UNDERSTANDING EARTH

FOURTH EDITION

PRESS SIEVER GROTZINGER JORDAN

UNDERSTANDING EARTH

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MEET THE AUTHORS

Frank Press

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, the California Institute of Technology (Caltech), and the Massachusetts Institute of Technology (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.

John Grotzinger

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 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. These field-mapping studies are the starting point for more topical laboratory-based studies involving geochemical, paleontological, and geochronological techniques. 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 MIT faculty in 1988. From 1979 to 1990, he was engaged in regional mapping for the Geological Survey of Canada.

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 1998, he was appointed director of MIT's Earth Resources Laboratory. 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.

Raymond Siever

Raymond Siever is an internationally known expert in sedimentary petrology, geochemistry, and the evolution of oceans and the atmosphere. Dr. Siever is 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 (with F. J. Pettijohn and Paul Potter) the classic textbook *Sand and Sandstone* (Springer-Verlag). Dr. Siever is 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.

Thomas H. Jordan

Tom Jordan is a geophysicist whose interests include the composition, dynamics, and evolution of the solid Earth. He has conducted research into the nature of plate tectonic return flow, the formation of a thickened tectosphere beneath the ancient continental cratons, and the question of mantle stratification. He has developed a number of seismological techniques for elucidating structural features in the Earth's interior that bear on these and other geodynamic problems. He has also worked on modeling plate motions, measuring neotectonic deformations in plate-boundary zones, quantifying various aspects of 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 recently moved from MIT to the University of Southern California (USC), where he is the W. M. Keck Professor of Geological Sciences and Director of the Southern California Earthquake Center.

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

New Voices

It has been said that science is a history of superseded theories. New theories and innovative approaches to research and teaching are mostly the work of the next generation of scientist-authors. John Grotzinger of MIT and Tom Jordan of USC have joined the author team and will succeed Frank Press and Raymond Siever in future editions. We are lucky to partner with colleagues who share the philosophy and idealism represented in our book and bring a vision of the future to it as well. John's and Tom's influence is apparent in every chapter of the book and in its overall reorganization, most is evident in the prominent Earth systems approach and in the early coverage of plate tectonic theory.

A New Vision

When 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,* Fourth Edition, we are taking another step forward. One might characterize it as an attempt to answer the question: what comes after plate tectonics? We present geology as a unified, process-based science with the power to convey global meaning to geologic features wherever they are found. To do so, we draw 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 plates in motion, mountains being raised and eroded, crustal strain building up before an earthquake, global warming, glaciers retreating, sea level rising—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, revealing patterns of rising plumes and subducting plates. These new technologies also reveal startling new insights into links between climate and tectonics that have been poorly understood in the past, such as the possibility that the flow of metamorphic rocks through mountain belts may be strongly influenced by surface weathering patterns. The view of Earth as a system of interacting components subject to interference by humankind can no longer be called ideologically based opinion—it is backed by solid scientific evidence. The power of geology has never been greater. Geological science now informs the decisions of public policy leaders in government, industry, and community organizations.

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 link connecting geologic phenomena. For instance, **Chapter 4** now presents metamorphism in terms of plate interactions, **Chapter 8** offers a new section on plate tectonics and sedimentary basins, and **Chapter 9** has a significantly

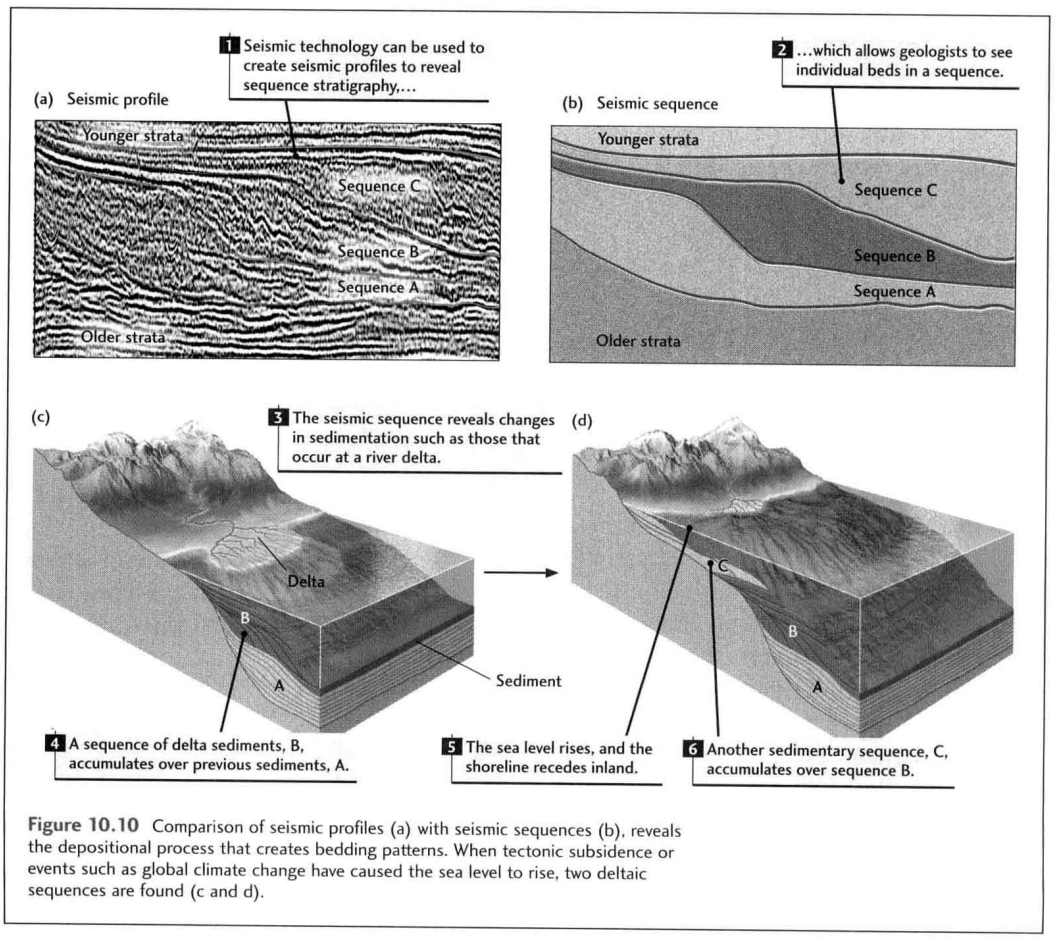


Figure 10.10 Comparison of seismic profiles (a) with seismic sequences (b), reveals the depositional process that creates bedding patterns. When tectonic subsidence or events such as global climate change have caused the sea level to rise, two deltaic sequences are found (c and d).

updated section on pressure-temperature-time paths and their significance for interpreting tectonic processes, including exhumation and uplift. The section of the book dedicated to surface processes is capped with a revised **Chapter 18**, in which landscape evolution integrates previous chapters and makes the case for significant interactions between climate and tectonics. This process-based treatment of a revitalized branch of Earth science is made possible only by having introduced plate tectonics early on.

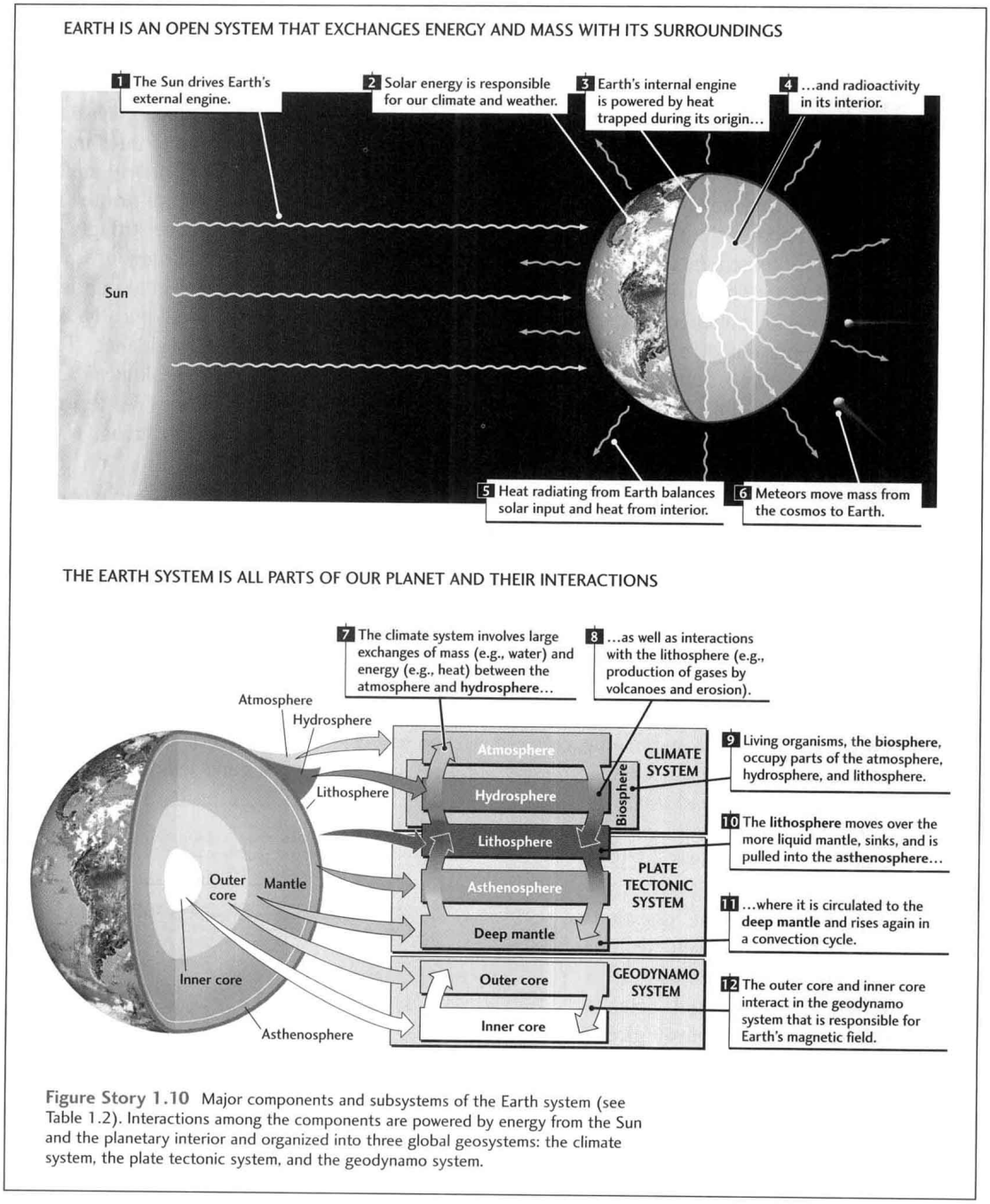


Figure Story 1.10 Major components and subsystems of the Earth system (see Table 1.2). Interactions among the components are powered by energy from the Sun and the planetary interior and organized into three global geosystems: the climate system, the plate tectonic system, and the geodynamo system.

Viewing Earth as a System

We begin with an expanded 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.

Chapter 5, Igneous Rocks: Solids from Melts, now includes a section entitled Spreading Centers as Magmatic Geosystems.

Volcanoes (**Chapter 6**) are discussed as geosystems, coupled to plate motions and interacting with the atmosphere, the oceans, and the biosphere.

The discussion of weathering in **Chapter 7** emphasizes the relationship between the climate geosystem and weathering. In **Chapter 9**, Metamorphism; **Chapter 18**, Landscape Evolution; and **Chapter 19**, Earthquakes, we stress the interactions among metamorphism, climate, plate tectonics, and the earthquake behavior of regional fault systems.

Chapter 21 delves into the convective engines of Earth's deep interior, which drive the plate tectonic and geodynamo systems.

Chapter 23 concludes with a discussion of how greenhouse gas emissions from fossil-fuel burning and other human activities may be changing Earth's climate system.

New Topics and Updates Throughout

- New material on exoplanets, early introduction of Earth system concepts, and a new section on Earth through geologic time (**Chapter 1**)
- A new section on spreading centers as magmatic geosystems (**Chapter 5**)
- A new section on volcanoes as geosystems, new material on large igneous provinces, and updated coverage of hot spots and the mantle plume hypothesis (**Chapter 6**)
- New sections on coral reefs and the evolutionary process and on plate tectonics and sedimentary basins (**Chapter 8**)

• Updated coverage of pressure-temperature paths (**Chapter 9**)

• Updated material on dome and basin formation (**Chapter 11**)

• New material on ice streaming, the instability of the West Antarctic ice sheet, and Snowball Earth (**Chapter 16**)

• Updated discussions of seafloor topography and methods for surveying the seafloor (**Chapter 17**)

• New sections on foreshocks and aftershocks, shaking intensity, plate boundaries and earthquakes, and regional fault systems (**Chapter 19**)

• An updated chapter on continental evolution, with a strong focus on North America that brings together recent insights about the history of mountain building and the formation of stable cratons (**Chapter 20**)

• An updated chapter on the deep interior, including new sections on mantle tomography, the geoid, and the geodynamo (**Chapter 21**)

• A completely revised chapter on Earth's environment and human impacts (**Chapter 23**)

Telling Stories with Words and Pictures

The most visible improvement in this new edition is the artwork. Our enduring goal to tell a story rather than provide aggregated facts is now apparent in the illustrations, particularly the new *Figure Stories*. Figure Stories bring photographs, line drawings, and text together to walk students through the major ideas behind important geologic processes.

Many more illustrations pair photographs and maps with schematics, so that students will see the context for the geologic phenomena as well as the underlying geologic features of what we can see with our eyes. Finally, much more descriptive text appears in the illustrations to help point students to their most important features.

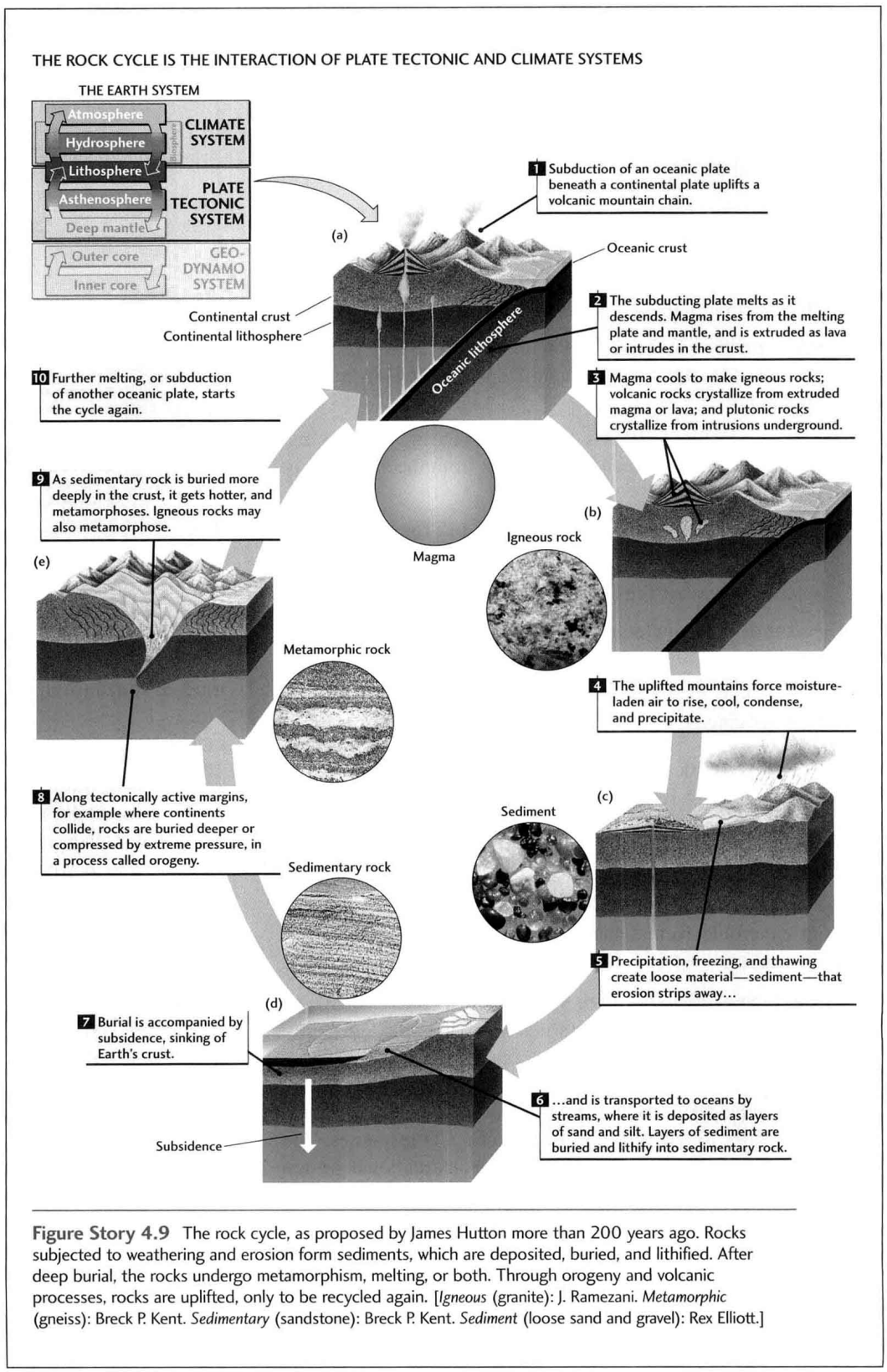


Figure Story 4.9 The rock cycle, as proposed by James Hutton more than 200 years ago. Rocks subjected to weathering and erosion form sediments, which are deposited, buried, and lithified. After deep burial, the rocks undergo metamorphism, melting, or both. Through orogeny and volcanic processes, rocks are uplifted, only to be recycled again. [*Igneous* (granite): J. Ramezani. *Metamorphic* (gneiss): Breck P. Kent. *Sedimentary* (sandstone): Breck P. Kent. *Sediment* (loose sand and gravel): Rex Elliott.]

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 0-7167-5782-6) contains

- High-resolution PowerPoint presentations, organized by chapter, that include *every* figure and table from the text
- PowerPoint presentations with Lecture Notes prepared by Peter Copeland and William Dupré of the University of Houston
- High-resolution JPEGs of *every* image in the text and from the Slide Set (including images from the slide sets of previous editions)
- Microsoft Word files of the *Test Bank* for easy editing and printing
- Adobe Acrobat files of the *Instructor's Manual*
- Animations, including over 40 *new* Macromedia Flash animations of the actual textbook figures that can be easily incorporated into PowerPoint presentations
- Short videos

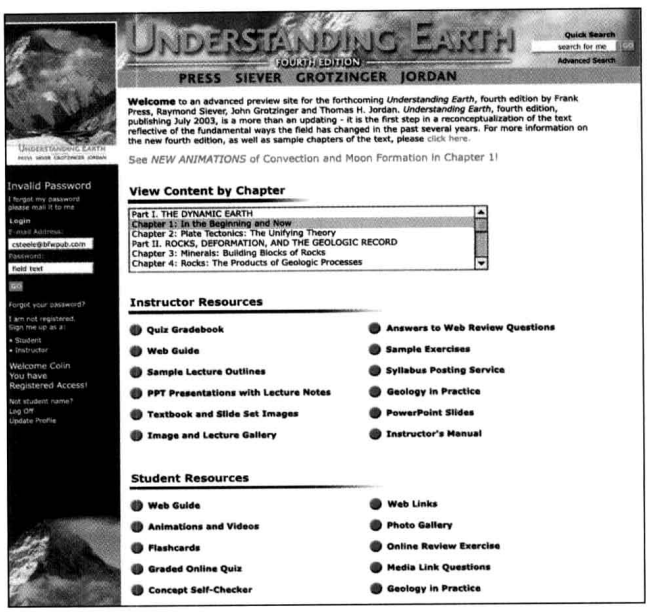
The **Test Bank** (ISBN 0-7167-5784-2 [print] and ISBN 0-7167-5783-4 [CD-ROM]), written by Simon M. Peacock of Arizona State University and Sondra Peacock, includes approximately 50 multiple-choice questions for each chapter (over 1000 total), some of which incorporate illustrations from the text. The CD-ROM provides the *Test Bank* files in an electronic format that allows professors to edit, resequence, and add questions.

The **Instructor's Resource Manual** (ISBN 0-7167-5781-8), written by Peter Kresan and Reed Mencke 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 and Instructor's CD resources. The *Instructor's Manual* also includes an instructional design section that contains teaching tips from many instructors at the University of Arizona Learning Center. The *Instructor's Manual* is also available on both the Instructor's CD and the Companion Web Site.

The **Overhead Transparency Set** (ISBN 0-7167-5780-X) includes *every* textbook figure and table in full-color acetate transparencies.

The **Slide Set with Lecture Notes** (ISBN 0-7167-5779-6), prepared by Peter Kresan of the University of Arizona, contains approximately 100 additional images that are all fully annotated in the accompanying booklet of lecture notes.

The **Companion Web Site** at **www.whfreeman.com/understandingearth** 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 JPEGs available on the Instructor's CD, the *Instructor's Manual,* and the Quiz Gradebook (which keeps track of students' Graded Online Quiz scores).

For Students

The **Companion Web Site*** at **www.whfreeman.com/understandingearth** 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 *new* 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

*The Student Companion Web Site is also available on request as a CD-ROM. Please contact your W. H. Freeman Sales Representative for more details.

• Photo Gallery, additional photographs of geologic phenomena

• Current Events in Geology, an archive of geologically relevant articles from popular news sources, updated monthly

The **Student Study Guide** (ISBN 0-7167-5776-1), written by Peter Kresan and Reed Mencke 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 **Lecture Notebook** (ISBN 0-7167-5778-8) is a workbook containing all the figures from the text in black and white with space for students to take notes.

The **EarthInquiry** 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 EarthInquiry module asks students to analyze real-time data in order 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 EarthInquiry, 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, and accessible and stimulating to students. To each one we are grateful.

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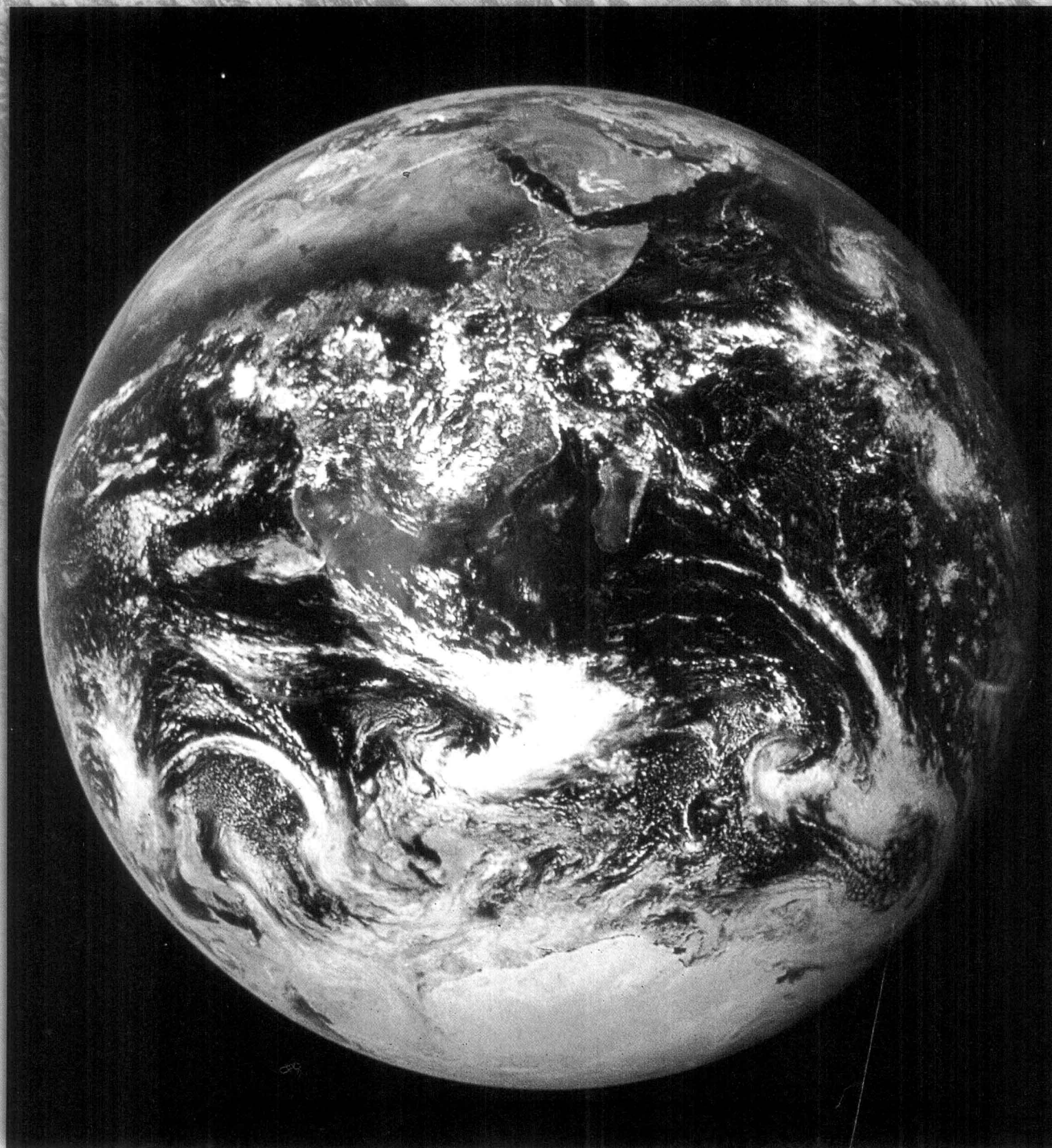

First image of the whole Earth showing the Antarctic and African continents, taken by the *Apollo 17* astronauts on December 7, 1972. [NASA.]

BRIEF CONTENTS

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