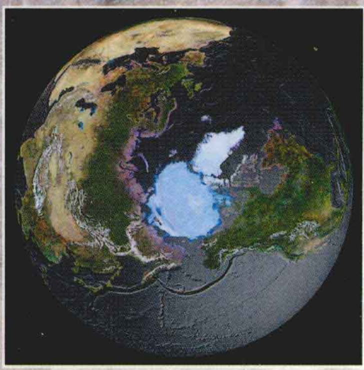
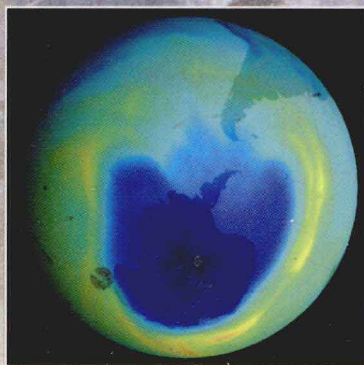
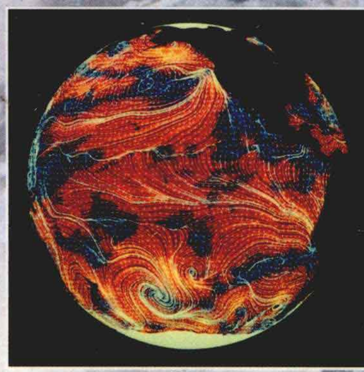
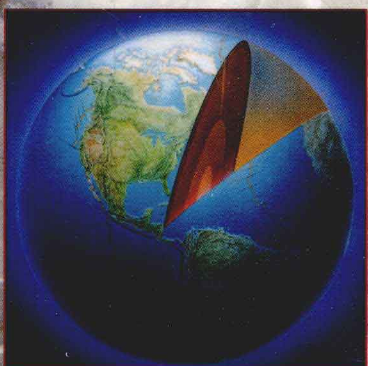
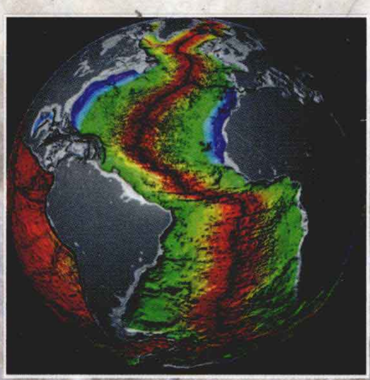
UNDERSTANDING EARTH

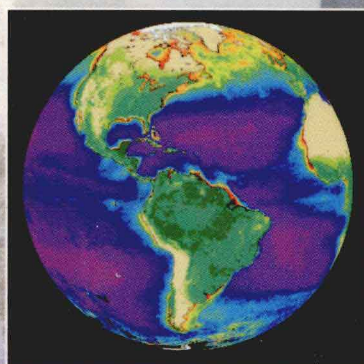












THIRD EDITION

Frank Press
Raymond Siever

UNDERSTANDING EARTH

Third Edition

Frank Press
The Washington Advisory Group

Raymond Siever
Harvard University

W. H. Freeman and Company
New York

To our children, and our children's children:
May they live in harmony with Earth's environment.

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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 built the instruments used and was a member of the team that discovered the fundamental difference between oceanic and continental crust. 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.

Dr. Press has advised four presidents on scientific issues. President Jimmy Carter appointed Frank Press Science Adviser to the President. President 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

Raymond Siever is an internationally known expert in sedimentary petrology, geochemistry, and the evolution of oceans and the atmosphere. Dr. Siever is a longtime 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 rock, especially sandstone and cherts.

In addition to co-writing the popular geology text *Earth* with Frank Press, Dr. Siever wrote (along with F. J. Pettijohn and Paul Potter) the classic textbook *Sand and Sandstone* (Springer-Verlag). His book *Sand* (W. H. Freeman and Company) is a highly regarded addition to the Scientific American Library series. He 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.

Preface

When we wrote our first textbook, *Earth,* geology was a field flush with the excitement of new discovery. Recognition of continental drift only a decade earlier had triggered a revolution in understanding our planet. For the first time, an all-encompassing synthesis of geological knowledge was being advanced. Plate-tectonic theory gave us a framework for learning about the immense forces turning cyclically in Earth's mantle and crust and their effects on the atmosphere, oceans, and biosphere. This new picture of Earth as a dynamic, coherent system was central to our writing of that book and its successor, *Understanding Earth.* We wanted to share with as many students as possible something of the exhilaration and intellectual excitement the profession was feeling. We have been enormously gratified by the warmth and loyalty with which each edition of *Earth* and, later, *Understanding Earth,* has been received.

More than thirty years into the plate-tectonics revolution, an understanding of the whole Earth system is more necessary than ever. The world in which we live has changed. With its growing population and increasingly industrial societies, our world is using more resources, contributing more to pollution of air, water, and land, and becoming more vulnerable to environmental disaster than ever before. Human disturbances of the environment now equal or exceed natural disturbances in magnitude and rate. Our planet enjoys a unique and delicate balance of conditions that allowed life to begin and countless life forms to flourish. Because they affect multiple systems and ultimately the whole Earth, relentless abuses of the environment are a threat to life on the planet.

Students now in college belong to the generation that will lead our world through the first decades of this new century. We believe that the social, political, and economic issues they face will prove many times more challenging than those we have already encountered. To make wise decisions about such issues as resource development, waste management, environmental protection, and land use, they will have a tremendous need for scientific literacy in general and an understanding of geology in particular. We have brought this conviction to our textbook.

Goals of the Third Edition

This book is written for a one-semester course in physical geology. In working on this new edition, we have been aware of how much the discipline of geology has changed in the last decade, not only through new discoveries but also in the realm of public policy. We have also seen how the teaching of this course has evolved, especially in the coming-of-age of educational media. These developments have convinced us that we continue on the right track. Now more than ever, students need to understand what physical geology teaches us about the world.

Our goal has been to retain the features that were so successful in the previous editions, such as:

- the organization into four parts
- the careful and scientifically accurate development of topics
- the use of real-life analogies
- the excellent illustration program
- end-of-chapter pedagogy, including **Summaries, Key Terms, Exercises, Thought Questions, Team Projects, Suggested Readings,**
- the interactive CD-ROM

At the same time many new features and updates have been added. We have also made the new edition somewhat shorter than its predecessor. The text was reviewed closely and objectively to remove material that was outdated, redundant, or rarely used in the course. The two resource chapters have been combined into a single chapter.

In revising *Understanding Earth,* we focused on making the material as current, accessible, and relevant to students' lives as possible. This Third Edition places new emphasis on Earth systems as an underlying theme to go along with the continuing theme of plate tectonics. Key issues in geology are highlighted in boxed features focusing on public policy and on interpreting Earth and its systems. We've added new chapter outlines, new, highlighted chapter goals, and many new and revised line drawings and photographs.

What's New

While continuing the successful pedagogy of the previous editions, we have added some exciting new features, including:

- **An Expanded Earth Systems Theme**
  This theme is now introduced in a separate section in Chapter 1, revisited in separate sections in many chapters throughout all four parts of the book, and brought together in the final chapter, "Earth Systems, Cycles, and Human Impacts."

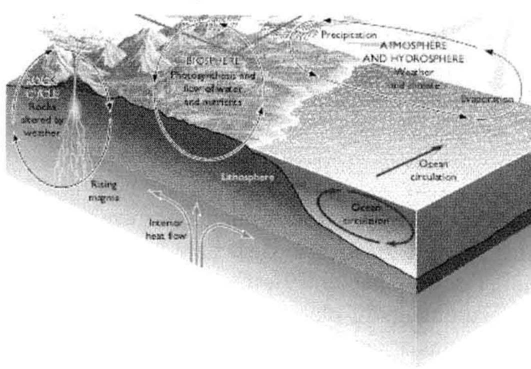


Figure 1.9 Earth's lithosphere, atmosphere, hydrosphere, and biosphere are linked. Driven by solar energy and Earth's internal heat, matter and energy cycle through them and determine weather, influence the formation and modification of rocks, and affect all living organisms.

Metamorphism and the Earth System

Metamorphism, like all other geologic processes, is part of the Earth system. A major aspect of metamorphism is Earth's internal heat, which drives metamorphism that is temperature controlled. By this control, Earth's interior runs the parts of the Earth system that govern metamorphic—and igneous—processes. As we will see later in this chapter, metamorphism results in the exhalation of water vapor, carbon dioxide, and other gases. These gases leak to the surface and contribute to the atmosphere, thus affecting processes that depend on atmospheric composition, such as weathering and carbon dioxide.

Sediments in the Earth System

The sedimentary stages of the rock cycle can be seen as linked components of the Earth system that governs the surface and shallow crust of Earth. For example, weathering and erosion are the results of interaction of the solid crust with the atmosphere and oceans. The more weathering that occurs, the more transportation of material there is, through flowing water, blowing wind, and moving ice. Deposition depends on transportation to bring it the materials to deposit. As deposits accumulate, they are buried by later arrivals of sediment. And, as sediments are buried, they begin to undergo diagenesis. The Earth system affecting the production and distribution of sediment links all of the system variables, such as tectonics and climate, to the specific mechanisms that produce sediments and sedimentary rocks. In this chapter and succeeding ones, we will see how individual processes, such as stream flow, play their roles in the system.

Changes in Sea Level: Glaciers and Earth Systems

You may recall from our coverage of the hydrologic cycle in Chapter 12 that the sea is the source of much of the water that falls as snow on the continents. Thus, during the Pleistocene epoch, the more water tied up as ice in continental glaciers, the less water there was in the ocean. As continental glaciers grew, sea level dropped everywhere on the globe. Accumulation of a large amount of ice—say, 400,000 km^3—corresponds to only a small drop in sea level—about 1 m—depending on the density of the ice and the configuration of the shallow ocean and low-lying land areas. But, during the maximum extent of the most recent glaciation 18,000 years ago, sea level dropped about 130 m, corresponding to an enormous volume of ice, about 70 million cubic kilometers, or almost three times the amount of ice on Earth today.

- **Newly Organized Boxed Features**
  Now organized into two types, *Earth Policy* and *Interpreting Earth and Its Systems*, these boxes draw on the experiences of one author as a presidential adviser and head of the National Academy of Sciences. These commentaries, many of them completely new, help students to see the importance of scientific research in the formation of vital public policy and in understanding the Earth system.

15.2 Interpreting Earth and Its Systems

Vostok and GRIP: Ice-Core Drilling in Antarctica and Greenland

At the Vostok science station in the frozen Antarctic, Russian scientists have been working year round since 1960 to discover the climatological history of Earth that is hidden in the ice, which may prove to be a source of insight into global climate change.

Russian scientists at Vostok science station in Antarctica carefully removing an ice core from a drill. The layers produced by annual cycles of ice formation are visible. [*R. J. Delmas, Laboratorie de glaciologie et géophysique de l'environnement, Centre National de la Recherche Scientifique*.]

In the 1970s, scientists at Vostok drilled boreholes 500 to 952 m deep in the eastern Antarctic ice and brought up a set of ice cores showing layers produced by annual cycles of ice formation from snow. Careful counting of the layers, working from the top down, revealed the age of the ice, much as tree rings reveal how old a tree is. This time-stratigraphic record of the ice proved to correlate with the temperatures thought to prevail when the layers formed. A high ratio of oxygen-18 to oxygen-16 in an ice layer indicates that the ice formed when the atmospheric temperature was relatively high. In addition, high concentrations of carbon dioxide, methane, and other "greenhouse gases," so called for their warming

Meanwhile, in the Arctic, a group of scientists in 1992 completed two years of drilling of the Greenland ice cap at the top of 3 km of ice. The Greenland Ice Core Project, better known as GRIP, is an outstanding example of international scientific cooperation in Europe. GRIP is sponsored by the European Science Foundation, which includes the governments of Belgium, Denmark, France, Germany, Iceland, Italy, Switzerland, and the United Kingdom. The GRIP core penetrated ice layers of the last glacial period (11,000 to 115,000 years before the present) and the last interglacial period (the Eemian, 115,000 to 135,000 years before the present) and stopped in layers going back 235,000 years, near the end of the preceding interglacial period, as shown in the adjoining diagram.

The GRIP core was complemented by a parallel core drilled 30 km to the west of the GRIP site by the United States Greenland Ice-Sheet Project, known as GISP2. The GRIP and GISP2 ice cores agreed very closely back 110,000 years, confirmed the glacial chronology at Vostok, and gave a good picture of tl changes in climate and atmospheric composition ol past 250,000 years. Analysis of the cores also corre earlier suggestions that the climates of the Eemian interglacial period were unstable and changed appreciably on a short time scale. The GRIP and G findings confirmed the remarkably rapid climate oscillations during the last glacial period. Both the and the Vostok cores yielded precise oxygen-18 pr that correlate closely with those of deep-sea sedim giving further detail and further supporting the chronology of glacial–interglacial climate change. become clear that temperature changes between gla and interglacial periods were much larger than scie had thought.

These triumphs have not been won without difficulties. Extreme care had to be taken not to mc contaminate the ice cores during coring operations, transportation to the laboratories, and storage until

23.3 Earth Policy

The Politics of Global Warming

World political leaders have at long last been convinced by scientists that using the atmosphere as a dump for carbon dioxide (CO_2) and other greenhouse gases could lead to global warming in the next 100 years with serious consequences. The readiness of governments to take joint action culminated in a historic conference that took place on December 10, 1997, in Kyoto, Japan, where 160 nations reached agreement to limit emissions of greenhouse gases. Each country negotiated from a position that corresponded to its own self-interest out of concern that curtailing the use of fossil fuels, the major source of greenhouse-gas emissions, would slow its economic growth. Nevertheless, all agreed to the Kyoto Protocol, a legally binding treaty. It requires 39 industrial countries currently responsible for three/fourths of the world release of CO_2 from fossil fuels to limit their annual emissions between 2008 and 2012 to a percentage of their 1990 levels. For the European Union, the reduction is 8 percent below 1990

The world's leading climate scientists, convened by the United Nations, warned that the first human-caused global warming has already been detected. Others pointed out that, because of the long lifetimes of CO_2 in the atmosphere, early action to reduce emissions is needed to reduce the long-term risk. Hundreds of America's leading economists declared in a statement: "As economists we believe that global climate change carries with it significant environment, economic, social, and geopolitical risks and that preventive steps are justified. Economic studies have found that there are many potential policies to reduce greenhouse gas emissions in which total benefits outweigh total costs." What they had in mind was a "no regrets" policy—one in which actions taken now make good sense economically and socially even if global warming does not occur. They view this policy as low-cost "insurance"—something done cheaply now to avoid high costs later. Examples of actions to be taken include raising energy taxes to induce conservation, using energy more efficiently, further developing and utilizing

- **New Topics and Updates Throughout** Included are new information on Mars (Chapter 1), the role of biology in weathering (Chapter 6), cold water carbonates (Chapter 6), computer models of alluvial sedimentation (Chapter 7), new dates on the geologic time scale (Chapter 9), real-time earthquake hazard warning (Chapter 18), new information on the duration of magnetic reversals (Chapter 19), the discovery of shear waves in the solid inner core (Chapter 19), new material on GPS measurements of plate motions (Chapter 20), new discoveries about the core–mantle boundary (Chapter 9), and much more.

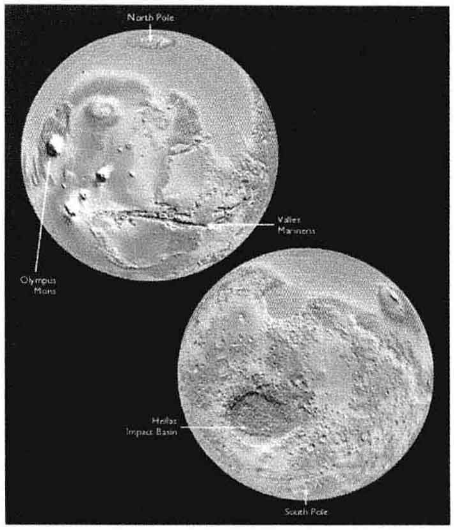


Figure 1.10 Mars topography revealed by laser altimeter measurements through 1999 from orbiting *Mars Global Surveyor* spacecraft. Note the elevation difference between the low, smooth northern hemisphere and the high, heavily cratered southern hemisphere. Although water is not discernible today on the surface of Mars (other than frozen in the polar icecaps), the northern lowlands were probably the site of an ocean some 3 to 4 billion years ago. The huge Hellas Basin is the remnant of a giant asteroid impact. It is 9 km deep and 2100 km across. The layer of materials thrown out contributes to the high topography of the southern hemisphere. Olympus Mons is probably the largest volcano in the solar system—27 km high and 600 km wide. The immense canyon Valles Marineris is 2700 km long and, in some places, 500 km wide and 6 km deep. The Grand Canyon is puny by comparison. Although it is believed to be a crack opened up by internal stretching forces, it also shows

The Core–Mantle Boundary Layer There is heightened interest in the **core–mantle boundary** (CMB), a layer some 200 km thick at the bottom of the mantle. Recent detailed studies of seismic waves that have traversed this layer have revealed large lateral variations in its thickness and composition, as well a drop in P-wave velocity of 10 percent or more in the bottommost 20 km of the CMB—an indication of partial melting. As is often the case in the early stages of rapid scientific de-

- **New Chapter Outlines** Outlines at the beginning of each chapter make it easier for students to navigate the material.
- **Newly Highlighted Chapter Goals** Specify the underlying themes of each chapter.
- **A Reduced Number of Key Terms** Consistent with our view that understanding concepts is more important than memorizing terms.
- **All New Chapter Opening and Part Opening Photos** Plus more than 70 new photos throughout the text.

The Rock Record and the Geologic Time Scale

- Timing the Earth
- Timing the Earth System
- Reconstructing Geologic History Through Relative Dating
- Radiometric Time: Adding Dates to the Time Scale
- From Three Lines of Evidence: A Reliable Dating Tool

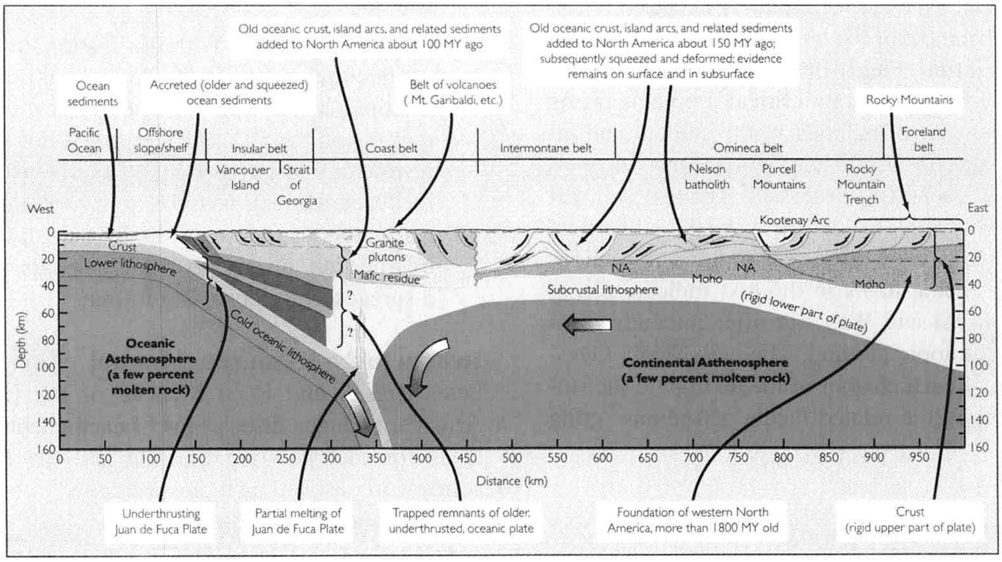
Throughout the past millions of years, Earth wa less stable than it currently seems to be: contin oceans, and mountains moved great distan Even at this instant, there is hardly a place on Earth is not moving vertically and horizontally, however slo Learning the patterns and rates of these movements key job of the geologist.

The geological processes that shape Earth's su and give structure to its interior take place over mil and billions of years.

In this chapter, we examine some of the way which geologists deal with these extraordinarily lon tervals, both to understand the processes and to re struct the geologic history of the planet.

One of the most important reasons for placing logical processes in their proper sequence is to learn a the evolution of the planet that we see today. When the Rocky Mountains formed? How often have there continent-sized glaciers in the past? What was hap ing in East Africa when early humans were evolving answer these kinds of questions, we need a tool fo ganizing and dating the rock record: a geologic cale to determine the sequence in which rock layers for and their ages, as well as a way to compare the age rocks situated continents apart. Two centuries of mo

- **Many Revised Figures** With more than 65 figures improved or entirely new (such as Figures 1.9, 2.7, 2.18, 5.29, 16.14, 18.11).



- **New Media Icons** Direct students to related animations and exercises on the Web site and CD-ROM.

This icon indicates a related virtual reality field trip.

This icon indicates a related animation or video.

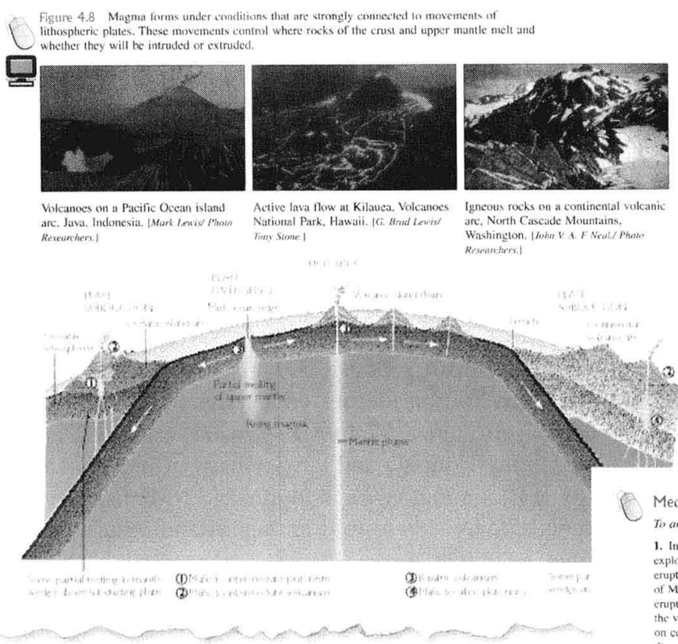
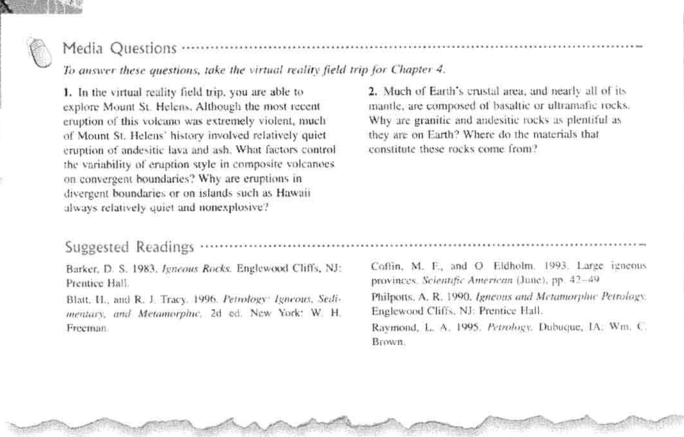


Figure 4.8 Magma forms under conditions that are strongly connected to movements of lithospheric plates. These movements control where rocks of the crust and upper mantle melt and whether they will be intruded or extruded.

Volcanoes on a Pacific Ocean island arc, Java, Indonesia. [*Mark Lewis/ Photo Researchers.*]

Active lava flow at Kilauea, Volcanoes National Park, Hawaii. [*G. Brad Lewis/ Tony Stone.*]

Igneous rocks on a continental volcanic arc, North Cascade Mountains, Washington. [*John V. A. F. Neal/ Photo Researchers.*]


Media Questions

To answer these questions, take the virtual reality field trip for Chapter 4.

1. In the virtual reality field trip, you are able to explore Mount St. Helens. Although the most recent eruption of this volcano was extremely violent, much of Mount St. Helens' history involved relatively quiet eruption of andesitic lava and ash. What factors control the variability of eruption style in composite volcanoes on convergent boundaries? Why are eruptions in divergent boundaries or on islands such as Hawaii always relatively quiet and nonexplosive?

2. Much of Earth's crustal area, and nearly all of its mantle, are composed of basaltic or ultramafic rocks. Why are granitic and andesitic rocks as plentiful as they are on Earth? Where do the materials that constitute these rocks come from?

Suggested Readings

Barker, D. S. 1983. *Igneous Rocks*. Englewood Cliffs, NJ: Prentice Hall.

Blatt, H., and R. J. Tracy. 1996. *Petrology: Igneous, Sedimentary, and Metamorphic*. 2d ed. New York: W. H. Freeman.

Coffin, M. F., and O. Eldholm. 1993. Large igneous provinces. *Scientific American* (June), pp. 42–49.

Philpotts, A. R. 1990. *Igneous and Metamorphic Petrology*. Englewood Cliffs, NJ: Prentice Hall.

Raymond, L. A. 1995. *Petrology*. Dubuque, IA: Wm. C. Brown.

- **New Media Questions** At the end of each chapter, these questions ask students to apply and evaluate what they have learned from the highly interactive virtual reality field trips on the CD-ROM.

Media/Supplements Package

A vast selection of print, visual, and electronic supplements is available to students and instructors using *Understanding Earth.* Many are completely new to this edition and take advantage of the best and latest technology. Twenty-three **Virtual Fieldwork** exercises on the accompanying CD-ROM focus on critical problems facing today's geologists. Also included in the student and instructor media are 17 useful animations and 14 short videos that show geological processes. The text and media are thoroughly integrated: The virtual reality field trips are extensively cross-referenced to relevant sections in the text, and media icons in the text indicate places where the CD-ROM and Web site offer interactive enhancements to the topic at hand. The new Media Questions at the end of each chapter in the text invite the student to first explore the related media before answering the questions.

For Instructors

Instructor's CD-ROM The Instructor's CD contains approximately 1000 images, 17 animations, and 14 short videos (the animations and video are also included on the student CD) from the new edition's text and slide set, from the CD of the Second Edition, and from other sources. These images are available in JPEG format or preloaded into our *Presentation Manager Pro* lecture software—which lets you assemble a playlist of still and animated graphics by following a few simple instructions.

Test Bank CD-ROM (Windows and Mac on One Disk) Prepared by Simon M. Peacock of Arizona State University and Sondra Peacock. Approximately 1200 multiple-choice questions, or 50 questions per chapter (including questions that incorporate geological drawings), in a format that lets instructors add, edit, and resequence questions. The CD is also the access point for . . .

- **Online Testing** With Diploma, the computerized test bank package from Brownstone Research Group, instructors can create and administer exams on paper, over a network, and now, over the Internet as well. Instructors can include graphics, movies, sound, and interactive activities in their questions Security features allow instructors to restrict tests to specific computers or time blocks. The package also includes an impressive site of grade-book and question-analysis features.
- **Online Companion at www.whfreeman.com/presssiever** Instructors have access to all student Web site features, plus all text art and slide set images in downloadable format.
- **Online Quizzing** With this feature, instructors can conduct quizzes over the Web using prewritten, multiple-choice questions (either new or from the quizzes on the CD and Web site—not from the instructor's test bank). Students get instant feedback and can take the quizzes multiple times; instructors can view results by quiz, by student, or by question, or can get weekly results via e-mail in a spreadsheet-compatible format.

Instructor's Resource Manual This manual, by Peter Kresan and Reed Mencke of the University of Arizona, includes discussions of each chapter and many ideas for incorporating the CD and the Internet into coursework, as well as figures designed to be copied and used as handouts and quizzes.

Printed Test Bank Prepared by Simon Peacock of Arizona State University and Sondra Peacock.

Slide Set with Lecture Notes Prepared by Peter Kresan of Arizona State University. Contains approximately 100 nontext images, all fully annotated in the lecture note booklet.

Overhead Transparency Set Includes full-color overheads of all diagrams from the book.

For Students

Understanding Earth 3.0 CD-ROM The CD for the Third Edition focuses on a series of 23 highly interactive self-guided **Virtual Fieldwork** exercises, created by Jeremy Dunning and Larry Onesti of Indiana University at Bloomington. Each multistaged exercise takes students step by step toward an understanding of, and possible solutions for, a specific, conceptual problem in geology, offering leading questions, exercises, specific electronic tools, and extensive cross-referencing to the text. Descriptions of each of these virtual reality field trips are listed in the Media Table of Contents. Also on the CD are 17 original animations of outstanding quality and clarity and 14 video clips (topics for these animations and videos are listed in the Media Table of Contents), a searchable text glossary, a photo gallery of 300 images supplemental to the text, and other useful resources.

Online Companion at

www.whfreeman.com/presssiever

For students, the *Online Companion* features all the CD features plus:

- Quizzes for each chapter with feedback for incorrect answers to prepare for exams.
- 34 Interactive Geology Exercises that encourage students to gain a deep visual sense of geological processes.
- Pertinent essays and articles on current geological issues that explore various topics in greater depth.
- An ever-current and growing list of Internet sources and links that encourage students to access other important geological Web sites.

Study Guide Peter L. Kresan, Reed Mencke, and Robert L. Bingham of the University of Arizona have designed the Study Guide to enhance use of the text with the Web site/CD-ROM. The Study Guide includes chapter summaries and outlines as well as exercises that incorporate the Web site/CD materials as resources.

Physical Geology of Canada This supplement, by Bob and AnnMarie Ryan of Dalhousie University, is offered packaged with the text to Canadian adopters. This adds to the text, chapter by chapter, relevant and interesting Canadian topical and regional information.

Lecture Notebook A student workbook consisting of key illustrations from the text, with space for taking notes.

Acknowledgments

It is a challenge both to geology instructors and to authors of geology texts to encompass the many important aspects of geology into a single course and to inspire interest and enthusiasm in the student. To meet this challenge, we have called on the advice of many colleagues teaching 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 deciding on 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.

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

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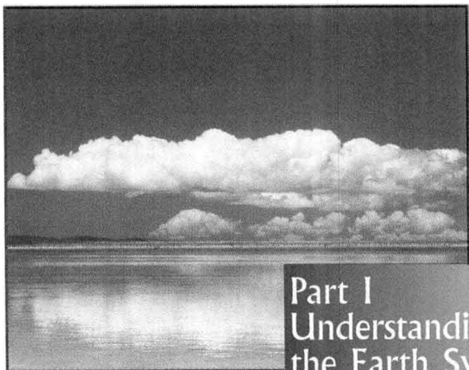


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