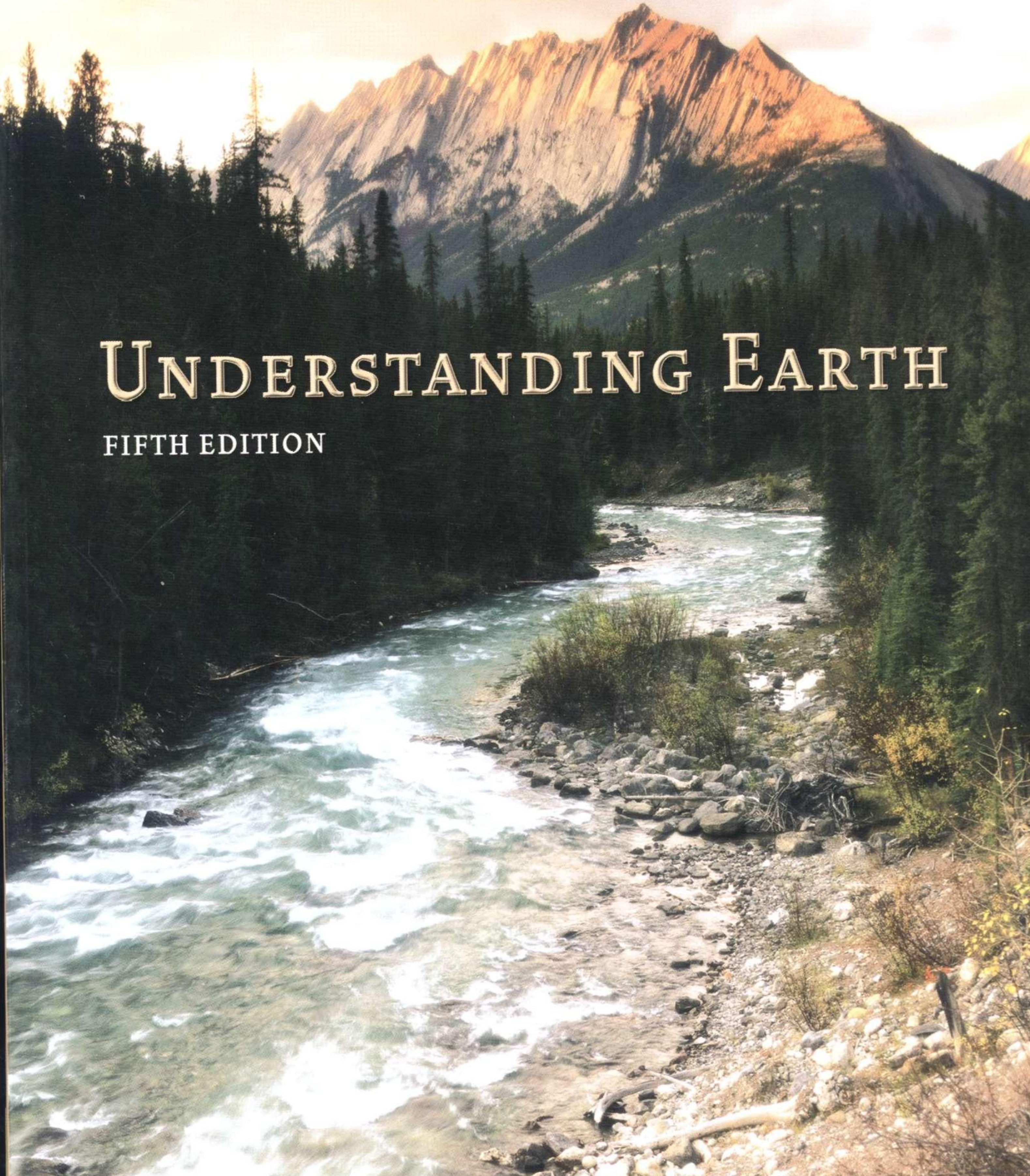
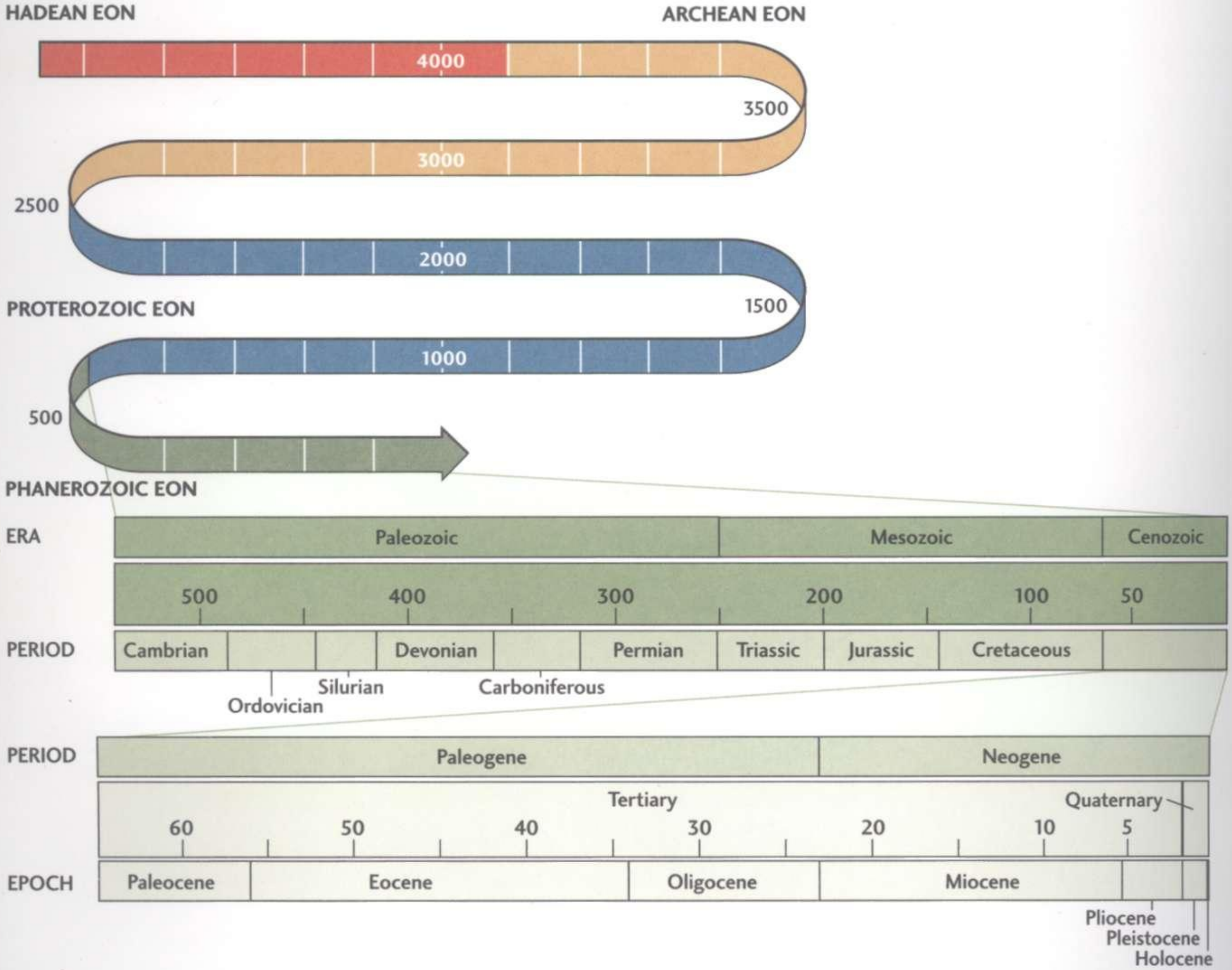


UNDERSTANDING EARTH

FIFTH EDITION

GROTZINGER · JORDAN · PRESS · SIEVER

The ribbon of geologic time shows the complete geologic time scale.



UNDERSTANDING EARTH

Fifth Edition

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W. H. FREEMAN AND COMPANY
New York

PUBLISHER: Susan Finnemore Brennan
ACQUISITIONS EDITOR: Valerie Raymond
MARKETING MANAGER: Scott Guile
DEVELOPMENTAL EDITOR: Randi Rossignol
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SENIOR PROJECT EDITOR: Mary Louise Byrd
ILLUSTRATIONS: Imagineering Media Services, Inc.
ILLUSTRATION COORDINATOR: Bill Page
PRODUCTION COORDINATOR: Susan Wein
COMPOSITION: Sheridan Sellers, W. H. Freeman and Company, Electronic Publishing Center
PRINTING AND BINDING: RR Donnelley

Library of Congress Control Number: 2005939158

ISBN: 0-7167-6682-5
EAN: 9780716766827

Printed in the United States of America

First printing

W. H. Freeman and Company
41 Madison Avenue
New York, NY 10010
Houndmills, Basingstoke RG21 6XS, England

www.whfreeman.com

To our colleague and friend Raymond Siever: whose vision and dedication as a scientist, educator, and author have helped us all to better understand Earth's environment.

Meet the Authors

JOHN GROTZINGER is a field geologist interested in the evolution of Earth's surficial environments and biosphere. 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. He has contributed to developing the basic geologic framework of a number of sedimentary basins and orogenic belts in northwestern Canada, northern Siberia, southern Africa, and the western United States. 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 Tech in 1985. He spent three years as a research scientist at the Lamont-Doherty Geological Observatory before joining the Massachusetts Institute of Technology (MIT) faculty in 1988. From 1979 to 1990, he was engaged in regional mapping for the Geological Survey of Canada. He currently works as a geologist on the *Mars Exploration Rover* team. This mission is the first to conduct ground-based exploration of the bedrock geology of another planet, resulting in the discovery of sedimentary rocks formed in aqueous depositional environments.

In 1998, Dr. Grotzinger was named the Waldemar Lindgren Distinguished Scholar at MIT and in 2000 became the Robert R. Shrock Professor of Earth and Planetary Sciences. In 2005, he moved from MIT to the California Institute of Technology (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, and the Henno Martin Medal of the Geological Society of Namibia in 2001. 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 the 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 motions, measuring tectonic deformations, quantifying seafloor morphology, and characterizing large earthquakes. He received his Ph.D. in geophysics and applied mathematics at Caltech in 1972 and taught at Princeton University and the Scripps Institution of Oceanography before joining the 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, W. M. Keck Professor of Earth Sciences, and Director of the Southern California Earthquake Center.

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.

FRANK PRESS has made pioneering contributions to the fields of geophysics, oceanography, lunar and planetary sciences, and natural resource exploration. He was a member of the team that discovered the fundamental difference between oceanic and continental crust and built the instruments used in the research. Dr. Press was on the faculties of Columbia University, Caltech, and MIT. In addition, he served as president of the U.S. National Academy of Sciences and as a senior fellow at the Department of Terrestrial Magnetism, Carnegie Institution of Washington. He is currently with The Washington Advisory Group. In 1993, Frank Press was awarded the Japan Prize by the emperor for his work in the Earth sciences.

Dr. Press has advised four presidents on scientific issues. Jimmy Carter appointed him Science Advisor to the President. Bill Clinton awarded him the National Medal of Science. Three times, *U.S. News & World Report* surveys named him the country's most influential scientist.

RAYMOND SIEVER was an internationally known expert in sedimentary petrology, geochemistry, and the evolution of oceans and the atmosphere. Dr. Siever was a long-time member of Harvard University's Department of Earth and Planetary Sciences, and he chaired the geology department for eight years. He was one of the first sedimentologists to apply the techniques of geochemistry to the study of sedimentary rocks, especially sandstones and cherts.

In addition to cowriting the popular geology text *Earth* with Frank Press, Dr. Siever wrote *Sand* (Scientific American Library) and (with F. J. Pettijohn and Paul Potter) the classic textbook *Sand and Sandstone* (Springer-Verlag). Dr. Siever was a fellow of the Geological Society of America and the American Academy of Arts and Sciences and has been honored with distinguished awards from the Society of Sedimentary Geology, the Geochemical Society, and the American Association of Petroleum Geologists.

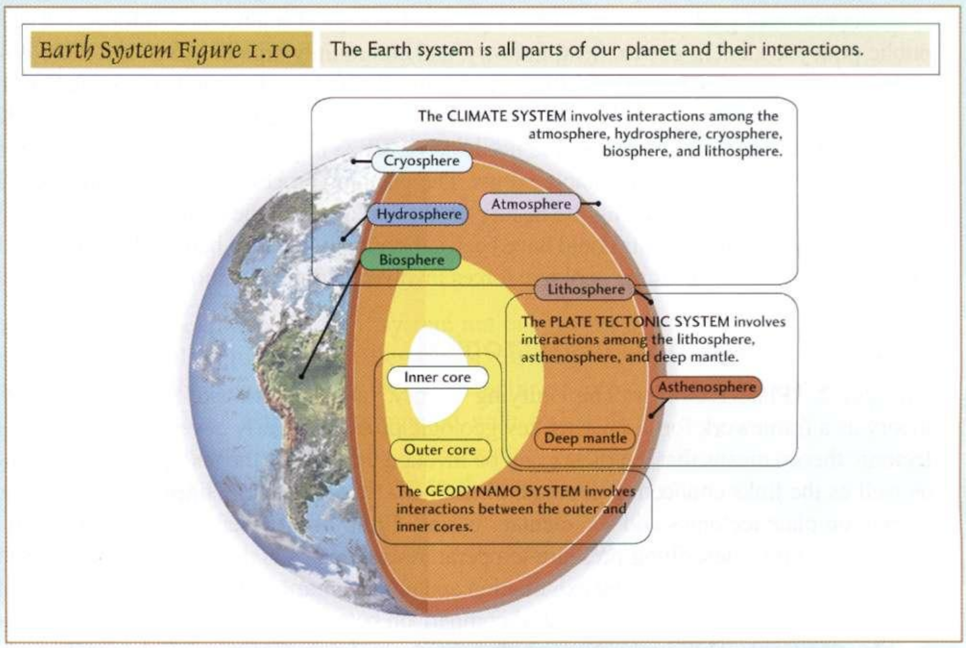
Brief Contents

Contents

OUR VISION

hen the first edition of *Earth* was published, the concept of plate tectonics was still new. For the first time, an all-encompassing theory could be used as a framework for learning about the immense forces at work in Earth's interior. Given this new paradigm, our strategy was to make the learning of Earth science as process-based as possible. This new picture of Earth as a dynamic, coherent system was central to *Earth* and to its successor, *Understanding Earth.*

Now, with *Understanding Earth,* Fifth Edition, we are taking another step forward. We present geology as a unified, process-based science with the power to convey global meaning to geologic features wherever they are found. **Our approach to *Understanding Earth* emphasizes global-scale "system" interactions,** but we also use this approach to characterize the components of the global system, such as the dynamics of ocean crust formation ("Spreading Centers as Magmatic Geosystems," p. 92) and the dynamics of soil formation ("Soils as Geosystems," p. 381).



Earth System Figure 1.10 The Earth system is all parts of our planet and their interactions.

Geology is as much about climate as it is about tectonics, and in this edition we describe the geologic processes that unite these historically separate fields. Our discussions of such core concepts as the rock cycle, metamorphism and exhumation, and landscape evolution help illustrate important links. Further, **we consider the concept of geologic time and the historical development of Earth (and the other terrestrial planets) to be as important a process.** We illustrate this principle by grouping together material that underscores long-term evolution, whether it involves our solar system **(Chapter** 9, "Early History of the Terrestrial Planets"), Earth itself **(Chapter** 10, "Evolution of the Continents"), or life **(Chapter** 11, "Geobiology: Life Interacts with the Earth"). Our preparation of **Chapters** 9 **and** 11—new to this edition of *Understanding Earth*—was motivated by our desire to expose students to the fresh perspective on our solar system provided by the increasing number of geologically oriented

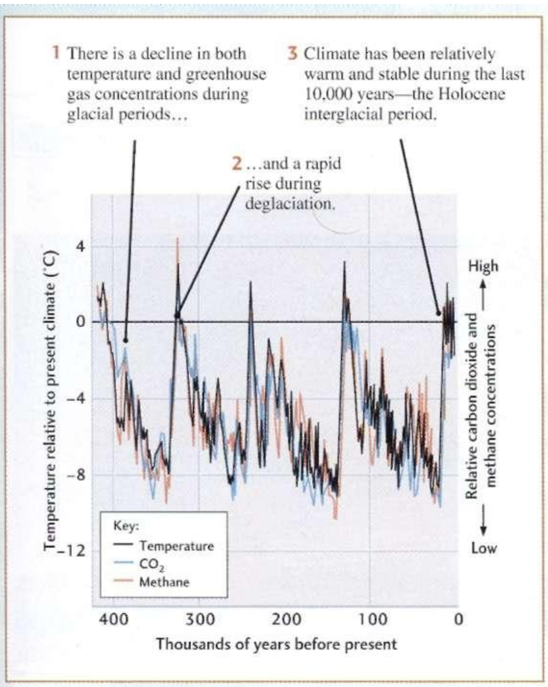


Figure 15.10 A graph showing three types of data recovered from the Vostok ice core in East Antarctica: temperatures inferred from oxygen isotope (black line) and the concentrations of two important greenhouse gases, carbon dioxide (blue line) and methane (red line). The gas concentrations come from measurements of air samples trapped as tiny bubbles within the Antarctic ice. [IPCC, *Climate Change 2001: The Scientific Basis.*]

missions to other planets (especially Mars) and the recognition that life (especially microbial life) has had a profound effect on Earth.

In writing this edition of *Understanding Earth,* **we have drawn on powerful new laboratory and field tools and new theoretical approaches.** New technology such as GPS and continuous satellite monitoring of Earth from space allows us to view the motion of plates, the raising and erosion of mountains, the buildup of crustal strain before an earthquake, global warming, the retreat of glaciers, and rising sea level—all in almost real time. It is remarkable that we can now use earthquake waves to image the flow of the solid mantle hundreds and thousands of kilometers deep in the Earth, revealing patterns of rising plumes and subducting plates. And we can now send robotic geologists to other planets to investigate geologic processes, such as the role of water in shaping the early surface of Mars and constraining its climate history. Finally, rapid scanning of the genetic makeup of even the tiniest microorganism allows us to determine how organisms control geologically important processes. The view of Earth as a system of interacting components subject to interference by humankind is now backed by solid scientific evidence, enabled by these new technologies.

The power of geology has never been greater. Geological science now informs the decisions of public policy leaders in government, industry, and community organizations. But there is still work to do in helping to make this flow of information more effective. Recent disasters such as the Indian Ocean tsunami of 2004 (see **Chapter 13)** and the flooding of New Orleans by Hurricane Katrina in 2005 (see **Chapter 20)** underscore the need for vigilance in planning for and limiting exposure to these rare but powerful and inevitable events. The planning process begins with understanding how Earth works and by appreciating the history of similar events in the geologic past. The devastation caused by both of these events could have been substantially reduced had public policy leaders been more knowledgeable about the geologic forces involved and the likelihood (history) of such events.

Early Coverage of Plate Tectonics

Chapter 2, "Plate Tectonics: The Unifying Theory," allows us to take full advantage of tectonic theory as a framework for discussing key geologic processes. Early coverage of the basic tenets of tectonic theory means that the theory can be invoked throughout the text, providing the big picture as well as the links connecting geologic phenomena. For instance, **Chapter** 5 offers an expanded section on plate tectonics and sedimentary basins. **Chapter 6** presents metamorphism in terms of plate interactions, describing pressure-temperature-time paths and their significance for interpreting tectonic processes, including exhumation and uplift. **Chapter 9**—new to this edition of *Understanding Earth*—allows a process-based comparison between "flake tectonics" on Venus and plate tectonics on Earth. This treatment is made possible by having introduced plate tectonics early on. Finally, the section of the book dedicated to surface processes is capped with **Chapter 22,** in which the discussion of landscape evolution integrates previous chapters and makes the case for significant interactions between climate and tectonics.

Viewing Earth as a System

We begin with an improved discussion of the Earth system in **Chapter 1.** The components of the Earth system are described, and the exchanges of energy and matter through the system are illustrated. This discussion serves as the springboard for the Earth systems perspective that pervades the text. In **Chapter 3,** the rock cycle first illustrates how plate tectonic and climate processes interact as a system to generate the three basic classes of rocks. In **Chapter 4** (in the section entitled "Spreading Centers as Magmatic Geosystems"), we then show how one of the components of the

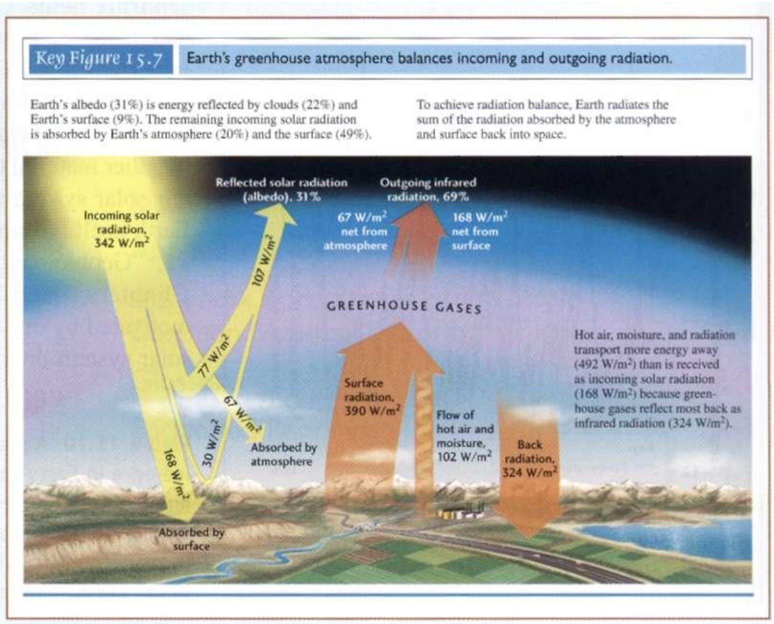


Figure 15.7 Earth's greenhouse atmosphere balances incoming and outgoing radiation. [IPCC, *Climate Change 2001: The Scientific Basis.*]

Earth system (spreading centers) can be studied as a system itself, with inputs, processes, and outputs. This pedagogical approach is reinforced later in the same chapter when we discuss "Subduction Zones as Magmatic Geosystems." Throughout the book, we use this construct to illustrate particularly well-defined geosystems, as in the case of volcanoes **(Chapter 12)** and soils **(Chapter 16).**

Traditionally isolated geologic processes such as metamorphism **(Chapter 6)** and landscape evolution **(Chapter 22)** are discussed in the context of system interactions between tectonics and climate, illustrated with examples of pressure-temperature paths and models for denudation and exhumation. In **Chapter 13,** the relationship among stress, strain, and the behavior of regional fault systems in controlling earthquakes illustrates how geosystems behave. The convective processes of Earth's deep interior are discussed in **Chapter 14** as the driving mechanisms behind the plate tectonic and geodynamo systems.

Our discussion of the climate system **(Chapter 15)** is updated to provide a more comprehensive understanding of the major processes that control Earth's climate, as well as an understanding of Earth's climate history. Subsequent chapters in this section of the book—which discusses surface processes—are rewritten to emphasize not just the particular process (such as the flow of groundwater or wind) but how these processes are controlled by the climate system and, where relevant, the plate tectonic system. Finally, the role of biology in Earth system behavior is presented in **Chapter 11** and then reinforced later with examples from many chapters.

New Chapters

Comparative Planetology

Chapter 9, "Early History of the Terrestrial Planets," explores the solar system not only in the vast reaches of interplanetary space but also backward in time to its earliest history. It discusses how Earth and the other planets formed around the Sun and how they differentiated into layered bodies. The geologic processes that have shaped Earth are compared with those of Mercury, Mars, Venus, and the Moon. The history of climate as well as tectonics is emphasized in the discussion of Venus and Mars. Mars receives special attention owing to the spectacular new results from recent geologically oriented missions, culminating with the first in situ outcrop studies on another planet. Finally, we discuss how exploration of the solar system by

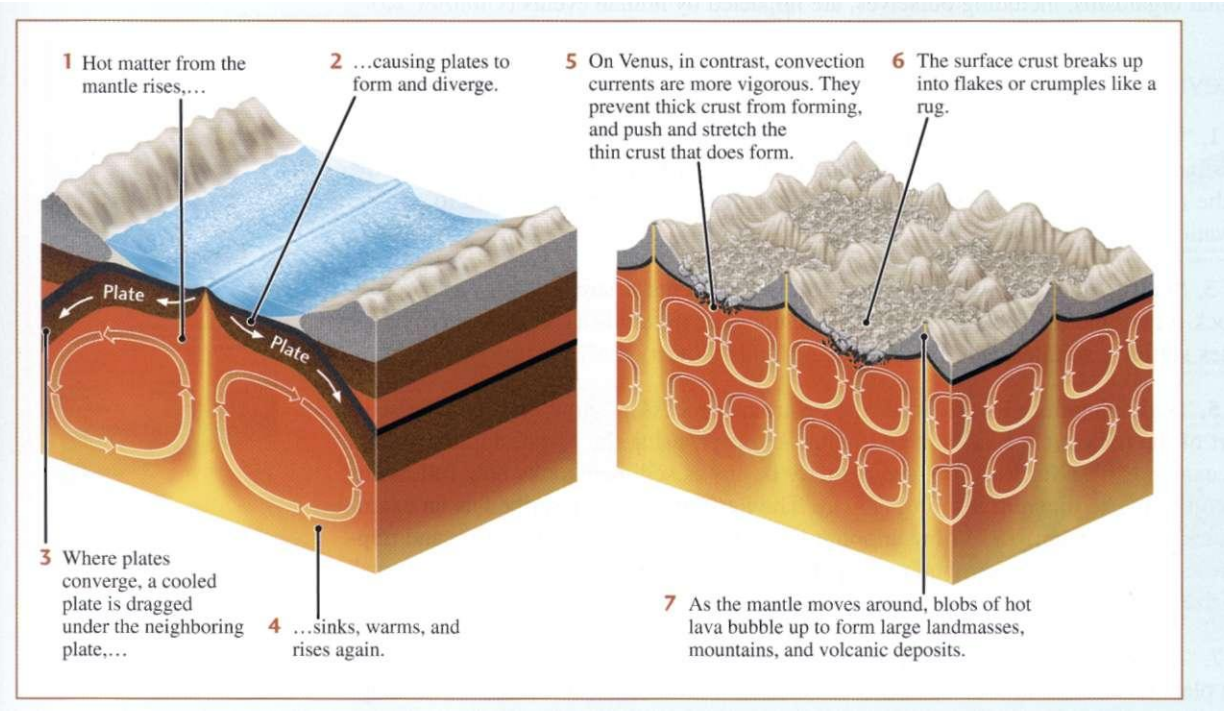


Figure 9.15 Plate tectonics on Earth versus flake tectonics on Venus.

spacecraft might answer fundamental questions about the evolution of our planet and the life it harbors.

Concepts in planetary geology also appear in other chapters. Sulfate minerals thought to be of importance on Mars are described in **Chapter 3;** impact (shock)-related metamorphism is discussed in **Chapter 6;** and the search for extraterrestrial life is presented in **Chapter 11.**

Geobiology

Chapter 11, "Geobiology: Life Interacts with the Earth," explores the links between life and environment on Earth. We describe how the biosphere works as a system and what gives Earth its ability to support life through the cycling of biologically important elements. The chapter discusses the remarkable role of microorganisms in Earth processes, including mineral and rock formation (and destruction). We also discuss geobiological interactions throughout Earth's history and some of the major evolutionary events that changed our planet. Finally, we consider the key ingredients for sustaining life on Earth and searching for life on other planets and in other solar systems.

Geobiological processes are discussed in other chapters as well, including their role in the formation of sedimentary rocks **(Chapter 5);** the occurrence of extremophiles living in volcanoes and mid-ocean ridges **(Chapter 12);** how the Earth's magnetic field helps some organisms to navigate **(Chapter 14);** the role of organisms in modulating climate **(Chapter 15)** and in influencing weathering **(Chapter 16)** and groundwater potability **(Chapter 17);** and in the way that organisms, including ourselves, are impacted by human events **(Chapter 23).**

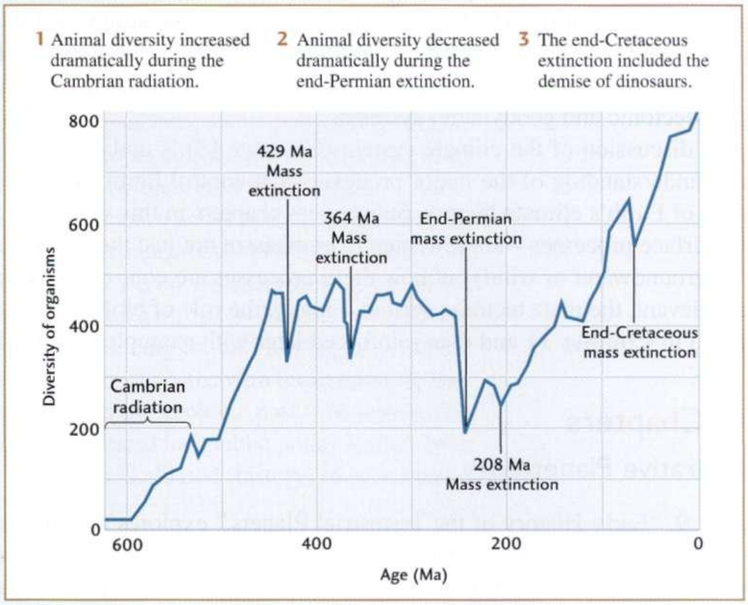


Figure 11.21 The diversity of organisms reveals both extinctions and radiations. During a radiation, such as the Cambrian explosion, the number of new groups of organisms increases. During a mass extinction, the number of groups decreases.

Major Revisions

- **Chapter 1,** "The Earth System," features a new section called "Peeling the Onion," a complete discussion of Earth's layered internal structure. The scientific method is introduced in the context of the discovery of Earth's shape and the hypotheses that were developed to explain early observations.

- **Chapter 3,** "Earth Materials: Minerals and Rocks," presents a streamlined overview of minerals, rock types, and the rock cycle. It now includes ore minerals as well. A new feature box discusses sulfides, sulfates, acid mine drainage, and sulfates on Mars.

- **Chapter 5,** "Sedimentation: Rocks Formed by Surface Processes," now develops the sedimentary part of the rock cycle as a "source-to-sink" concept, using the Mississippi River and delta as the example. The discussion of sedimentary basins as sediment sinks now follows as the logical end of the sediment transport pathway. The Persian Gulf is described as an example of a flexural basin, making clear how important such basins are to the generation and trapping of oil reserves, such as those found in Iraq. The section on "Sedimentary Environments" now emphasizes process up front.

- **Chapter 7,** "Deformation: Modification of Rocks by Folding and Fracturing," is now solidly grounded in plate tectonics and includes a current view of continental deformation. The chapter contains a more complete description of geologic maps and mapping.

• **Chapter 13,** "Earthquakes," includes new material on the 2004 Sumatra earthquake and tsunami.

• **Chapter 14,** "Exploring Earth's Interior," has a new section on Earth's magnetic field and the biosphere.

• **Chapter 15,** "The Climate System," now appears earlier in the text and with a greater focus on climate as a global geosystem that can be understood in terms of interacting components. Climate variability is also discussed, with special emphasis on ancient ice ages and Milankovitch cycles.

• **Chapter 16,** "Weathering, Erosion, and Mass Wasting: Interface Between Climate and Tectonics," now integrates material previously separated in different parts of the book. Weathering is discussed in the context of its important variables, including climate. The chapter has a completely revised and updated discussion of soils and takes a process-oriented approach in the new section entitled "Soil as a Geosystem." The chapter now also uses a widely accepted classification scheme for soils (U.S. soil taxonomy system).

A small headland near Banda Ache on the west coast of Sumatra previously covered by dense jungle to the waterline but now stripped clean to height of about 15 m by the tsunami. [José Borrero, University of Southern California/Tsunami Research Group.]

• **Chapter 18,** "Stream Transport: From Mountains to Oceans," is completely reorganized so that the larger-scale, geomorphic aspects of stream systems come first, followed by the discussion of fluid flow and sediment transport. The final section, called "Streams as Geosystems," pulls it all together. The chapter begins with the Lewis and Clark expedition, which is referred to throughout the chapter (for example, in the discussion of stream networks).

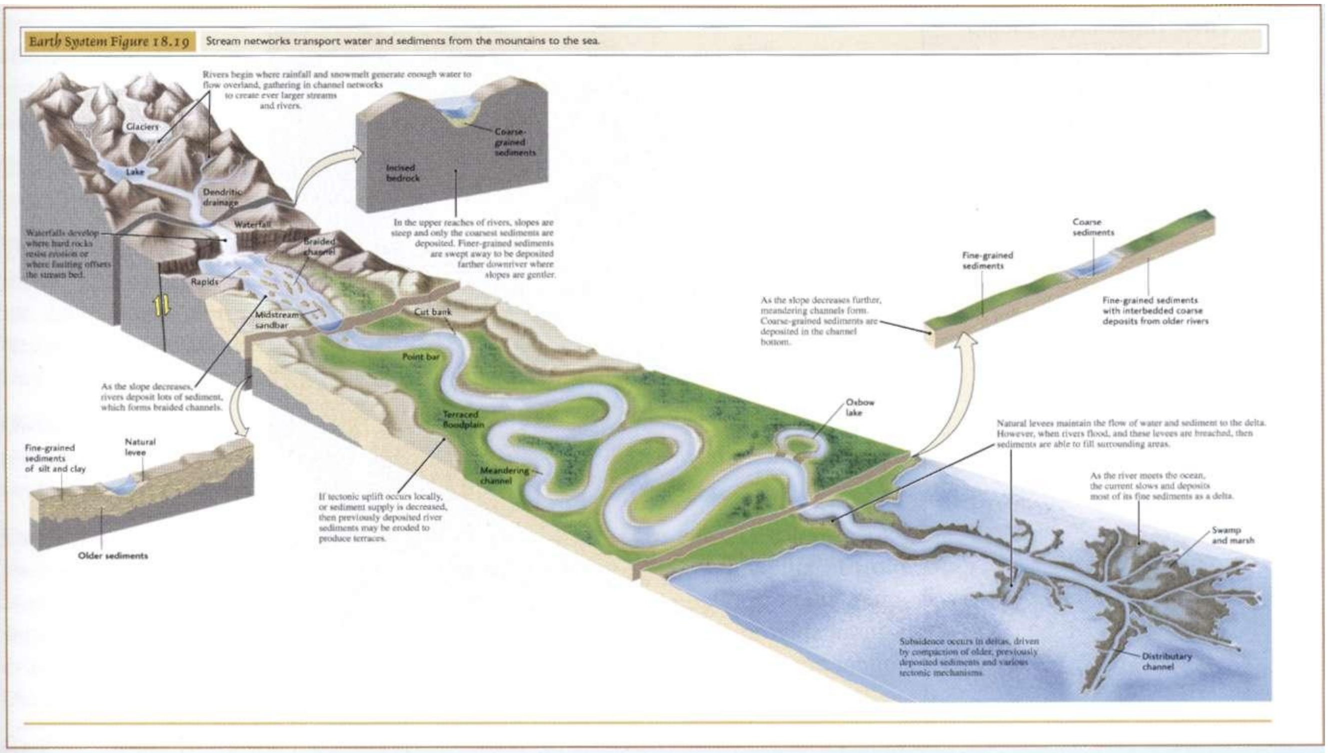


Figure 18.19 Stream networks transport water and sediments from the mountains to the sea.

- **Chapter 20,** "Coastlines and Ocean Basins," has a new section on hurricanes and storm surge, along with a new feature box on the great New Orleans flood of 2005 and a new table on the hurricane intensity scale. The chapter has been reorganized to progress from the coast to the continental margin to the deep ocean.
- **Chapter 21,** "Glaciers: The Work of Ice," includes a new section called "Glaciations and the Climate System," which discusses the Wisconsin glaciation.
- **Chapter 23,** "The Human Impact on Earth's Environment," now treats human civilization as a global geosystem that interacts strongly with the carbon cycle and other components of the Earth system, focusing on the depletion of petroleum as an energy resource and the potential for climate change that arises from fossil-fuel burning.

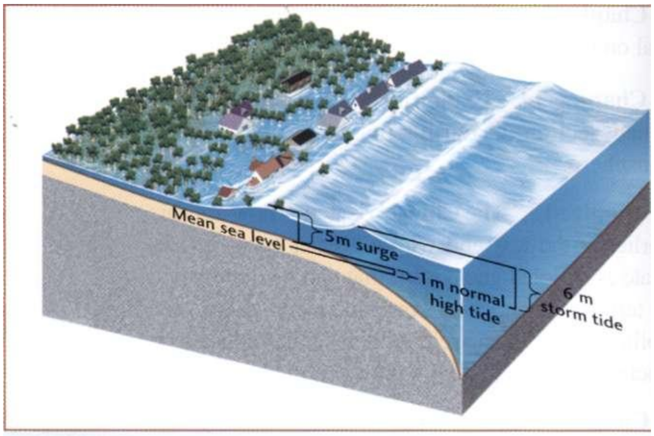


Figure 20.8 A storm tide is the combination of storm surge and the normal astronomical tide.

Telling Stories with Words and Pictures

Our enduring goal is to tell a story rather than provide an aggregated set of facts, and the illustrations of this edition of *Understanding Earth* reflect that goal. Each chapter features several **Key Figures,** illustrations of the chapter's most important concepts and geologic processes. Key Figures not only represent the key geologic processes but also help the reader to focus on the chapter's key ideas.

Most chapters also feature **Earth System Figures** that illustrate geologic processes as part of global, regional, or even local geosystems. These illustrations should reinforce the reader's understanding of Earth as a system of interacting components, with inputs, processes, and outputs.

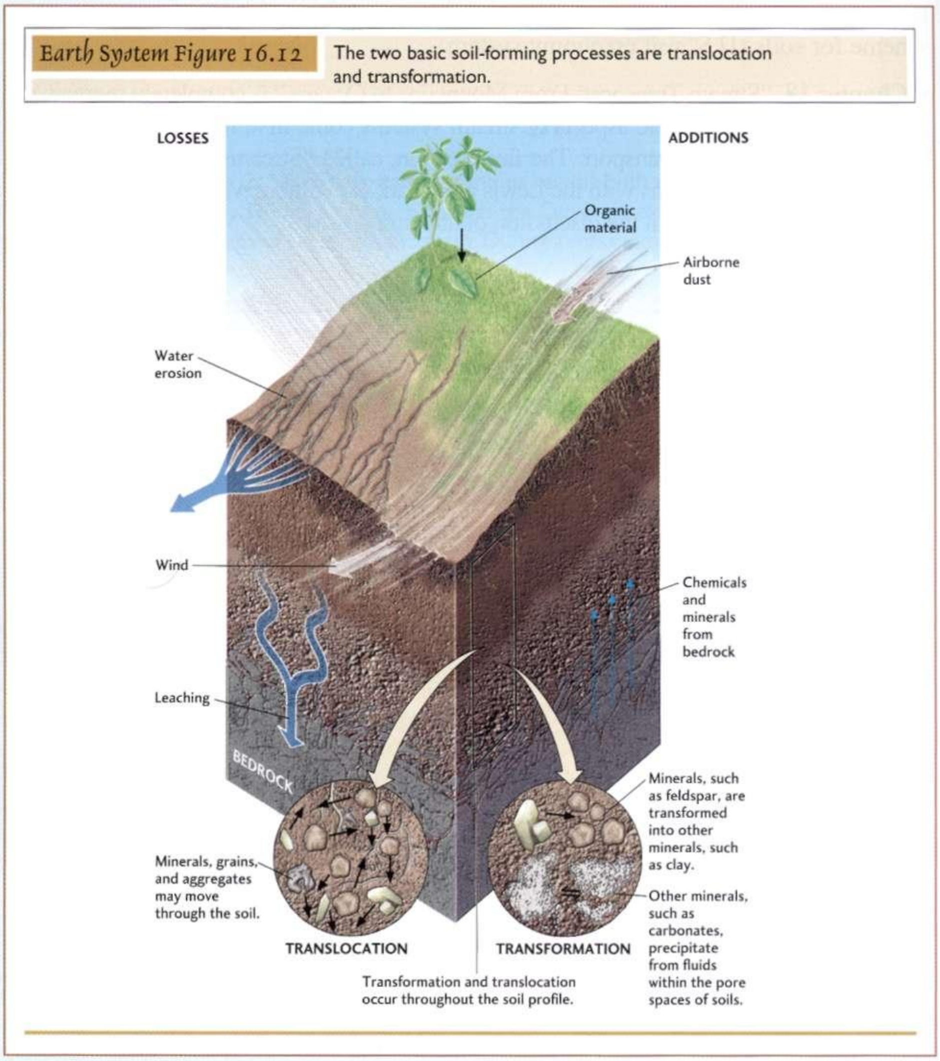


Figure 16.12 There are two important soil-forming processes: transformation and translocation.

MEDIA AND SUPPLEMENTS PACKAGE

A selection of electronic media and printed supplementary materials designed to support both instructors and students is available to users of this new edition of *Understanding Earth.* By focusing primarily on the importance of visualizing key concepts in geology, we are providing instructors with the presentation tools they need to help their students truly understand Earth's processes and students with the study tools they need to study geology effectively and apply their newly acquired knowledge.

For Instructors

The **Instructor's Resource CD-ROM** (ISBN 0-7167-4509-7) allows instructors to **search** and **export** all the resources listed below by key term or chapter:

- All text images
- Animations, videos, flashcards, and more
- *Instructor's Resource Manual*
- PowerPoint files (lecture slides)
- *Test Bank* files
- Expeditions in Geology
- Geology in the News

The **Test Bank** ([print] ISBN 0-7167-4516-X and [CD-ROM] ISBN 0-7167-3803-1) includes approximately 50 multiple-choice questions for each chapter (over 1000 total).

The **Computerized Test Bank CD-ROM** provides the *Test Bank* files in an electronic format that allows instructors to edit, resequence, and add questions.

The **Instructor's Resource Manual** (ISBN 0-7167-4507-0), written by Peter L. Kresan and Reed Mencke, formerly of the University of Arizona, includes chapter-by-chapter sample lecture outlines, ideas for cooperative learning activities and exercises that can be easily copied and used as handouts and quizzes, and guides to the Web resources. The *Instructor's Resource Manual* also includes an instructional design section that contains teaching tips from many instructors at the University of Arizona Learning Center. The *Instructor's Resource Manual* is also available on both the Instructor's Resource CD-ROM and the Companion Web Site.

The **Overhead Transparency Set** (ISBN 0-7167-3842-2) includes *all* textbook illustrations in full-color acetate transparencies.

The **Companion Web Site,** at **www.whfreeman.com/understandingearth5e,** provides access to all student materials on the Web site in addition to a password-protected Instructor's site that contains all the PowerPoint presentations and text art available on the Instructor's Resource CD-ROM, the *Instructor's Resource Manual,* and the Quiz Gradebook (which keeps track of students' Graded Online Quiz scores).

Online Course Materials (WebCT, Blackboard): As a service for adopters, we will provide content files in the appropriate online course format, including the instructor and student resources for this text.

Expeditions in Geology: A virtual field trip for your whole class! Explore geological phenomena with these brief video tutorials. Accompany Jerry Magloughlin of Colorado State University as he flies across the continent and around the world filming extraordinary examples of Earth in action. Your lecture comes to life as you provide an up-close examination of the splendor and intrigue of various geological processes and landmarks. (Available in high-definition format on the Instructor's Resource CD-ROM.)

Geology in the News (on the **Instructor's Resource CD-ROM):** This series of one-to three-minute news features (all recently aired on prime-time news) offers expert analysis of geological events that have headline-making impacts on our lives. By connecting what students see and hear every day in the mainstream media to the processes of geology, this series allows you to convey the relevance of geology and geologists to our lives.

For Students

Understanding Earth, Fifth Edition eBook! The *Understanding Earth,* Fifth Edition, eBook is a complete online version of the textbook that provides a rich learning experience by taking full advantage of the electronic medium. This online version integrates all existing media resources and adds features unique to the eBook, such as

- Easy access from any Internet-connected computer via a standard Web browser
- Quick, intuitive navigation to any section or subsection, as well as any printed book page number
- Integration of all student Companion Web Site animated tutorials and activities
- In-text self-quiz questions
- In-text links to all glossary entries
- Interactive chapter summary exercises
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- A bookmarking feature that allows for quick reference to any page
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- Online Quizzing: The online quizzes from the student Companion Web Site are integrated into the eBook.

The eBook is available FREE with the text (use special package ISBN: 0-7167-76650), or online at http://ebooks.bfwpub.com or at the **Companion Web Site** at **www.whfreeman.com/understandingearth5e.**

The **Companion Web Site,** at **www.whfreeman.com/understandingearth5e,** includes many study tools that allow students to visualize geological processes and practice their newly acquired knowledge. The Companion Web Site contains

- Animations, including more than 40 animated figures from the textbook
- Online Review Exercises, which include interactive exercises, virtual reality field trips, drag-and-drop exercises, and matching exercises
- Flashcards
- Online Quizzing
- Concept Self-Checker
- Geology in Practice exercises: inquiry-based learning activities that ask students to apply their newly acquired knowledge and think like geologists
- Current Events in Geology: an archive of geologically relevant articles from popular news sources, updated monthly

The **Student Study Guide** (ISBN 0-7167-3981-X), written by Peter L. Kresan and Reed Mencke, formerly of the University of Arizona, includes tips on studying geology, chapter summaries, practice exams, and practice exercises that incorporate figures from the text and Web resources.

The **Earthlnquiry** series, developed by the **American Geological Institute** in collaboration with experienced geology instructors, is a collection of Web-based investigative activities that provides a direct way for students to explore and work with the vast amount of geological data now accessible via the Web. Covering such diverse topics as earthquakes and plate boundaries and the recurrence interval of floods, each Earthlnquiry module asks students to analyze real-time data to develop a deeper understanding of fundamental geoscience concepts. Each module consists of a password-protected Web component and an accompanying workbook.

For more information about Earthlnquiry or to read about the various modules currently available, please visit **www.whfreeman.com/earthinquiry.**

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.

The following instructors were involved assisted in the planning or reviewing stages of this new edition:

Kathryn A. Baldwin
Washington State University
Charly Bank
Colorado College
Ray Beiersdorfer
Youngstown State University
Larry Benninger
University of North Carolina at Chapel Hill
Elisa Bergslien
State University of New York at Buffalo
Grenville Draper
Florida International University
Eric Essene
University of Michigan
Sharon Gabel
State University of New York at Oswego
Steve Gao
Kansas State University
David H. Griffing
Hartwick College
Scott P. Hippensteel
University of North Carolina at Charlotte
Linda C.Ivany
Syracuse University
Thomas J. Kalakay
Rocky Mountain College
Haraldur R. Karlsson
Texas Tech University
David T. King Jr.
Auburn University
Andrew H. Knoll
Harvard University
Jeffrey R. Knott
University of California at Fullerton
Kelly Liu
Kansas State University
Sakiko N. Olsen
Johns Hopkins University
Dr. Leslie Reid
University of Calgary
Steven Semken
Arizona State University
Eric Small
University of Colorado at Boulder
John Waldron
University of Alberta

We remain indebted to the following instructors who helped shape earlier editions of *Understanding Earth:*

Wayne M. Ahr
Texas A & M University
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Others have worked with us more directly in writing and preparing manuscript for publication. At our side always were the editors at W. H. Freeman and Company: Randi Rossignol and Valerie Raymond. Mary Louise Byrd supervised the process from final manuscript to printed text. Diana Siemens and Eleanor Wedge were our copyeditor and proofreader. Victoria Anderson coordinated the media supplements. Blake Logan designed the text, and Ted Szczepanski and Christina Micek obtained and edited the many beautiful photographs. We thank Sheridan Sellers, our compositor and layout artist; Susan Wein, our production manager; and Bill Page, our illustration coordinator.

CHAPTER ONE