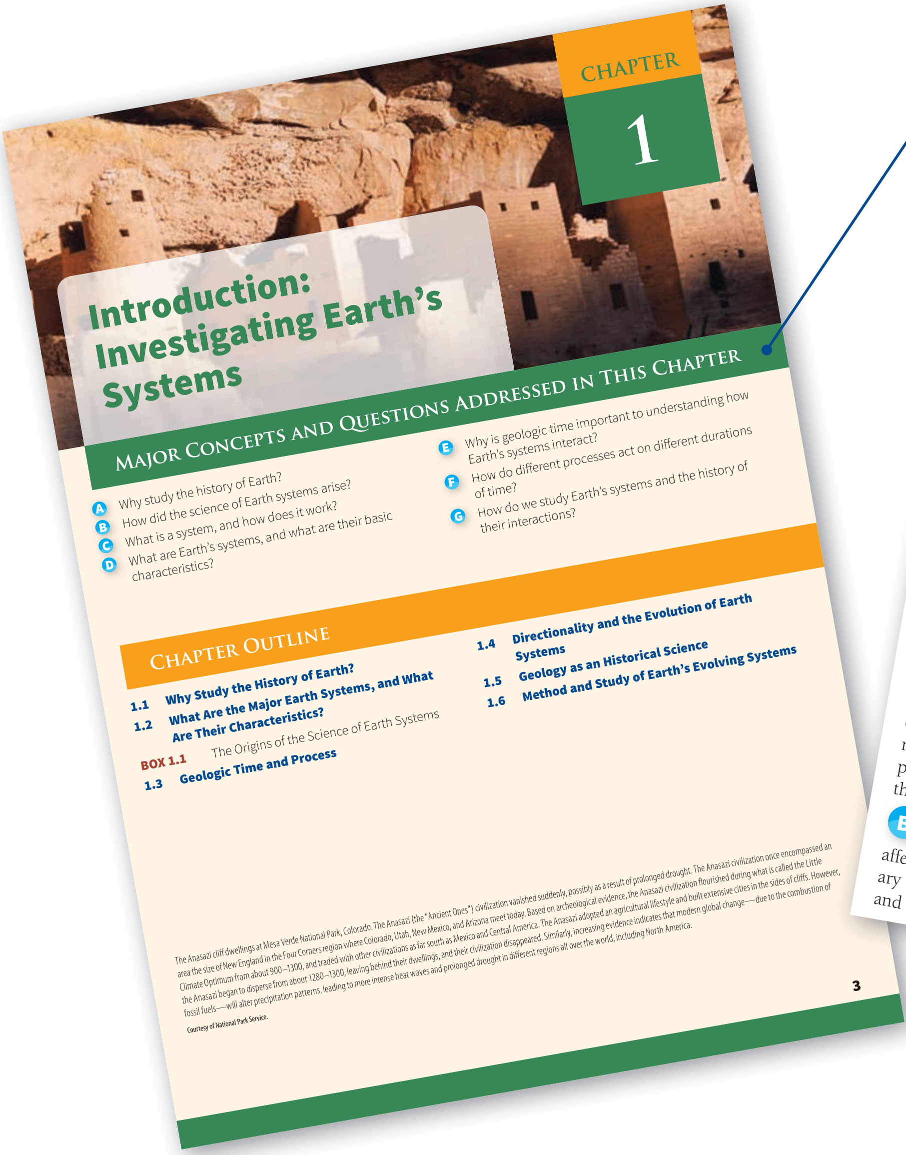
- **Chapter 16**: As before, Chapter 16, which is on rapid climate change, sets the stage for the Gordian knot of natural versus anthropogenic climate change and its sociopolitical implications for future climate and energy resources, which are discussed in Chapter 17.
- **Chapter 17**: As explained in Chapter 1, the initial study of Earth systems was a response to anthropogenic effects. Humans are now a major, if not the most important, geologic force on the planet. The emphasis on the environment and "sustainability" at many academic institutions, including my own, does not diminish the importance of historical sciences, such as geology, in addressing these problems. In fact, the inclusion of chapters on anthropogenic impacts and their potential resolution is a prime opportunity to make historical geology not just an exercise in the "past" but to make it "contemporary" and "relevant" and to potentially awaken students' latent interest in the history of Earth and its lifeforms. Consequently, I have occasionally tied certain portions of Chapters 16 and 17 to examples from the geologic record.

Ron Martin
Newark, Delaware
August 10, 2016

THE STUDENT EXPERIENCE

The second edition of *Earth's Evolving Systems: The History of Planet Earth* was designed with numerous features to create an engaging learning environment for students and to enhance their experience with the text:

- **Major Concepts and Questions Addressed in This Chapter**—Every chapter opens with a list of questions that will be addressed throughout the chapter. Students should review this list prior to digging into the chapter to help guide their focus. The new text design also incorporates icons identifying where in the chapter each concept is addressed to help guide study and review.



CHAPTER 1

Introduction: Investigating Earth's Systems

MAJOR CONCEPTS AND QUESTIONS ADDRESSED IN THIS CHAPTER

A Why study the history of Earth?
B How did the science of Earth systems arise?
C What is a system, and how does it work?
D What are Earth's systems, and what are their basic characteristics?
E Why is geologic time important to understanding how Earth's systems interact?
F How do different processes act on different durations of time?
G How do we study Earth's systems and the history of their interactions?

CHAPTER OUTLINE

1.1 Why Study the History of Earth?
1.2 What Are the Major Earth Systems, and What Are Their Characteristics?
BOX 1.1 The Origins of the Science of Earth Systems
1.3 Geologic Time and Process
1.4 Directionality and the Evolution of Earth Systems
1.5 Geology as an Historical Science
1.6 Method and Study of Earth's Evolving Systems

The Anasazi cliff dwellings at Mesa Verde National Park, Colorado. The Anasazi (the "Ancient Ones") civilization vanished suddenly, possibly as a result of prolonged drought. The Anasazi civilization once encompassed an area the size of New England in the Four Corners region where Colorado, Utah, New Mexico, and Arizona meet today. Based on archeological evidence, the Anasazi civilization flourished during what is called the Little Climate Optimum from about 900–1300, and traded with other civilizations as far south as Mexico and Central America. The Anasazi adopted an agricultural lifestyle and built extensive cities in the sides of cliffs. However, the Anasazi began to disperse from about 1280–1300, leaving behind their dwellings, and their civilization disappeared. Similarly, increasing evidence indicates that modern global change—due to the combustion of fossil fuels—will alter precipitation patterns, leading to more intense heat waves and prolonged drought in different regions all over the world, including North America.

Courtesy of National Park Service.

3

1.1 Why Study the History of Earth?

A *Earth's Evolving Systems* is about the history of the Earth, the natural processes that have shaped it, and the history of these processes and their interactions through vast intervals of time. *Geology* is the science that studies the history of the Earth and its life preserved as fossils.

Why should we be concerned about Earth's history? Because understanding how the Earth changes and has changed tells us about how natural processes affect humans and how humans affect natural processes. The history of the Earth confronts us with events and possibilities that we cannot imagine. Many natural processes act so slowly we would be unaware of them except for the geologic record of their activities preserved by rocks and fossils. Most people are unaware that Earth's environments are constantly changing. We assume that landscapes—mountains, valleys, rivers and streams, and coasts—do not change because the changes are typically so slow and subtle they take place over time spans equivalent to many, many human generations; from many millions of years down to millennia and centuries. Also, some processes are so infrequent or sudden, we would not know they occur except, again, to look at the geologic record.

B Scientists have only recently begun to appreciate just how strongly changes in Earth's environments have affected—and still affect—humankind, from our evolutionary beginnings through the origins of ancient settlements and civilizations—and perhaps their collapse—right up to

xv

■ **Featured Boxes**—Many chapters contain boxes providing greater depth on special topics.

BOX 13.3 Late Cretaceous Extinctions and the Scientific Method

Most mass extinctions appear to be somehow related to the tectonic cycle. However, the Late Cretaceous extinctions involved—and may well have resulted primarily from—an impact, as indicated by the occurrence of shocked mineral assemblages (**Box Figure 13.3A**). Whereas the impact hypothesis certainly arouses our imaginations, how the hypothesis came to be widely accepted by the scientific community is also a prime example of how scientific investigation works (see Chapter 1). Moreover, the corroboration of the hypothesis paved the way for the acceptance of extraterrestrial impacts as important—even extraordinary—agents of geologic, climatic, and biospheric change. It also radically altered—once and for all—earth scientists unquestioned acceptance of Lyell's dogma of slow, gradual change to a broader doctrine that recognized that Earth systems processes vary through time and in rate (see Chapter 1).

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BOX FIGURE 13.3A An artist's visualization of the impact of an asteroid with Earth.

Initially, a dark sedimentary layer containing a high concentration of the element iridium was found near Gubbio, Italy, almost by accident (see Chapter 1). The iridium layer also occurred at the time of the mass extinction at the end of the Cretaceous Period about 65 million years ago, during which dinosaurs and many other organisms became extinct. Iridium is not normally found in rocks of Earth's crust and could have come from only two sources: volcanoes fed by the mantle, which is enriched in iridium, or from an extraterrestrial body. The hypothesis was that the iridium layer was generated by a meteor enriched in iridium. The impact presumably threw a gigantic dust cloud into Earth's stratosphere that suddenly cooled the planet, causing extinction; the blockage of sunlight also shut down marine photosynthesis causing a **Strangelove Ocean** (named after the character of the same name in a famous movie) in which there was a sudden, strong shift in carbon isotope ratios to much lower values (see Chapter 9; **Box Figure 13.3B**).

A prediction made from the hypothesis was that if an impact were responsible for the Late Cretaceous extinctions, an iridium layer should be found all over the world in rocks of exactly the same age. Scientists tested the hypothesis by exploring for the iridium layer all over the world, on land and in deep-sea cores, where the rocks were of the right age. The hypothesis was corroborated: the Late Cretaceous iridium layer is now known not only from Gubbio, Italy, but also from Stevns Klint (Steven's Cliff) near Copenhagen, Denmark; El Kef, Tunisia, in north Africa; and El Mimbral, Mexico (to name only a few of the more famous and intensively studied localities), as well as in many deep-sea cores (see Box Figure 13.3B).

■ **Concept and Reasoning Checks**—As students progress through the chapter they will encounter these questions, which will encourage them to pause and assess their grasp of the material.

CONCEPT AND REASONING CHECKS

1. Diagram the hydrologic cycle.
2. How are the hydrologic cycle and atmospheric circulation related?
3. What drives surface ocean circulation?
4. What causes the deep oceans to circulate?
5. How do the oceans influence Earth's albedo?

CONCEPT AND REASONING CHECKS

1. What is the evidence for the solar nebula hypothesis as opposed to the original Kant-Laplace hypothesis?
2. How do the inner planets, including Earth, differ from the outer planets?
3. Why might carbonaceous chondrites have been an important source of water for early Earth?

CONCEPT AND REASONING CHECKS

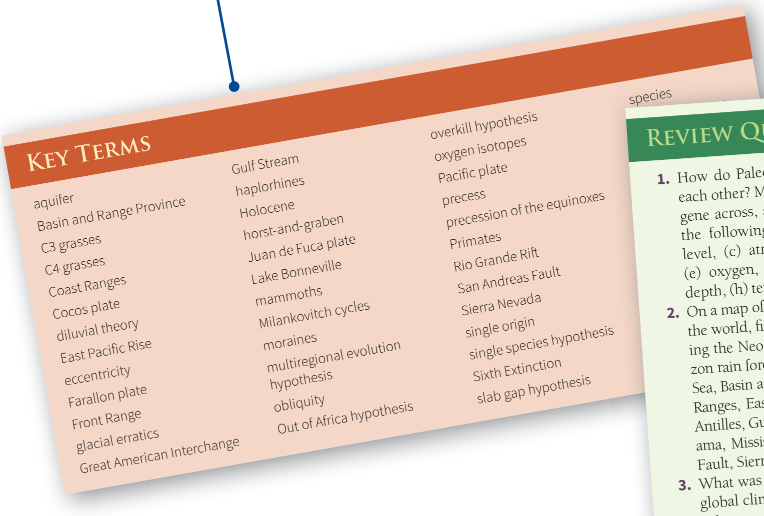
1. Volcanism has been implicated in several mass extinctions. Which ones?
2. Diagram the test of a meteor impact as the causal agent of the Late Cretaceous mass extinction in terms of the scientific method diagrammed in Chapter 1 (see Box 13.3).

■ **Summaries**—Each chapter concludes with a bulleted list of the key concepts addressed in the chapter.

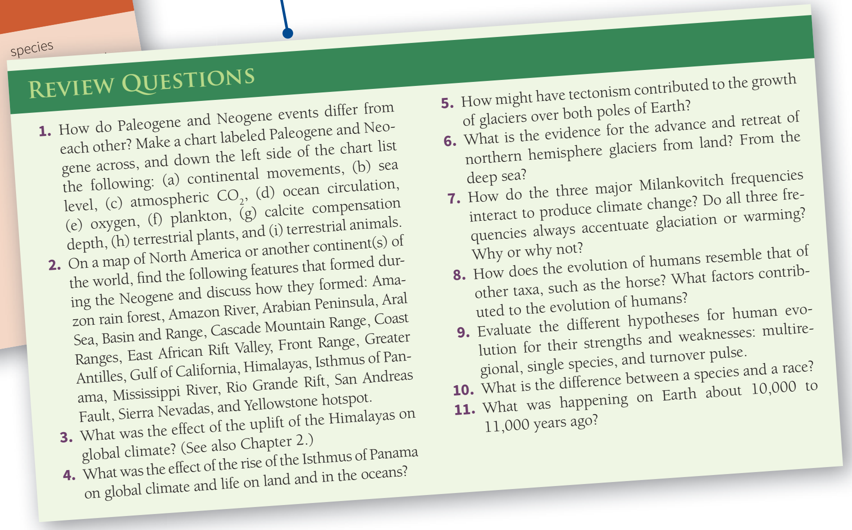
SUMMARY

- The theory of plate tectonics really began with early ideas about orogenesis, or mountain building. Hypotheses and theories of mountain building changed radically over the past two centuries, and their development is a prime example of how scientists work and think.
- The discovery of radioactivity led to more modern theories of mountain building. Of these, it is Alfred Wegener's hypothesis of continental drift—based on a variety of evidence—that paved the way for the modern theory of plate tectonics. Initially, Wegener's hypothesis was roundly criticized because he could not identify a mechanism to make continents drift. Consequently, continents (or at least many geologists' minds) remained "fixed" until the work of Harry Hess in the 1950s, which proposed the process of seafloor spreading as a mechanism to move continents.
- In the 1960s, the detection of magnetic seafloor stripes corroborated seafloor spreading and provided the mechanism of continental drift that had eluded Wegener. Seafloor spreading also corroborated Hess's views about the formation of guyots, heat flow beneath mid-ocean ridges, and the destruction of seafloor in trenches. Rearranging the continents into different positions also began to make sense of apparent polar wandering curves.
- Consequently, what had been known as continental drift was wedded to seafloor spreading to produce the theory of plate tectonics.
- Today, plate tectonics is recognized as an integral component of Earth's systems. We know that Earth's lithosphere (the crust and uppermost mantle) consists of about 15 large and small plates that are moved by the production of new seafloor at mid-ocean ridges. Forming portions of the plates are continents. The plates move over the asthenosphere of the mantle. Beneath the mantle are an outer fluid and a solid inner iron and nickel-rich core that generate Earth's magnetic field.
- Although convection cells are widely viewed as moving the plates, several hypotheses have been proposed to explain how the seafloor actually moves: (1) slab-pull, in which a descending slab pulls the rest of slab behind it downward; (2) ridge-push, in newly formed ocean crust as spreading centers pushes the slab ahead of it; (3) gravity slide, in which a slab slowly "slides" down the side of a spreading center, pushing the slab ahead of it; and (4) suction from the descending portion of a plate.
- Based on plate tectonics, different features of the planet can be arranged into a sequence of stages called the tectonic cycle: East African Rift Valley, Red Sea, Atlantic Ocean, Pacific Ocean, and suture (Himalayas). Not all rift valleys become seaways, however; many have become failed rift valleys or aulacogens, down which some of the world's major rivers such as the Amazon flow. The tectonic cycle has occurred a number of times during Earth's history, each cycle spanning several hundred million years.
- Based on the tectonic cycle, continental margins and plate boundaries can change through time. There are two basic types of continental margins: active and passive. Passive continental margins, like those along the Atlantic Ocean, accumulate sediment along their margins. Active margins, like those along the Pacific Ocean's ring of fire, are sites of subduction, volcanism, and earthquakes.
- Plate boundaries are classified into three basic categories: convergent (associated with sea floor trenches), divergent (associated with rifting), and transform, which are associated with offsets of mid-ocean ridges.
- Convergent boundaries are themselves of three types: volcanic island arc (for example, Japan), continental island arc (for example, the Cascades), and collisional (Himalayas).
- The three types of convergent plate boundaries parallel the different types of orogenesis and the formation of major geologic structures such as faults and folds: island arcs only, plate collisions without continents, and continent–continent collisions.
- As orogenesis occurs, smaller pieces of crust with distinctive geologic features (rock type, fossils, paleomagnetic directions) called microcontinents or exotic terranes can be sandwiched between the larger continents.
- No one has ever observed the tectonic cycle because of the immense amounts of geologic time involved in its completion, but it can be pieced together based on observations of modern tectonic settings.

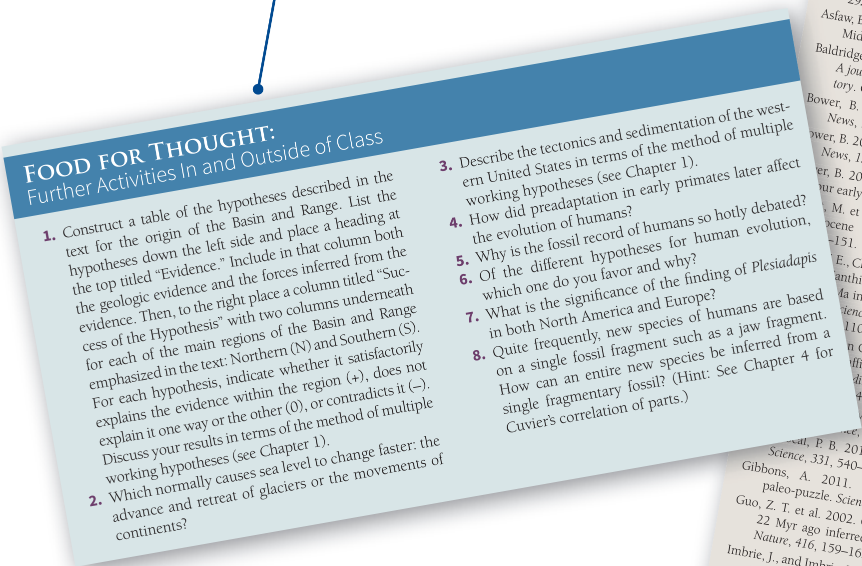
- **Key Terms List**—A list of the key terms from each chapter is provided to help students review new vocabulary.



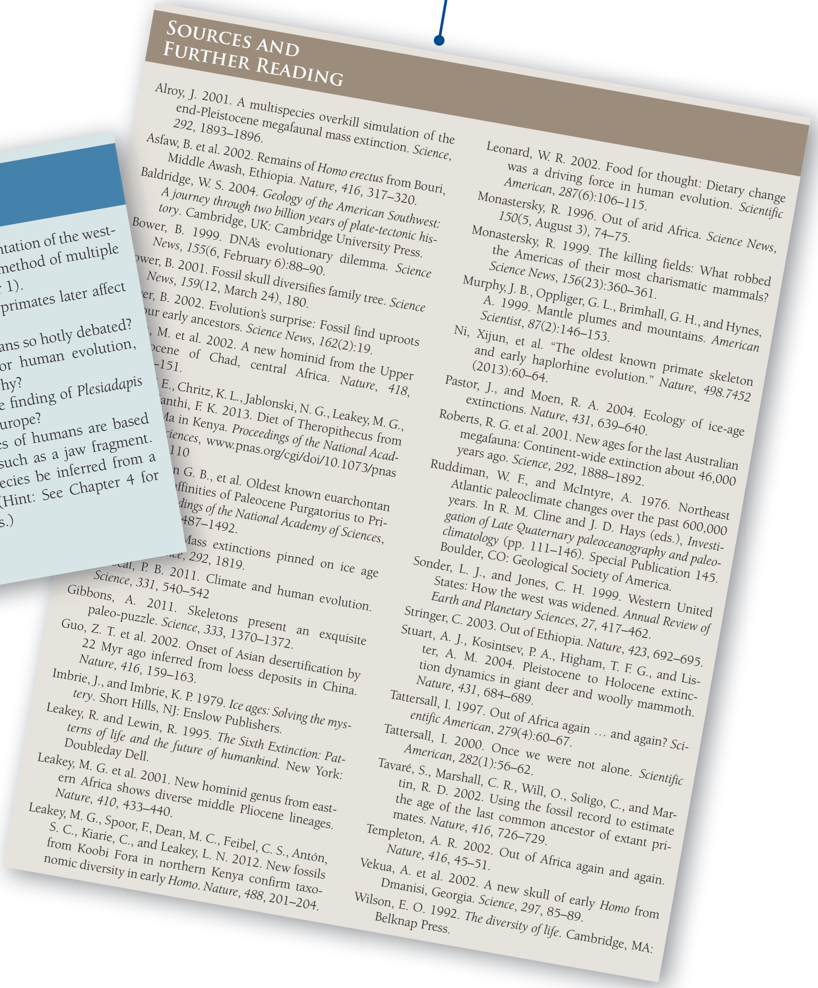
- **Review Questions**—These end-of-chapter questions are great for homework assignments or self-guided study.



- **Food for Thought**—More in-depth than the Review Questions, the Food for Thought activities are great for individual or group assignments in or out of the classroom. They will challenge students to think critically about the material presented in the chapter.



- **Sources and Further Reading**—The list of references for the chapter is a great place for students to begin additional research into special topics.



- **New and Revised Art and Photos**—The art in this second edition, including over 150 new images and 150 revised illustrations, has been significantly improved to support students as they absorb new information.

TABLE 7.1 Major features of the planets

	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Diameter (km)	4,878	12,104	12,756	6,794	142,800	120,540	51,200	49,500
Diameter in relation to Earth	38%	95%	X	53%	1,120%	941%	401%	388%
Mass in relation to Earth	5.5%	82%	X	10.7%	31,780%	9,430%	1,460%	1,720%
Density (g/cm³)	5.43	5.24	5.52	3.9	1.3	0.7	1.2	1.6
Rotation period (days)	58.6	−243	0.997	1.026	0.41	0.43	−0.72	0.67
Inclination of axis of rotation to equator (degrees)	0.0	177.4	23.4	25.2	3.1	26.7	97.9	29
Surface gravity in relation to Earth	38%	91%	X	38%	253%	107%	92%	118%

AU = astronomical unit, or the distance between the Earth and sun.

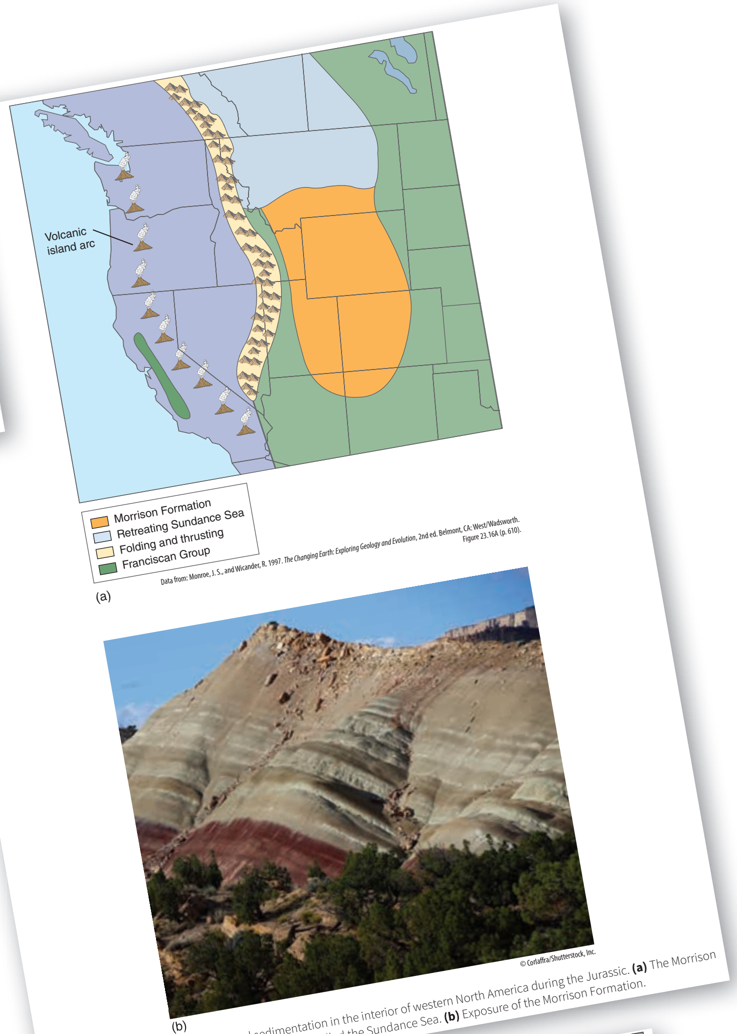


FIGURE 13.17 Seaways, tectonics, and sedimentation in the interior of western North America during the Jurassic. **(a)** The Morrison Formation, which is molasse shed from the west that filled the Sundance Sea. **(b)** Exposure of the Morrison Formation.

FIGURE 2.20 **(a)** Cross section of highly-folded thrust sheets in the Alps. The huge blocks of rocks that have been thrust over younger rocks are called nappes. **(b)** Photo of the Alps showing extensive folding.

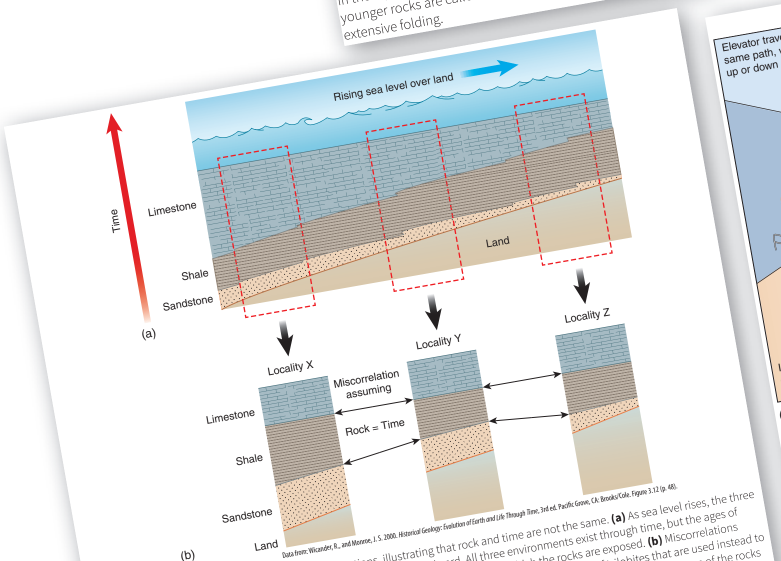


FIGURE 6.9 The difference between facies and formations, illustrating that rock and time are not the same. **(a)** As sea level rises, the three formations represented by sandstone, shale, and limestone, move landward. All three environments exist through time, but the ages of each of the types of rocks, which are recognized as formations, differs over the area in which the rocks are exposed. **(b)** Miscorrelations result if rock and time are considered equal (arrows). The red and orange dots represent the extinctions of trilobites that are used instead to produce more accurate time lines for correlation (see section "6.5.3 Biostratigraphy" for further discussion). Note how the ages of the rocks are not the same between the localities, even within the same formation.

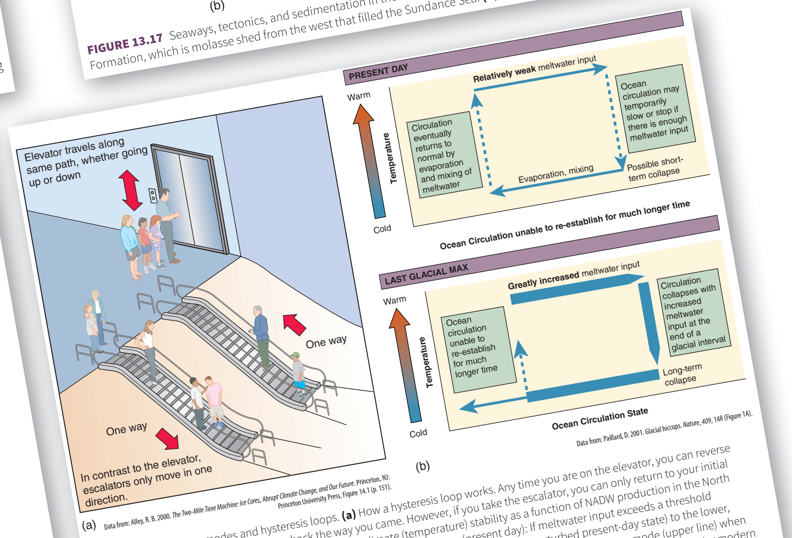
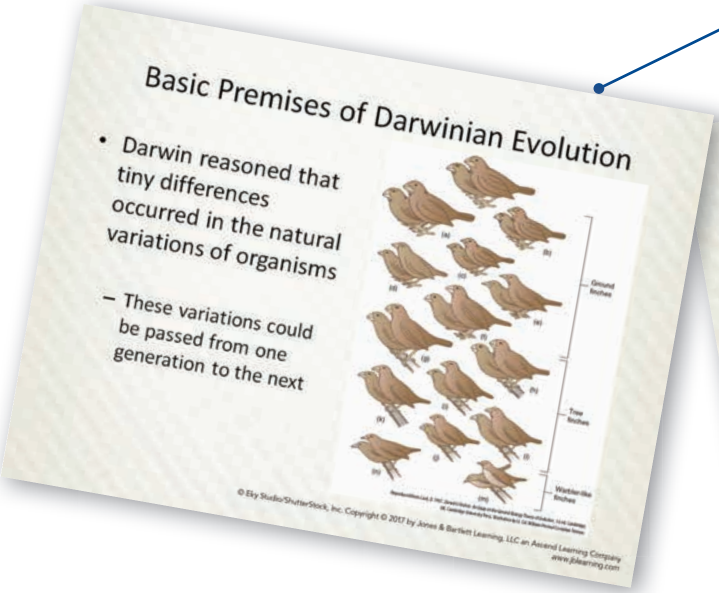


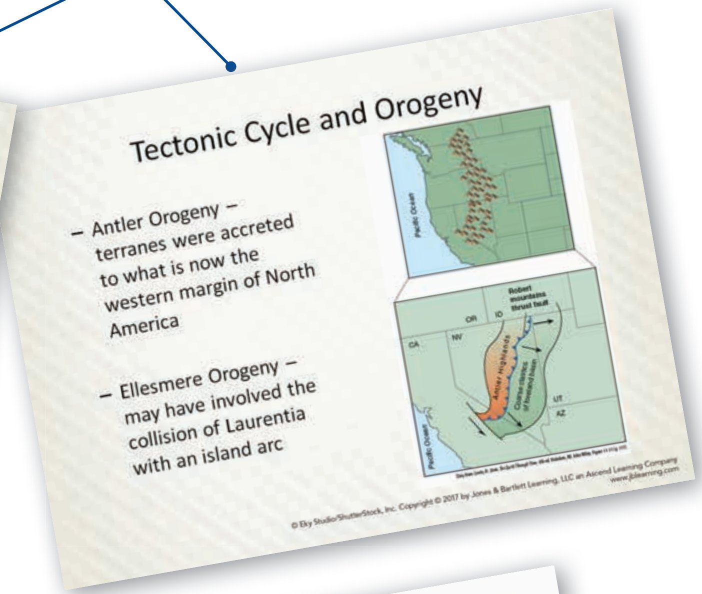
FIGURE 16.19 Climate modes and hysteresis loops. **(a)** How a hysteresis loop works. Any time you are on the elevator, you can reverse direction pretty much at any point and go back the way you came. However, if you take the escalator, you can only return to your initial position by a new path, as shown. **(b)** Hysteresis loop for climate (temperature) stability as a function of NADW production in the North Atlantic Ocean. The modern North Atlantic has two basic climate modes. Top (present day): If meltwater input exceeds a threshold value, ocean circulation jumps (dashed line pointing down) from the upper warm mode (unperturbed present-day state) to the lower, colder mode (solid blue line), where NADW slows. Climate can only return (dashed line pointing up) to the warm mode (upper line) when meltwater has mixed or evaporated sufficiently. Note that both of these more moderate warm and cold modes could occur under modern conditions. Bottom (last glacial maximum): Like the escalators in part A, it takes a much larger disturbance like a large influx of meltwater to shut down modern NADW formation for longer periods of time. This is presumably what happened during glacial intervals when much greater volumes of meltwater would have been released.

TEACHING TOOLS

A variety of Teaching Tools are available for qualified instructors to assist with preparing for and teaching their courses. These resources are accessible via digital download and multiple other formats:

- **Lecture Outlines in PowerPoint format**—The *Lecture Outlines in PowerPoint format* provide lecture notes and images for each chapter of *Earth's Evolving Systems: The History of Planet Earth*, *Second Edition*. Instructors with Microsoft PowerPoint can customize the outlines, art, and order of presentation and add their own material.





- **Key Image Review**—The *Key Image Review* provides the illustrations, photographs, and tables to which Jones & Bartlett Learning holds the copyright or has permission to reprint digitally. These images are not for sale or distribution but may be used to enhance your existing slides, tests, and quizzes or other classroom material.

- **Test Bank Material**—The author has provided 500+ multiple-choice questions, including true-false, matching, and identifications. Each chapter has approximately 30 to 40 questions. The author of this text has used some—but certainly not all—of these questions in his introductory course. Many questions ask for basic factual information, others are intended to make students "think about it." In some cases, essentially the same questions are worded differently. Alternative wordings and answers are suggested for some questions. Some questions refer to specific figures in the text. Instructors are welcome to modify the questions as they see fit. Short and long essay questions can be developed from the Review Questions and Food for Thought exercises at the end of each chapter and the Concept and Reasoning Checks embedded throughout. These could be used in smaller classes as writing assignments. Students could be assigned the questions ahead of time or given a list to choose from. These questions are available as an instructor download.
- **Instructor's Manual**—An Instructor's Manual containing an instructor's overview, instructional aids, answers to Review and Food for Thought questions, and suggestions for homework or in-class projects and assignments is available for each chapter.

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Jill Mignery, Miami University
Donald Neal, East Carolina University
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Ronald Martin
Newark, Delaware

ABOUT THE AUTHOR

Ron Martin is Professor of Geological Sciences at the University of Delaware. He grew up in southwestern Ohio, where world famous assemblages of Late Ordovician fossils drew his attention to paleontology. He received a B.S. degree in Geology and Paleontology from Bowling Green State University (Ohio), M.S. in Geology from the University of Florida, and Ph.D. in Zoology from the University of California at Berkeley. He worked as an operations micropaleontologist and biostratigrapher for Unocal in Houston (Texas) from 1981–1985 before coming to the University of Delaware. He has taught introductory courses in physical geology and Earth history (upon which *Earth's Evolving Systems* is based), Paleontology, Paleoecology, Sedimentology, and Stratigraphy, and Advanced (Sequence) Stratigraphy, among others and he has been nominated several times for the university-wide Best Teacher Award. His research interests include the taphonomy (preservation) and biostratigraphy of microfossil assemblages and, most recently, the role of phytoplankton evolution in the diversification of the marine biosphere. He is the author or co-author of more than 60 papers; in addition to *Earth's Evolving Systems*, he has also authored *One Long Experiment: Scale and Process in Earth History* (Columbia University Press) and *Taphonomy: A Process Approach* (Cambridge University Press) and edited *Environmental Micropaleontology: The Application of Microfossils to Environmental Geology* (Kluwer/Plenum Press). He received the Best Paper Award in 1996 from the journal *Palaios* for "Secular Increase in Nutrient Levels Through the Phanerozoic: Implications for Productivity, Biomass, and Diversity of the Marine Biosphere"; his work was also featured as the cover article in the June (2013) issue of *Scientific American*: "Tiny Engines of Evolution," which was translated into French, German, Spanish, and Japanese sister publications. He is past president of the North American Micropaleontology Section of the Society of Sedimentary Geology, former Editor of the *Journal of Foraminiferal Research,* and Associate Editor of *Palaios*. He was Visiting Professor at the Université de Lille (France) in 2014.