SECOND EDITION

Earth's Evolving Systems

The History of Planet Earth

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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

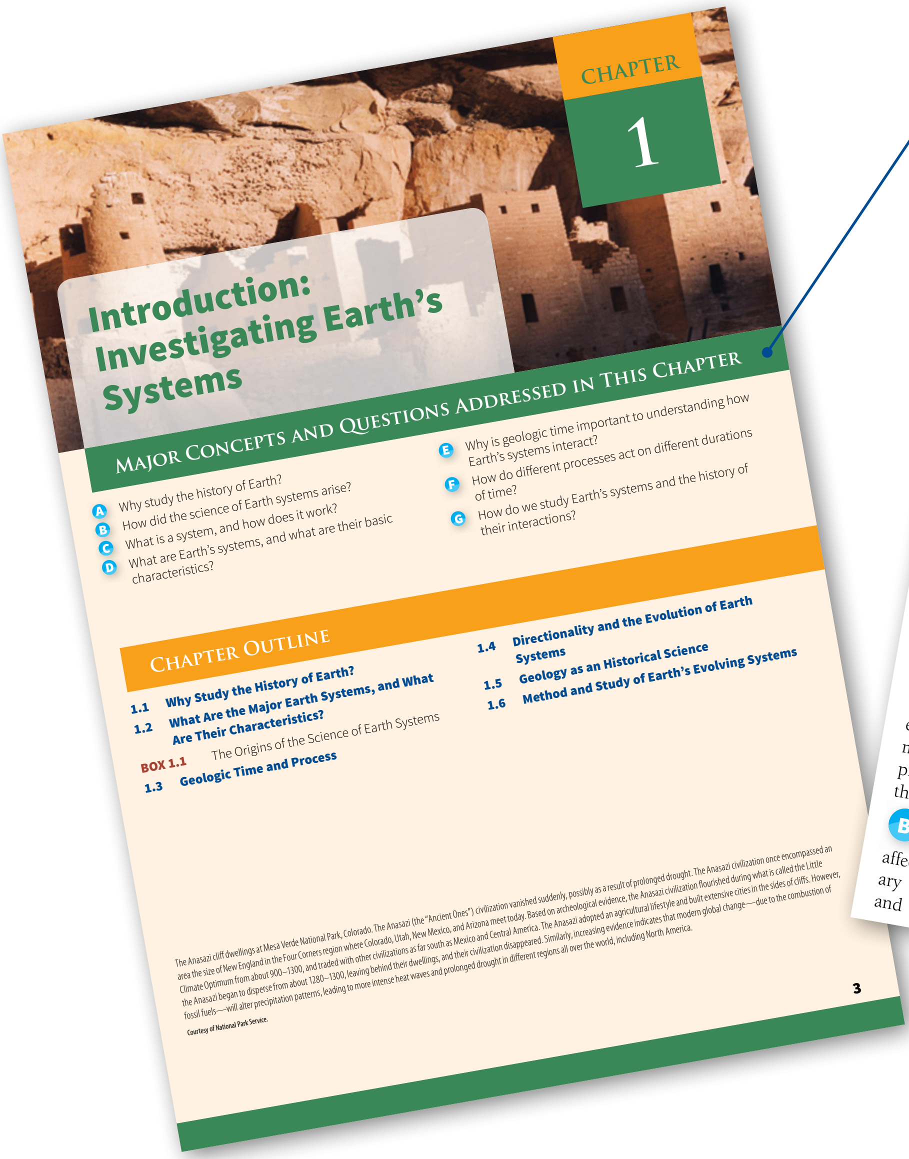
- **Chapter 16**: As before, Chapter 16, which is on rapid climate change, sets the stage for the Gordian knot of natural versus anthropogenic climate change and its sociopolitical implications for future climate and energy resources, which are discussed in Chapter 17.
- **Chapter 17**: As explained 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.

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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

- **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

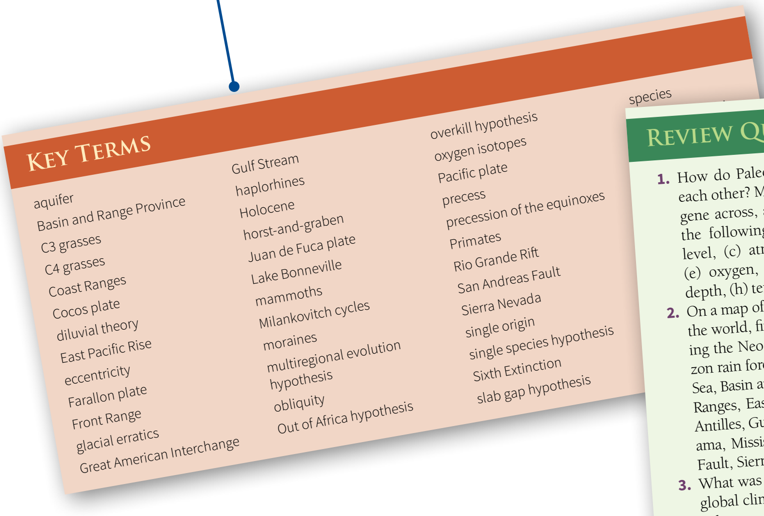
1. Volcanism has been implicated in several mass extinctions. Which ones?
2. Diagram the test of a meteor impact as the causal agent of the Late Cretaceous mass extinction in terms of the scientific method diagrammed in Chapter 1 (see Box 13.3).

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

SUMMARY

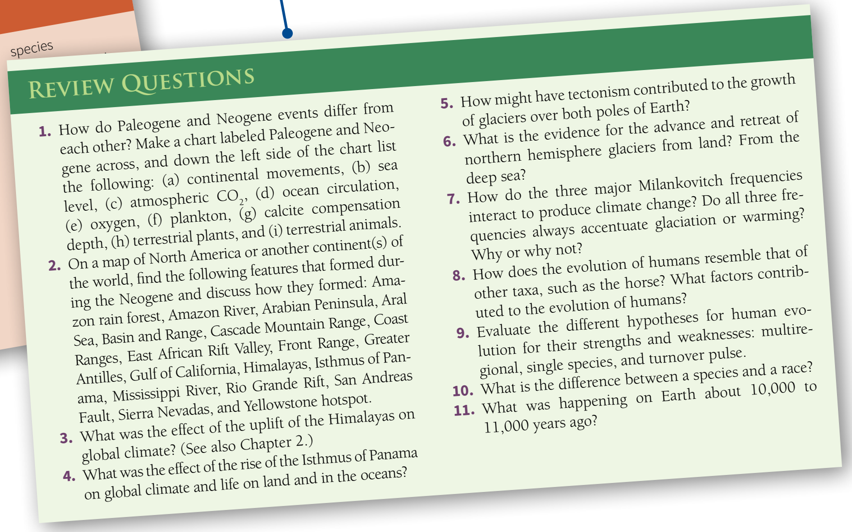
- The theory of plate tectonics really began with early ideas about orogenesis, or mountain building. Hypotheses and theories of mountain building changed radically over the past two centuries, and their development is a prime example of how scientists work and think.
- The discovery of radioactivity 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.


KEY TERMS

aquifer
Basin and Range Province
C3 grasses
C4 grasses
Coast Ranges
Cocos plate
diluvial theory
East Pacific Rise
eccentricity
Farallon plate
Front Range
glacial erratics
Great American Interchange
Gulf Stream
haplorhines
Holocene
horst-and-graben
Juan de Fuca plate
Lake Bonneville
mammoths
Milankovitch cycles
moraines
multiregional evolution hypothesis
obliquity
Out of Africa hypothesis
overkill hypothesis
oxygen isotopes
Pacific plate
precess
precession of the equinoxes
Primates
Rio Grande Rift
San Andreas Fault
Sierra Nevada
single origin
single species hypothesis
Sixth Extinction
slab gap hypothesis
species

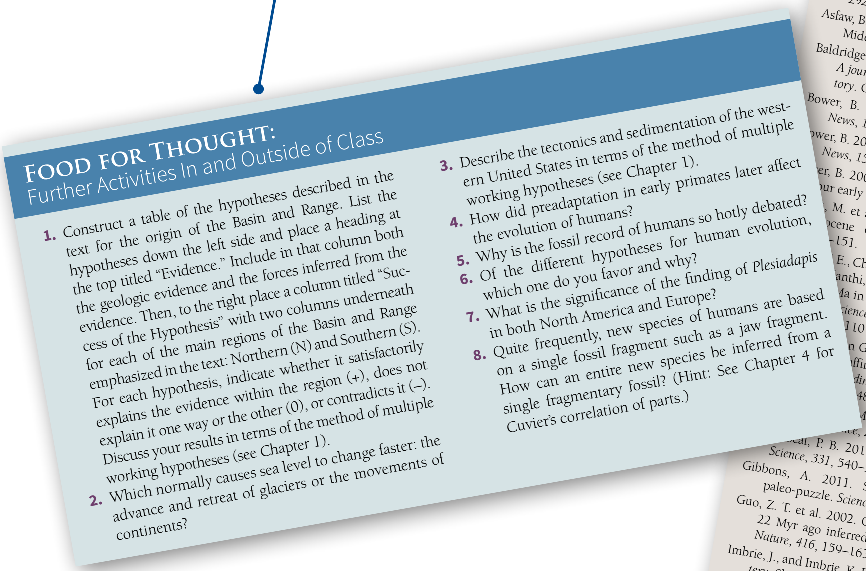
- **Review Questions**—These end-of-chapter questions are great for homework assignments or self-guided study.


REVIEW QUESTIONS

1. How do Paleogene and Neogene events differ from each other? Make a chart labeled Paleogene and Neogene across, and down the left side of the chart list the following: (a) continental movements, (b) sea level, (c) atmospheric CO_2, (d) ocean circulation, (e) oxygen, (f) plankton, (g) calcite compensation depth, (h) terrestrial plants, and (i) terrestrial animals.
2. On a map of North America or another continent(s) of the world, find the following features that formed during the Neogene and discuss how they formed: Amazon rain forest, Amazon River, Arabian Peninsula, Aral Sea, Basin and Range, Cascade Mountain Range, Coast Ranges, East African Rift Valley, Front Range, Greater Antilles, Gulf of California, Himalayas, Isthmus of Panama, Mississippi River, Rio Grande Rift, San Andreas Fault, Sierra Nevadas, and Yellowstone hotspot.
3. What was the effect of the uplift of the Himalayas on global climate? (See also Chapter 2.)
4. What was the effect of the rise of the Isthmus of Panama on global climate and life on land and in the oceans?
5. How might have tectonism contributed to the growth of glaciers over both poles of Earth?
6. What is the evidence for the advance and retreat of northern hemisphere glaciers from land? From the deep sea?
7. How do the three major Milankovitch frequencies interact to produce climate change? Do all three frequencies always accentuate glaciation or warming? Why or why not?
8. How does the evolution of humans resemble that of other taxa, such as the horse? What factors contributed to the evolution of humans?
9. Evaluate the different hypotheses for human evolution for their strengths and weaknesses: multiregional, single species, and turnover pulse.
10. What is the difference between a species and a race?
11. What was happening on Earth about 10,000 to 11,000 years ago?

- **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.


FOOD FOR THOUGHT:
Further Activities In and Outside of Class

1. Construct a table of the hypotheses described in the text for the origin of the Basin and Range. List the hypotheses down the left side and place a heading at the top titled "Evidence." Include in that column both the geologic evidence and the forces inferred from the evidence. Then, to the right place a column titled "Success of the Hypothesis" with two columns underneath for each of the main regions of the Basin and Range emphasized in the text: Northern (N) and Southern (S). For each hypothesis, indicate whether it satisfactorily explains the evidence within the region (+), does not explain it one way or the other (0), or contradicts it (–). Discuss your results in terms of the method of multiple working hypotheses (see Chapter 1).
2. Which normally causes sea level to change faster: the advance and retreat of glaciers or the movements of continents?
3. Describe the tectonics and sedimentation of the western United States in terms of the method of multiple working hypotheses (see Chapter 1).
4. How did preadaptation in early primates later affect the evolution of humans?
5. Why is the fossil record of humans so hotly debated?
6. Of the different hypotheses for human evolution, which one do you favor and why?
7. What is the significance of the finding of *Plesiadapis* in both North America and Europe?
8. Quite frequently, new species of humans are based on a single fossil fragment such as a jaw fragment. How can an entire new species be inferred from a single fragmentary fossil? (Hint: See Chapter 4 for Cuvier's correlation of parts.)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- **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.

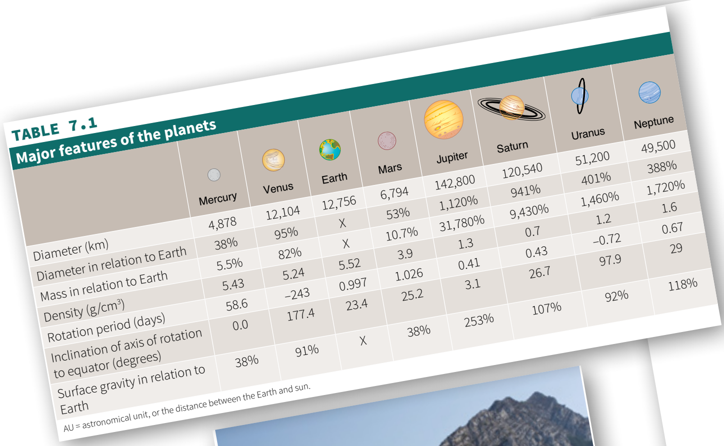


TABLE 7.1
Major features of the planets

	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 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.

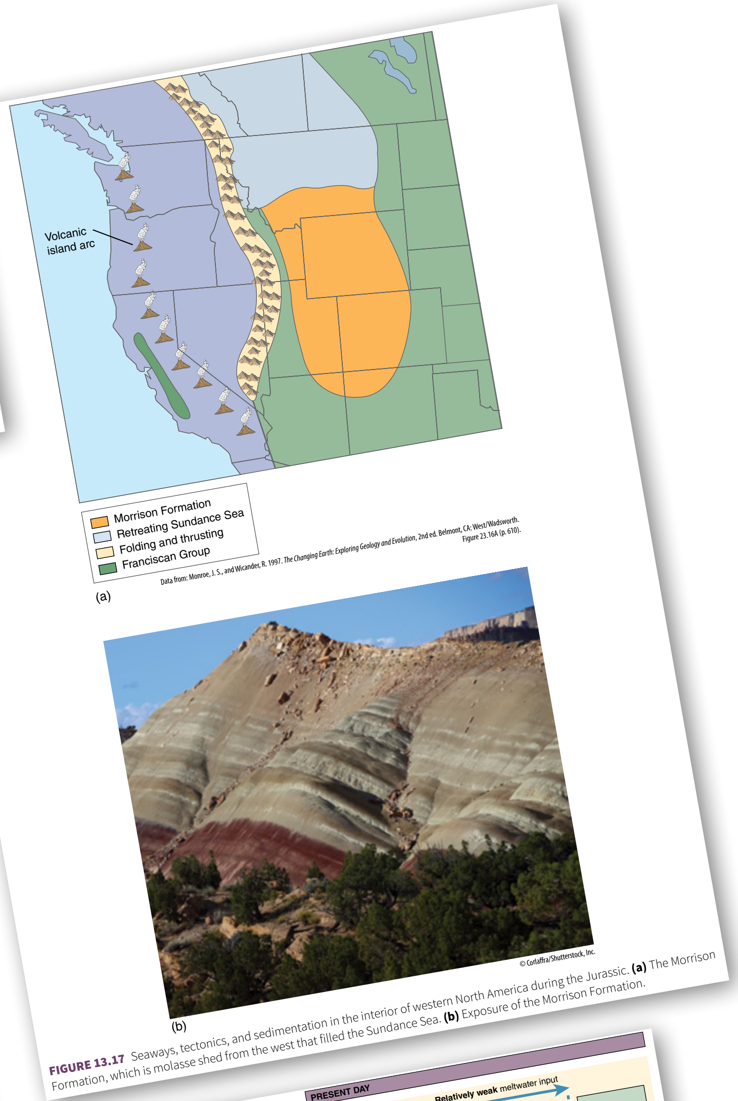


FIGURE 13.17 Seaways, tectonics, and sedimentation in the interior of western North America during the Jurassic. **(a)** The Morrison Formation, which is molasse shed from the west that filled the Sundance Sea. **(b)** Exposure of the Morrison Formation.

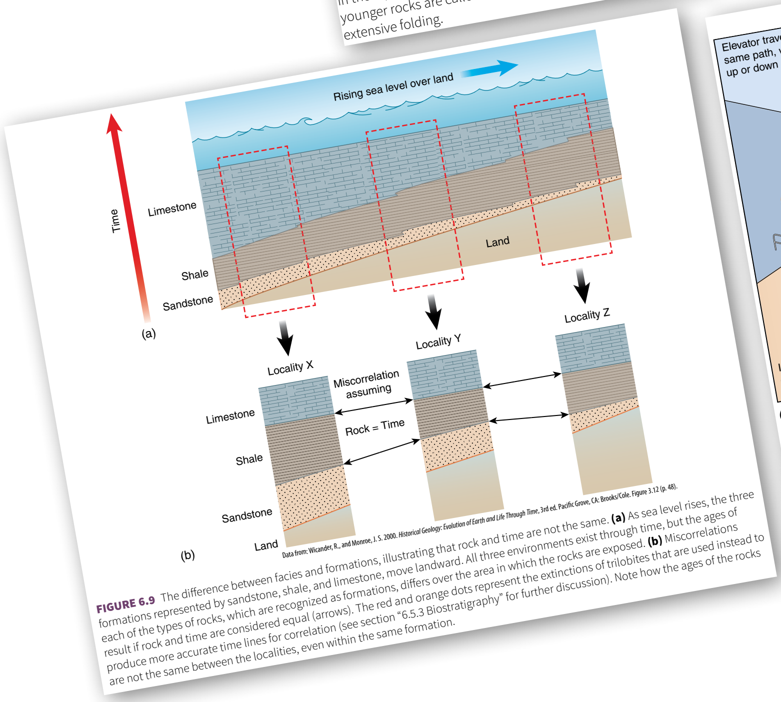


FIGURE 6.9 The difference between facies and formations, illustrating that rock and time are not the same. **(a)** As sea level rises, the three formations represented by sandstone, shale, and limestone, move landward. All three environments exist through time, but the ages of each of the types of rocks, 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.

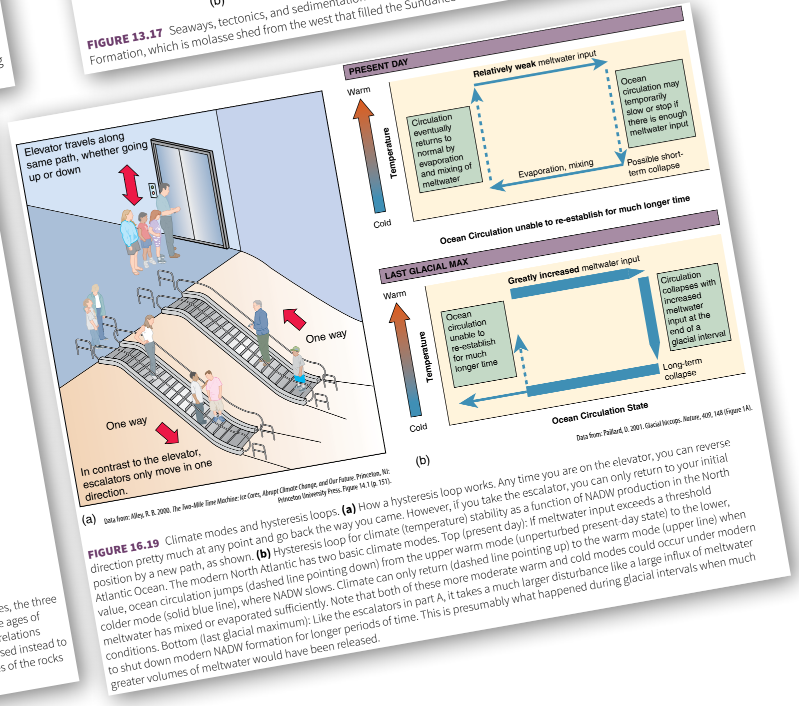
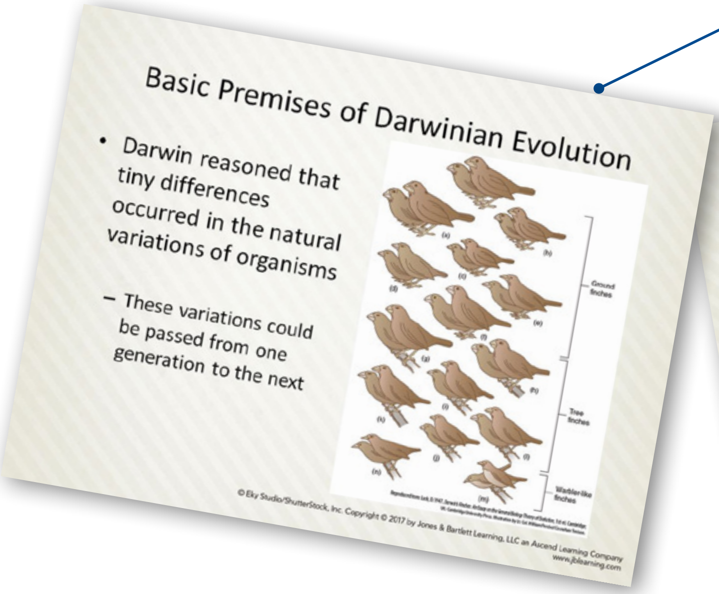


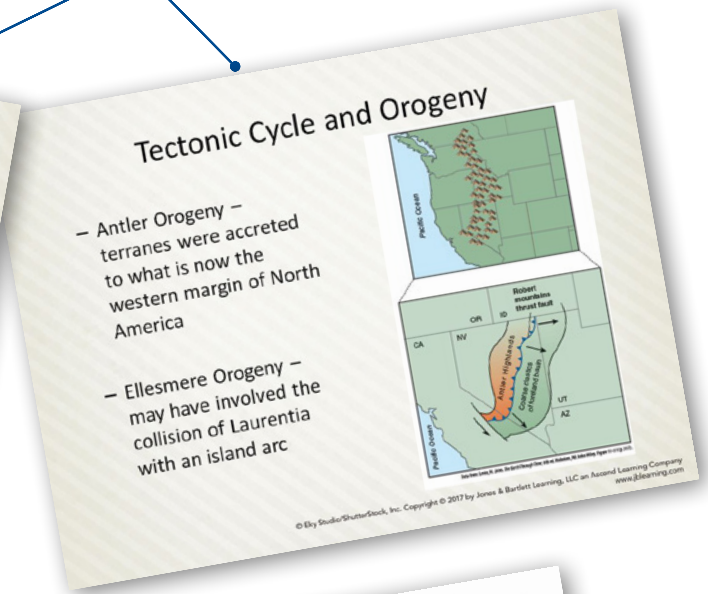
FIGURE 16.19 Climate modes and hysteresis loops. **(a)** How a hysteresis loop works. Any time you are on the elevator, you can reverse direction pretty much at any point and go back the way you came. However, if you take the escalator, you can only return to your initial position by a new path, as shown. **(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.





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- **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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Ronald Martin
Newark, Delaware

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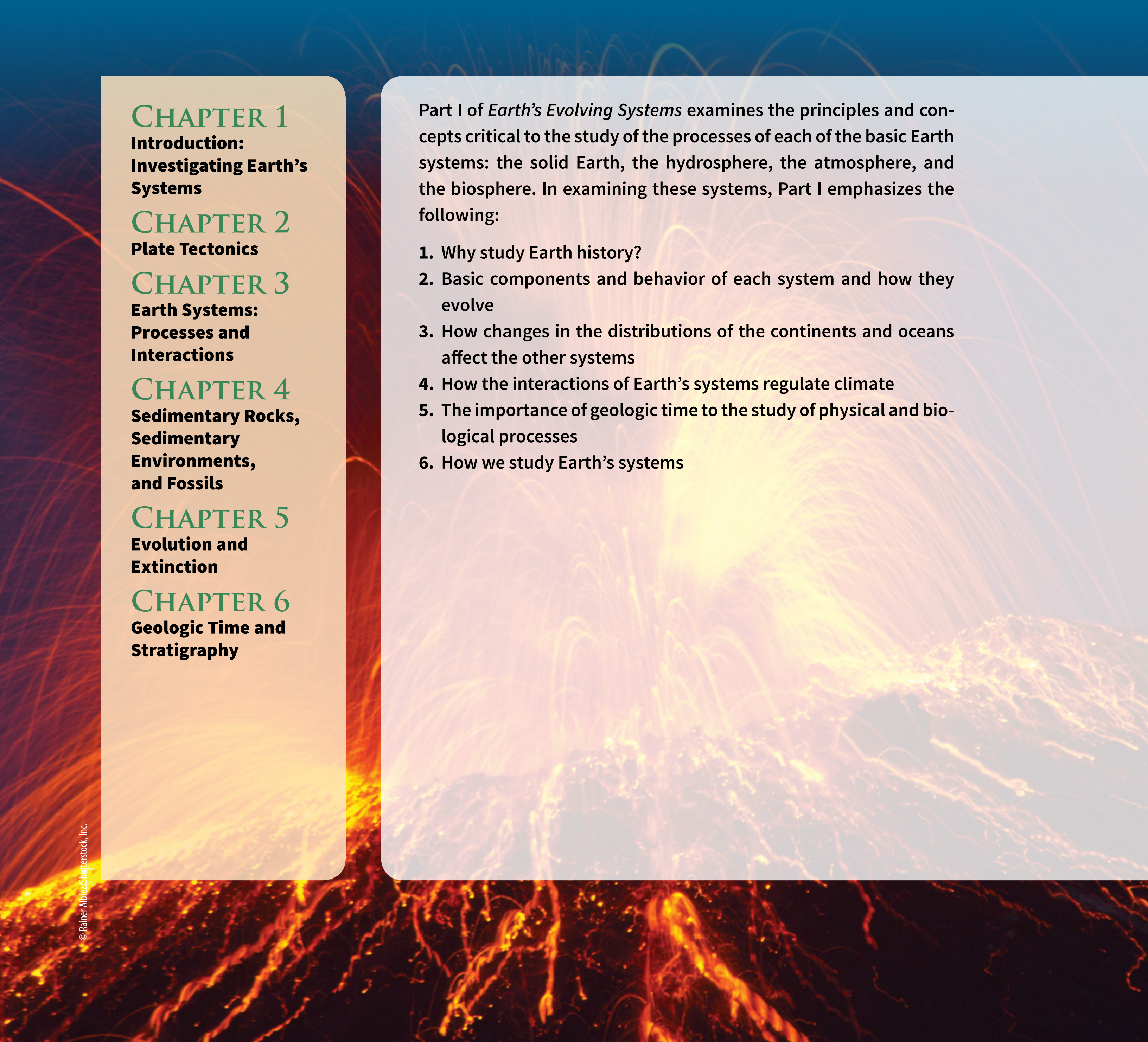
PART

I

Earth Systems: Their Nature and Their Study

Part I of *Earth's Evolving Systems* examines the principles and concepts critical to the study of the processes of each of the basic Earth systems: the solid Earth, the hydrosphere, the atmosphere, and the biosphere. In examining these systems, Part I emphasizes the following:

1. Why study Earth history?
2. Basic components and behavior of each system and how they evolve
3. How changes in the distributions of the continents and oceans affect the other systems
4. How the interactions of Earth's systems regulate climate
5. The importance of geologic time to the study of physical and biological processes
6. How we study Earth's systems



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

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.

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 the present (refer to this chapter's frontispiece). Humans have now begun to affect Earth's environments at rates much faster than the rates of natural processes. The rapid growth of human populations (**Figure 1.1**) has led to the spread of agriculture and deforestation, heavy industry and power plants fired by fossil fuels, and the dependence on petroleum (oil and gas) to power automobiles for transportation (**Figure 1.2**).

The burning of fossil fuels releases **greenhouse gases**, especially carbon dioxide, into the atmosphere. Greenhouse gas traps solar radiation as heat in Earth's atmosphere, causing the atmosphere and surface to warm (**Figure 1.3**). Without carbon dioxide in the atmosphere, Earth's average surface temperature would be about –18°C (0.5°F) instead of its current (and more comfortable!) temperature of +15°C (59°F). But humans have begun to burn fossil fuels at an unprecedented rate, and no one really knows what the outcome will be of the rapid accumulation of carbon dioxide in the atmosphere. In fact, carbon dioxide levels in the atmosphere have increased about 30% since the beginning of the Industrial Revolution (**Figure 1.4**). We know this based on carbon concentrations in gas bubbles found in core samples taken through the glacial ice of Greenland and Antarctica. The bubbles are a record of the composition of ancient atmospheres. As the use of fossil fuels has increased, so too has Earth's average surface temperature, so that the greenhouse effect is no longer considered by most scientists to be purely natural. As far as scientists can tell, these changes will continue through the 21st century and beyond, potentially affecting future human generations, environments, and ecosystems.

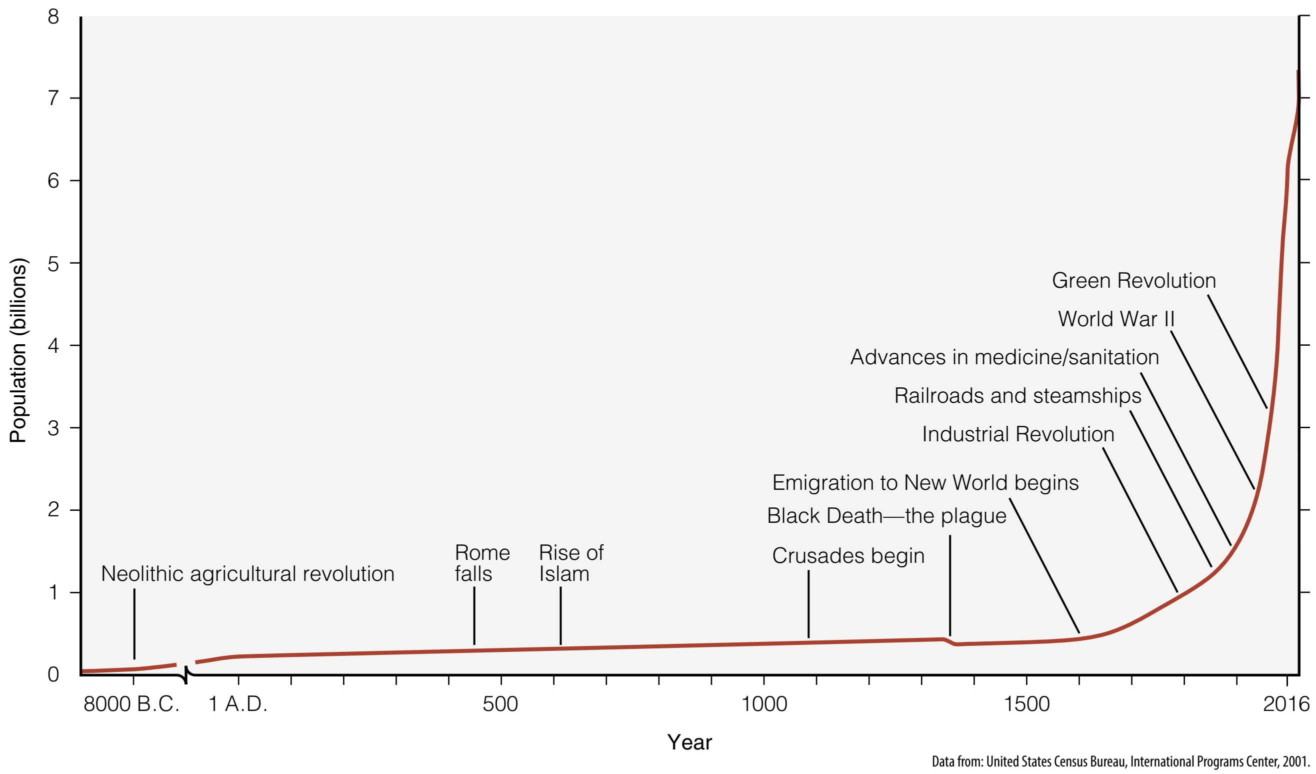
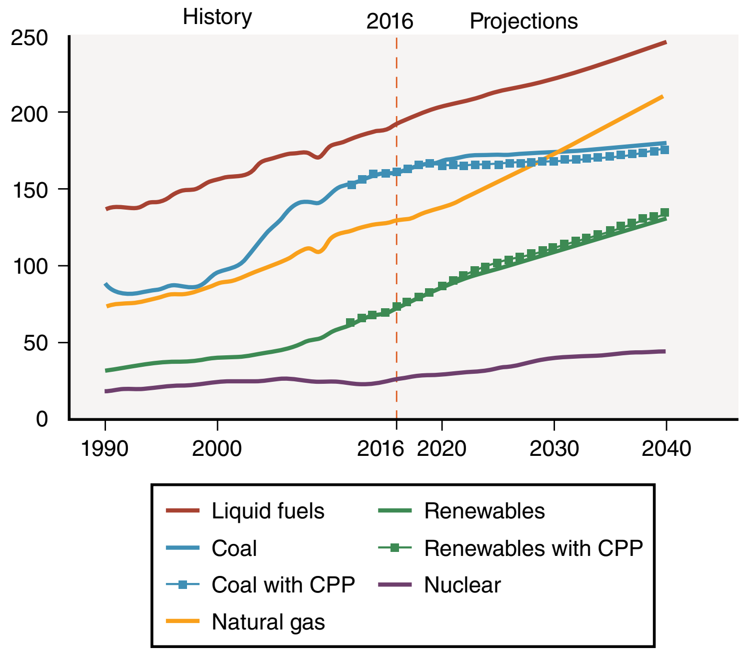


FIGURE 1.1 Human population growth. Global human population growth since 8,000 B.C. Note the steep rise of population growth beginning in the 1800s in response to the Industrial Revolution and advances in medicine and sanitation.



Data from: the United States Department of Energy, Energy Information Administration, *International Energy Annual*, 2002, 2003 (May–July 2005), 2005, and *System for the Analysis of Global Energy Markets*, 2005 and 2006.

FIGURE 1.2 Historical and projected trends of world energy consumption. Given the projection, society might become increasingly dependent on fossil fuels unless other energy sources are found.

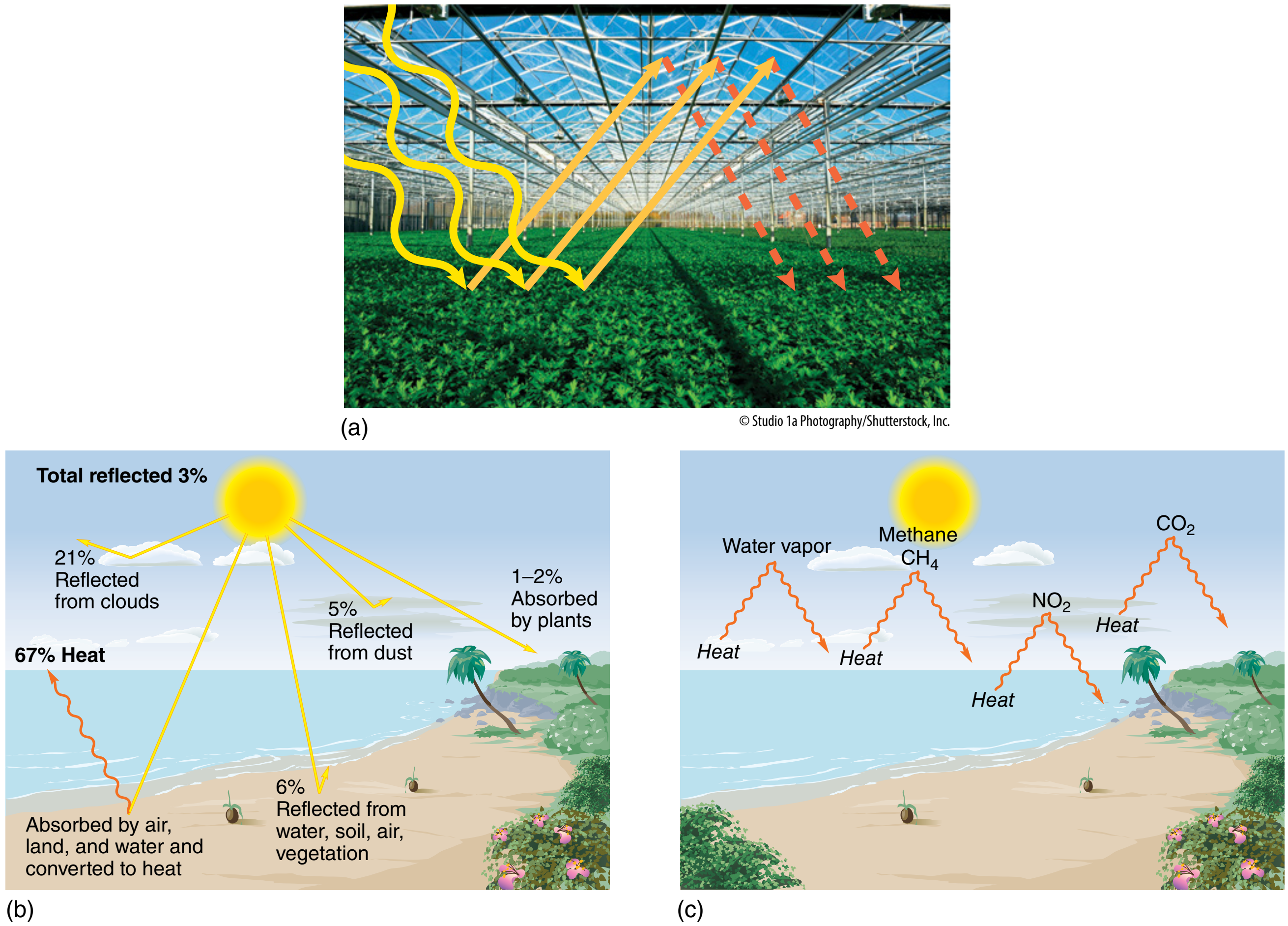


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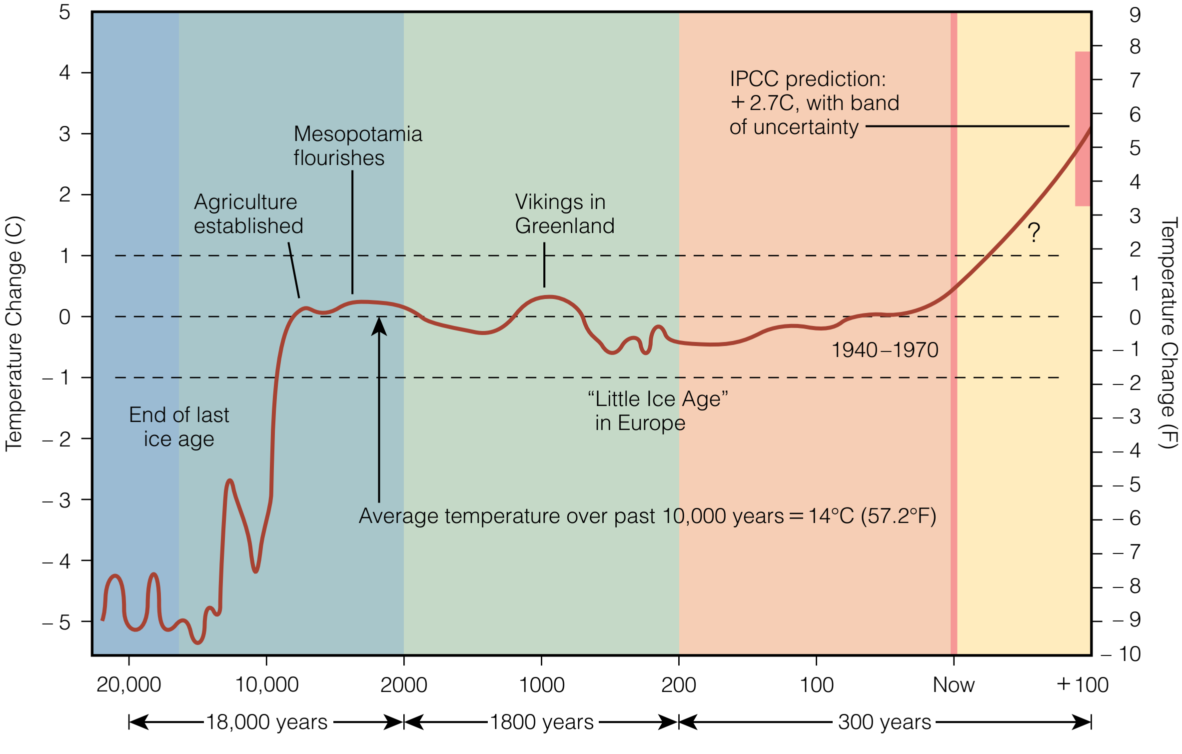
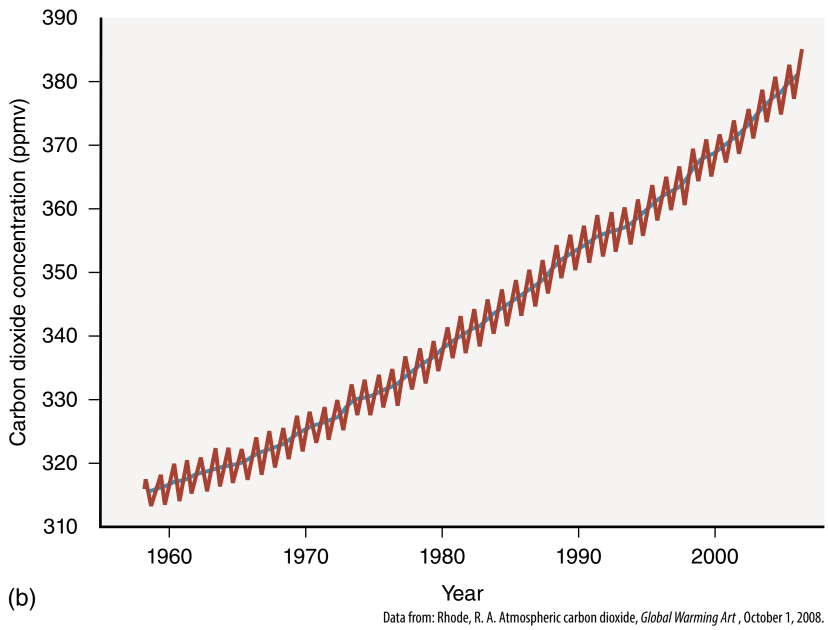
FIGURE 1.3 **(a)** How a greenhouse works. Solar energy penetrates through the glass and is reflected by the floor of the greenhouse as infrared radiation. The infrared radiation is trapped by the glass ceiling and warms the interior of the greenhouse. **(b)** The atmospheric greenhouse effect works in the same way; atmospheric carbon dioxide acts like the glass ceiling of the greenhouse by trapping solar energy that has been reflected by **(c)** the Earth's surface as infrared radiation; this warms the atmosphere. Other gases like methane (CH_4) can combine with oxygen to produce carbon dioxide (CO_2) and greatly exacerbate global warming. Water vapor also contributes to warming. But, scientists have focused on carbon dioxide because of the rapid increase of carbon dioxide concentrations in Earth's atmosphere during the past half century.



(a)

Data from: McMichael, A. J. 1993. *Planetary Overload*. Cambridge, UK: Cambridge University Press.



(b)

Data from: Rhode, R. A. Atmospheric carbon dioxide, *Global Warming Art*, October 1, 2008.

FIGURE 1.4 **(a)** Earth's average surface temperature increased during the last half century as compared to the previous 20,000 years. Note that some civilizations or settlements flourished during times of very mildly increased temperatures that were much lower than those of the past half century and projected into the future. There were also far smaller human populations during earlier times. (Compare Figure 1.1.) **(b)** Since carbon dioxide concentrations in the Earth's atmosphere began to be measured in 1958, atmospheric carbon dioxide has risen steadily. These measurements were taken at a station at Mauna Loa, Hawaii. Another station takes measurements in Antarctica. The oscillations reflect seasonal changes in photosynthesis.

C The fact that Earth's environment has likely affected past civilizations and that **anthropogenic**—or human-generated—activities such as fossil fuel combustion are thought by almost all scientists to be affecting Earth has led to the study of Earth as a series of systems. A **system** can be viewed as a series of parts or components that interact together to produce a larger, more complex whole.

Geology, then, is not just about describing and naming rocks and fossils. The entire Earth can be viewed as a system, and it is the record of the interactions of its component systems that we will study in this book. Geology is the science that examines the evolution of the natural processes on Earth, the evolution of life, and the evolution of these interactions and how they have caused Earth to evolve toward its present state. It is the geologic record of rocks and fossils that preserves the history of these interactions. This is what geology studies. Humans are now the primary geologic force on our planet because of the rapidity of anthropogenic change. It is the science of Geology that provides the clues as to how the Earth and its life have behaved—often unpredictably from a modern, anthropogenic view.

What are these systems and how do they interact? Over what scales of time do these systems and their processes interact? What methods do we use to study the history of these systems, and how do we determine the durations of time over which these systems interact? It is these questions to which we devote the rest of this chapter.

1.2 What Are the Major Earth Systems, and What Are Their Characteristics?

D Earth's surface environments are regulated by four major systems and their component subsystems (**Figure 1.5**). The **solid Earth system** consists of the nonliving, solid Earth, from its center to its surface, including the continents and the seafloor. The **atmosphere** comprises the gaseous envelope surrounding Earth, whereas the **hydrosphere** consists of the oceans, rivers and streams, lakes, and ice contained in mountain glaciers and polar ice caps. Glaciers and related environments are sometimes grouped into a separate system called the **cryosphere**. The **biosphere** consists of all living organisms and their dead remains.

In this chapter, we consider the traits systems share in common. First, each major Earth system consists of a series of parts or components that comprise a larger integrated and complex whole. Each of these components in turn consists of smaller parts with their own systems. Some compartments may serve as **reservoirs**, in which certain types of matter (e.g., carbon from photosynthesis) can be stored—or sequestered—for some length of time ranging from perhaps days or weeks to tens of millions of years or more. Second, most natural systems, both living and nonliving, are **open systems** (**Figure 1.6**). This means that the reservoirs of the

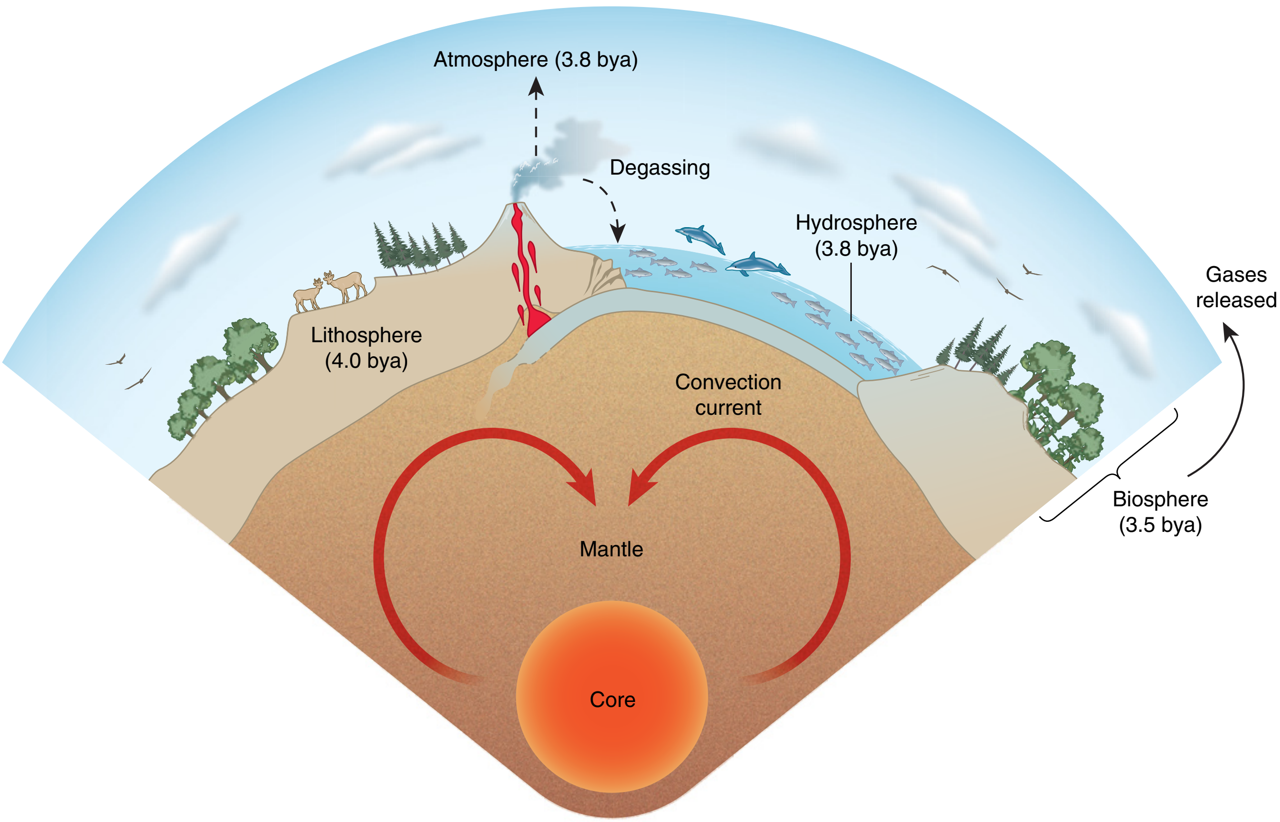


FIGURE 1.5 The four major systems of the Earth and the basic processes within each. Note that each system has its own components and that each system is cyclic. The approximate ages of the systems are shown as billions of years ago (bya).

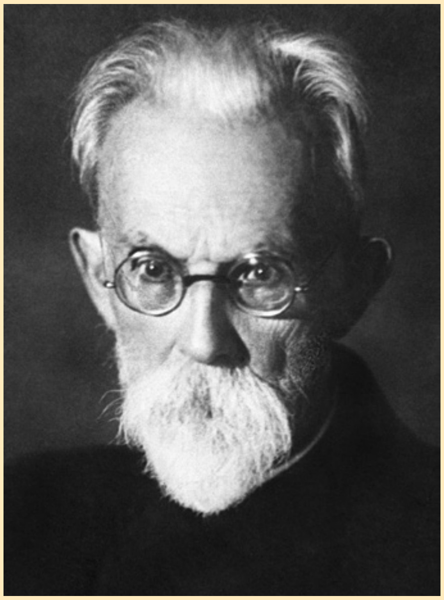
BOX 1.1 The Origins of the Science of Earth Systems*

Like so many other scientific disciplines, the science of Earth systems originated through the work of more than one person. But if its origins can be traced to one person in particular, it would likely be the Russian scientist Vladimir Ivanovich Vernadsky (1863–1945), whose work and integrity are a source of national pride in both Russia and the Ukraine (**BOX Figure 1.1A**). Vernadsky is so famous that he has had streets and monuments erected in his honor and his image reproduced on postage stamps. In perhaps his greatest work, *The Biosphere*, Vernadsky stated that life is not only *a* geologic force, it is *the* geologic force, and that the role of life on the Earth has increased through time. Indeed, ***humans have become the prime geologic agent on Earth.***

But Vernadsky also had very broad, interdisciplinary interests, stimulated by the work of the French chemist Louis Pasteur, one of the founders of medical microbiology, and the French physiologist Claude Bernard on the concept of **homeostasis** (the tendency of a system to maintain its internal stability in response to external disturbances). Vernadsky also conducted experimental studies on minerals with the French chemist Henri Louis Le Châtelier in Paris.

Vernadsky's *The Biosphere*, first published in Russian in 1926, was translated into French in 1930, but, unfortunately, was not translated into English until 1998; thus, many western scientists remained unaware of it until after the Second World War, when some of Vernadsky's major themes were summarized by the ecologist G. Evelyn Hutchinson (1903–1991). Vernadsky's work then began to give rise to various fields such as geomicrobiology and biogeochemistry: the study of geologically and biologically important chemical cycles like those discussed in this text.

Similar themes began to be advocated in the West during the 1970s by the British scientist James Lovelock in his Gaia hypothesis (named after the Greek goddess of mother Earth), which advocated a "physiology" of the Earth involving not only life but also temperature, atmospheric composition, and ocean chemistry. Nevertheless, many western scientists, including Lovelock, remained unaware of Vernadsky's work until after the Gaia hypothesis had been developed. As we will see, although Lovelock's hypothesis advocated homeostasis, the Earth's systems have also undergone profound directional change, or evolution.

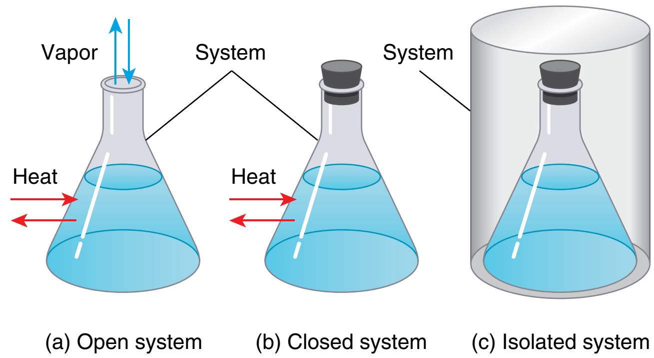


BOX FIGURE 1.1A Vladimir Ivanovich Vernadsky.

*Summarized from Margulis, L. Foreward, and Grinevald, J. 1998. Introduction: The Invisibility of the Vernadskian Revolution, in Vernadsky, V. I. *The Biosphere.* Copernicus/Springer-Verlag. New York, NY. (Translated by D. B. Langmuir; M. A. McMenamin, Editor), pp. 14–32.

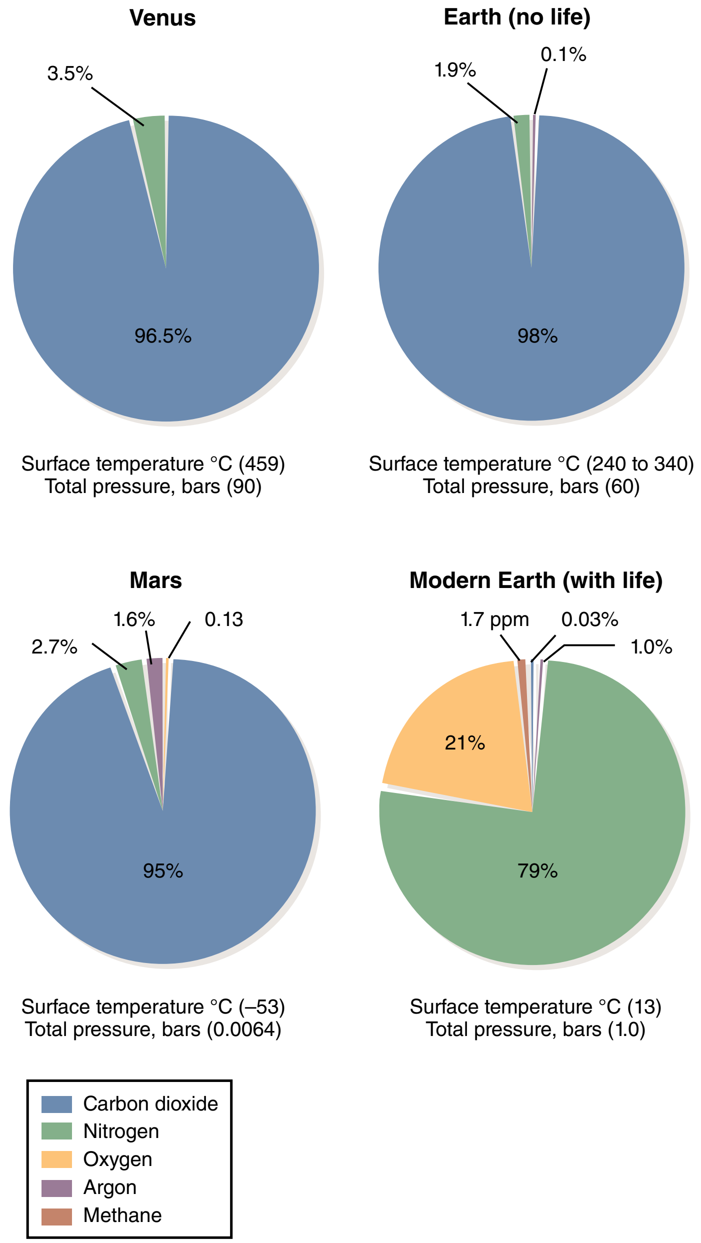
systems exchange matter (chemical substances) and energy (like sunlight) with their surrounding environment. It is the flow of matter and energy through systems and their exchange of matter and energy with other systems and the surrounding environment—termed **fluxes**—that keeps open systems functioning. For example, **convection cells** (like those found in a pot of boiling water) transfer heat and molten rock from deep within the Earth toward its surface during the process of seafloor spreading. The heat is radiated from Earth's surface into the surrounding environment (space) as the molten material cools to form solid rock to produce the ocean floor and continents of Earth's outer shell, or **crust**.

Convection cells and seafloor spreading are also responsible for the movement of the continents and large pieces of the lithosphere (the crust and uppermost mantle of the solid Earth), called plates, in what is known as **plate tectonics**. Plate tectonics (or tectonism) refers to the processes that cause the movement of these plates. These processes have produced mountain chains, ocean basins, and other



(a,b,c) Data from: Coveney, P., and Highfield, R. 1991. *The Arrow of Time: A Voyage through Science to Solve Time's Greatest Mystery*. New York: Fawcett Columbine.

FIGURE 1.6 **(a)** An open system exchanges both matter and energy with its surroundings. **(b)** A closed system exchanges energy (by temperature changes) with its surroundings. **(c)** An isolated system does not exchange matter and energy with its surroundings. Natural systems are typically open systems.



Data from: Lovelock, J. 1988. *The Ages of Gaia: A Biography of Our Living Earth*. New York: W. W. Norton.

FIGURE 1.7 The carbon dioxide concentration of the Earth's atmosphere as compared to that of Mars and Venus if life had not evolved on Earth.

features on Earth's surface, all the while interacting with the other Earth systems, which have profoundly affected Earth's climate through geologic time.

Convection cells also occur within Earth's atmosphere. Atmospheric convection cells result from the differential heating of Earth's surface and distribute heat and moisture over Earth's surface, thereby affecting surface temperatures and the precipitation patterns of the hydrosphere. Water is critical to life as we know it on Earth; most organisms consist of more than 60% water (and some more than 90%). Water also provides habitats for organisms. Like carbon dioxide, water vapor also acts as a greenhouse gas, affecting Earth's temperature and habitability.

The energy of sunlight penetrating the atmosphere is also used by plants during photosynthesis to produce simple sugars from carbon dioxide and water. These plants are then eaten by herbivores and their stored energy is in turn consumed by predators higher in food pyramids. The biosphere has had a profound impact on the evolution of the Earth. In fact, *life may be viewed as a geologic force*. Without the evolution of photosynthesis on Earth and the storage of carbon dioxide in plant matter, the carbon dioxide levels of Earth's atmosphere would more nearly resemble those of Mars or Venus and there would be little or no oxygen present for respiration (**Figure 1.7**). Plants also profoundly affect the physical and chemical breakdown—or **weathering**—of the rocks of Earth's crust. Weathering processes are critical to the long-term, or *geologic*, cycle of carbon that occurs over tens of millions of years, as we will see in coming chapters.

E These examples illustrate another important point about Earth's systems, namely that they interact to regulate Earth's climate and maintain it in a relatively stable state (homeostasis). These interactions occur through **feedback** (**Figure 1.8**). Positive feedback promotes an effect, whereas negative feedback counters an effect. Most of us are all too familiar with one type of positive feedback: audio feedback. In a sound system, the microphone converts sound (vibrations in the air) into electrical impulses that are sent to the amplifier, which enhances the signal and sends it to a speaker. The speaker then converts the amplified electrical signals back into vibrations (sound), which are picked up by the microphone and sent to the amplifier, producing an ear-piercing sound. Negative feedback in this system would have just the opposite effect: the reduction of sound.

Typically, however, positive and negative feedback act together to maintain homeostasis within a system; otherwise, the system would spiral out of control (positive feedback) or go to extinction (negative feedback). Another example of homeostasis produced by feedback is the temperature control of a house. If the house becomes too cold, a thermostat is triggered that turns on the furnace to warm the house to the desired level set on the thermostat. If the house becomes