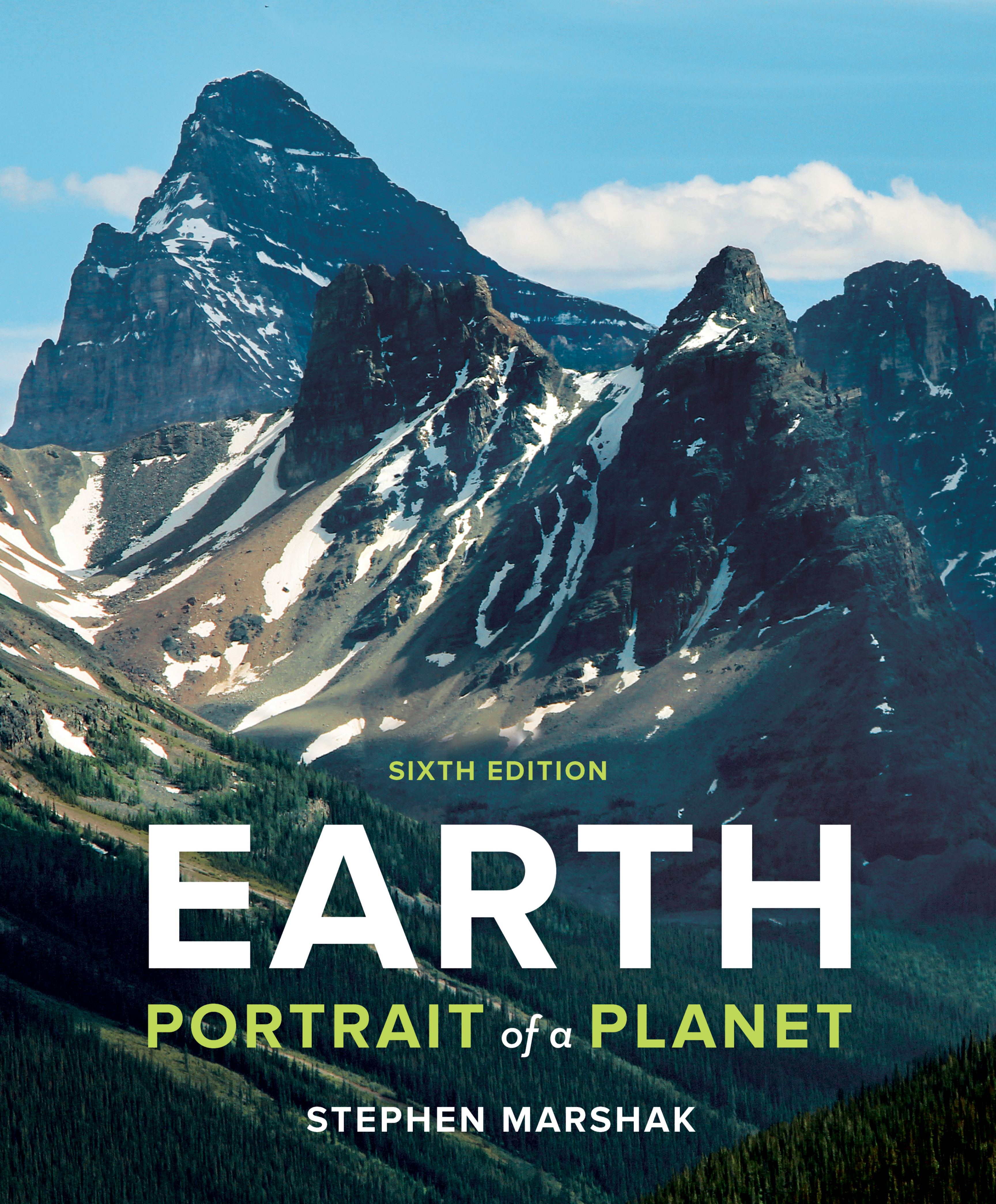

SIXTH EDITION

EARTH

PORTRAIT *of a* PLANET

STEPHEN MARSHAK

SIXTH EDITION

EARTH

PORTRAIT OF A PLANET

SIXTH EDITION

EARTH

PORTRAIT OF A PLANET

Stephen Marshak
UNIVERSITY OF ILLINOIS

W. W. NORTON & COMPANY
NEW YORK • LONDON

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To Kathy, David, Emma, and Michelle

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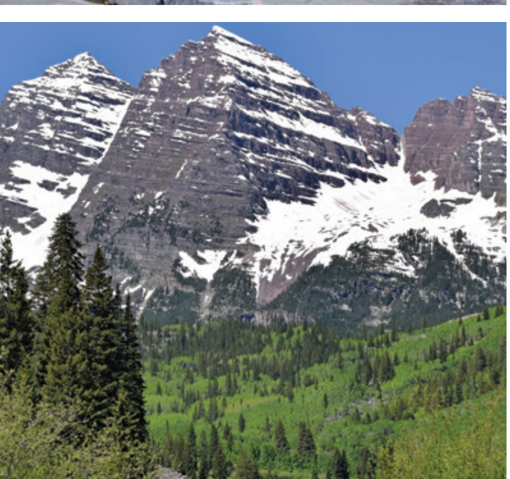

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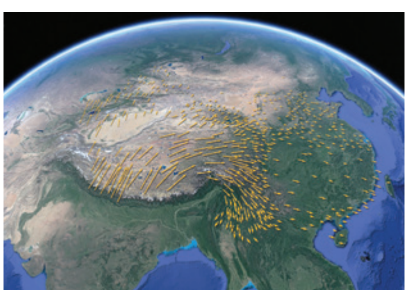

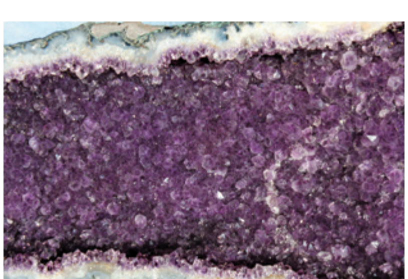

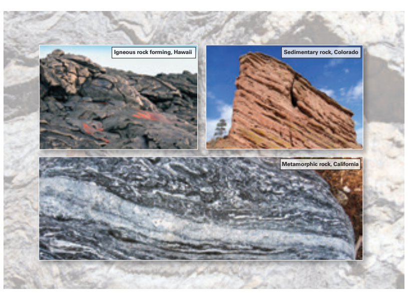
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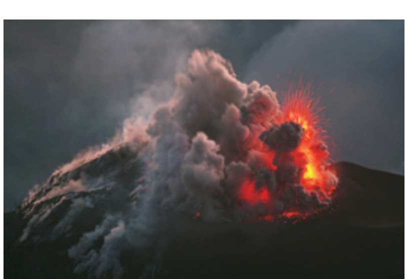

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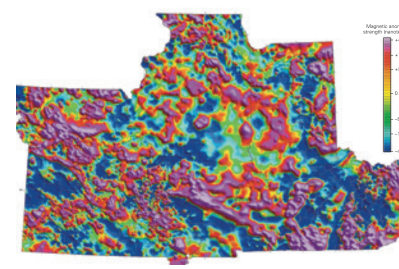

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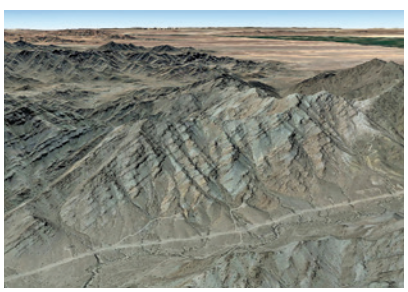

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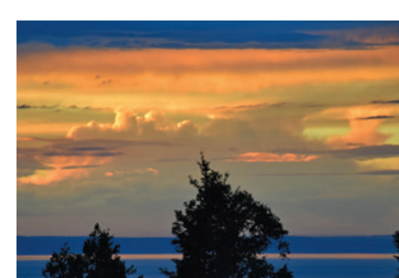

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Preface

Narrative Themes

Why do earthquakes, volcanoes, floods, and landslides happen? What causes mountains to rise? How do beautiful landscapes develop? How have climate and life changed through time? When did the Earth form, and by what process? Where do we dig to find valuable metals, and where do we drill to find oil? Does sea level change? Do continents move? The study of geology addresses these important questions and many more. But from the birth of the discipline, in the late 18th century, until the mid-20th century, geologists considered each question largely in isolation, without pondering its relation to the others. This approach changed, beginning in the 1960s, in response to the formulation of two paradigm-shifting ideas that have unified thinking about the Earth and its features. The first idea, called the *theory of plate tectonics*, states that the Earth's outer shell, rather than being static, consists of discrete plates that slowly move, relative to each other, so that the map of our planet continuously changes. Plate interactions cause earthquakes and volcanoes, build mountains, provide gases that make up the atmosphere, and affect the distribution of life on our planet. The second idea, the *Earth System concept*, emphasizes that the Earth's water, land, atmosphere, and living inhabitants are dynamically interconnected, so that materials constantly cycle among various living and nonliving reservoirs on, above, and within the planet. In the context of this idea, we have come to realize that the history of life is intimately linked to the history of the physical Earth, and vice versa.

Earth: Portrait of a Planet, Sixth Edition, is an introduction to the study of our planet that uses the theory of plate tectonics as well as the Earth System perspective throughout, to weave together a number of narrative themes, including:

1. The solid Earth, the oceans, the atmosphere, and life interact in complex ways.
2. Many important geologic processes involve the interactions of plates—pieces of the Earth's outer, relatively rigid shell.
3. The Earth is a planet formed, like other planets, from dust and gas. But, in contrast to other planets, the Earth is a dynamic place where new geologic features continue to form, and old ones continue to be destroyed.
4. The Earth is very old—indeed, about 4.56 billion years have passed since its birth. During this time, the map of the planet and its surface features have changed, and life has evolved.
5. Internal processes (driven by the Earth's interior heat) and external processes (driven by heat from the Sun) interact at the Earth's surface to produce complex landscapes.
6. Geologic knowledge can help society understand, and perhaps reduce, the danger of natural hazards, such as earthquakes, volcanoes, landslides, and floods.
7. Energy and mineral resources come from the Earth and are formed by geologic phenomena. Geologic study can help locate these resources and mitigate the consequences of their use.
8. Geology is a science, and the ideas of science come from observation, calculation, and experiment by researchers—it is a human endeavor. Furthermore, geology utilizes ideas from physics, chemistry, and biology, so the study of geology provides an excellent opportunity for students to improve their science literacy.

These narrative themes serve as the book's take-home message, a message that students hopefully will remember long after they finish their introductory geology course. In effect, the themes provide a mental framework on which students can organize and connect ideas, and can develop a modern, coherent image of our planet.

Pedagogical Approach

Educational research demonstrates that students learn best when they actively engage with a combination of narrative text and narrative art. Some students respond more to the words of a textbook, which help to organize information, provide answers to questions, fill in the essential steps that link ideas together, and help a student develop a context for understanding ideas. Some students respond more to figures and photos, for images help students comprehend, visualize, and remember the narrative. And some respond best to active learning, an approach where students can practice their knowledge by putting ideas to work. *Earth: Portrait of* *a Planet*, Sixth Edition, provides all three of these learning tools. The text has been crafted to be engaging, the art has been configured to tell a story, the chapters are laid out to help students internalize key principles, and the online activities have been designed both to engage students and to provide active feedback. This book's narrative doesn't merely provide a dry statement of facts. Rather, it provides the story behind the story—the reasoning and observation that led to our current understanding, as well as an explanation of the processes that cause a particular geologic phenomenon.

Each chapter starts with a list of *Learning Objectives* that frame key pedagogical goals for each chapter. These objectives are revisited in the end-of-chapter *Review Questions* and in the *Smartwork5 online activities*. *Take-Home Message* panels, which include both a brief summary and a key question, appear at the end of each section to help students solidify key themes before proceeding to the next section. Throughout the chapter, brief *Did You Ever Wonder?* questions prompt students with real-life questions they may already have thought about—answers to these questions occur in the nearby text. *See for Yourself* panels guide students to visit spectacular examples of geologic features, using the power of Google Earth. They allow students to apply their newly acquired knowledge to the interpretation of real-world examples. In the ebook version of the text, these features are live links that "fly" students to the precise locations discussed. Each chapter concludes with a concise, two-page chapter summary that reinforces understanding and provides a concise study tool at the same time. *Review Questions* at the end of each chapter include two parts: the first addresses basic concepts; and the second, labeled as *On Further Thought*, stimulates critical thinking opportunities that invite students to think beyond the basics. Some of the questions use visuals from the chapter.

To enhance active-learning opportunities, the *Smartwork5 online activity system* has been developed specifically for *Earth: Portrait of a Planet*, Sixth Edition. *Smartwork5* offers a wide range of visual exercises, including ranking, labeling, and sorting questions. *Smartwork5* questions make the textbook art interactive, and they integrate the Narrative Art Videos, animations, and simulations that have been created to accompany the text. Questions are designed to give students answer-specific feedback when they are incorrect, coaching them toward developing a thorough understanding of the core concepts discussed in the book.

Organization

The topics covered in this book have been arranged so that students can build their knowledge of geology on a foundation of overarching principles. To set the stage, the book starts by describing processes that led to the formation of the Earth, in the context of scientific cosmology. It then introduces the architecture of our planet, from surface to center. With this basic background, students are prepared to delve into plate tectonics theory. Plate tectonics appears early in the book, so that students can relate the content of subsequent chapters to the theory. Knowledge of plate tectonics, for example, helps students understand the suite of chapters on minerals, rocks, and the rock cycle. Knowledge of plate tectonics and rocks together, in turn, provides a basis for studying volcanoes, earthquakes, and mountains. And with this background, students are prepared to see how the map of the Earth has changed through the vast expanse of geologic time, and how energy and mineral resources have developed. The book's final chapters address processes occurring at or near the Earth's surface, such as the flow of rivers, the evolution of coasts, and the carving of landscapes by glaciers. We also consider the problems that the Earth's surface processes can cause, such as landslides and floods. This part concludes with a topic of growing concern in society—global change, particularly climate change.

In addition to numbered chapters, the book contains several *Interludes*. These are, in effect, "mini-chapters" that focus on topics that are self-contained but are not broad enough to require an entire chapter. By placing selected topics in interludes, we can keep the numbered chapters reasonable in length, and can provide additional flexibility in sequencing topics within a course.

Although the sequence of chapters and interludes was chosen for a reason, this book is designed to be flexible enough for instructors to choose their own strategies for teaching geology. Therefore, each self-contained chapter reiterates relevant material where necessary. For example, if instructors prefer to introduce minerals and rocks before plate tectonics, they simply need to reorder the reading assignments. A low-cost, loose-leaf version of the book allows instructors to have students bring to class only the chapters that they need.

We have used a tiered approach in highlighting terminology in *Earth: Portrait of a Planet*, Sixth Edition. Terminology, the basic vocabulary of a subject, serves an important purpose in simplifying the discussion of topics. For example, once students understand the formal definition of a mineral, the term can be used again in subsequent discussion without further explanation or redundancy. Too much new vocabulary, however, can be overwhelming. So we have tried to keep the book's *Guide Terms* (set in boldface and referenced at the end of each chapter for studying purposes) to a minimum. Other terms, less significant but still useful, appear in italic when presented, to provide additional visual focus for students as they read the chapters. We take care not to use vocabulary until it has been completely introduced and defined.

Special Features of this Edition

Earth: Portrait of a Planet, Sixth Edition, contains a number of new or revised features that distinguish it from all competing texts.

Narrative Art, *What a Geologist Sees,* and *See for Yourself*

It's difficult to understand many features of the Earth System without being able to see them. To help students visualize these and other features, this book is lavishly illustrated with figures that try to give a realistic context for the particular feature, without overwhelming students with too much extraneous detail. The talented artists who worked on the book have used the latest computer graphics software, resulting in the most sophisticated pedagogical art ever provided by a geoscience text. Many figures have been updated with an eye toward improving students' 3-D visualization skills. The figures have also been reconfigured to be more friendly and intuitive. All of the plate tectonics figures have been revised in this Sixth Edition in order to provide students the clearest, most vibrant, and most accurate visual understanding of the Earth's interior dynamics.

In addition to the drawn art, the book also boasts over 1,000 stunning photographs from all around the world. Many of the photographs were taken by the author, in order to illustrate the exact concept under discussion. Where appropriate, photographs are accompanied by annotated sketches named *What a Geologist Sees*. These figures allow students to see how geologists perceive the world around them and to encourage students to start thinking like geologists.

Throughout the book, drawings and photographs have been integrated into *narrative art*, which has been laid out, labeled, and annotated to tell a story—the figures are drawn to teach! Subcaptions are positioned adjacent to relevant parts of each figure, labels point out key features, and balloons provide important annotation. Subparts are arranged to convey time progression, where relevant. The color schemes of drawings have been tied to those of relevant photos, so that students can easily relate features in the drawings to those in the photos. The author has also written and narrated over a dozen Narrative Art videos, which bring this art to life.

Google Earth provides an amazing opportunity for students to visit and tour important geologic sites wherever they occur. Throughout the book, we provide *See for Yourself* panels, which offer coordinates and descriptions of geologic features that students can visit at the touch of a finger, or the click of a mouse. The adjacent box provides a quick guide for using these panels.

Featured Paintings—*Geology at a Glance*

In addition to individual figures, artists Gary Hincks and Stan Maddock have created spectacular two-page annotated paintings for each chapter. These paintings, called *Geology at a Glance*, integrate key concepts introduced in the chapters, visually emphasize the relationships between components of the Earth System, and allow students a way to review a subject . . . at a glance. The Sixth Edition includes three new paintings, illustrating the formation of minerals (Chapter 5), the life cycle of a tornado (Chapter 20), and the consequences of sea-level change (Chapter 23).

Enhanced Coverage of Current Topics

To ensure that *Earth: Portrait of a Planet* continues to reflect the latest research discoveries and help students understand geologic events that have been featured in current news, we have updated many topics throughout the book. For example, the Sixth Edition discusses the causes of and lessons learned from recent natural disasters such as Hurricanes Harvey, Irma, and Maria (Chapter 20), and assesses the impact of recent earthquakes in Nepal, Japan, and Ecuador (Chapter 8). The Sixth Edition also includes updated coverage of the economics of oil and other energy resources, and the difference between conventional and unconventional reserves (Chapter 14). These topics, along with expanded discussion of climate change and its impacts (Chapter 23), highlight the relevance of physical geology concepts and phenomena to students' lives today.

Other notable new content in the Sixth Edition includes a revision of the paleomagnetism discussion to makes this topic more accessible (Chapter 3); new coverage of mantle modeling technology, and how it has changed our understanding of the appearance and behavior of subducted plates (Interlude D); new introductions to the concepts of phylogenetics, ecosystems, and paleoecology (Interlude E); and an intensive revision of the explanation of the Coriolis force and other atmospheric concepts, using text and figures developed in collaboration with atmospheric scientist Robert Rauber of the University of Illinois, coauthor of the First Edition of a separate book, *Earth Science*. This reworking ensures that students have access to the most contemporary and accurate explanations of these important processes (Chapter 18).

See for Yourself
Using *Google Earth*

Visiting the SFY Field Sites Identified in the Text

There's no better way to appreciate geology then to see it first-hand in the field. The challenge is that the great variety of geologic features that we discuss in this book can't be visited from any one locality. So, even if your class takes geology field trips during the semester, at best you'll see examples of just a few geologic settings. Fortunately, Google Earth makes it possible to fly to spectacular geologic field sites anywhere in the world in a matter of seconds—you can take a virtual field trip electronically. In each chapter in this book, *See for Yourself* panels identify geologic sites that you can explore on your own computer (Mac or PC) using Google Earth software, or on your Apple/Android smartphone or tablet with the appropriate Google Earth app.

To get started, follow these three simple steps:

1. Check to see if Google Earth is installed on your personal computer, smartphone, or tablet. If not, download the free software from https://www.google.com/earth, or access the desktop version at earth.google.com. You can also download the app from the Apple or Android app store.
2. Each See for Yourself panel in the margin of the chapter provides a thumbnail photo of a geologically interesting site, as well as a very brief description of the site. The panel also provides the latitude and longitude of the site.
3. Open Google Earth and enter the coordinates of the site in the search window. As an example, let's find Mt. Fuji, a beautiful volcano in Japan. We note that the coordinates in the See for Yourself panel are as follows:

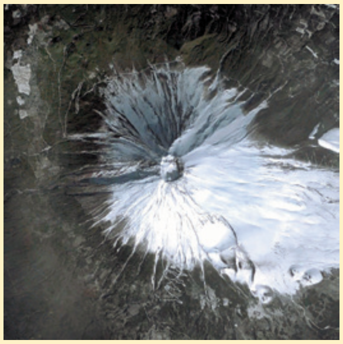
Latitude	35°21′41.78″N
Longitude	138°43′50.74″E

Type these coordinates into the search window of Google Earth as:

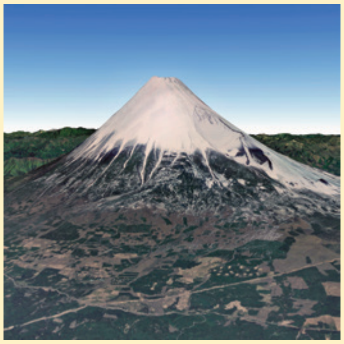
35 21 41.78N, 138 43 50.74E

with the degree, minute, and second symbols left blank. When you click "Enter" or "Return," your device will bring you to the viewpoint right above Mt. Fuji, as illustrated by the left-hand thumbnail above.

Google Earth contains many built-in and easy-to-use tools that allow you to vary the elevation, tilt, orientation, and position of your viewpoint, so that you can tour around the feature, see it from many different perspectives, and thus develop a three-dimensional sense of the feature. In the case of Mt. Fuji, you'll be able to see its cone-like shape and the crater at its top. By zooming out to higher elevation, you can instantly perceive the context of the given geologic feature—for example, if you fly up into space above Mt. Fuji, you will see its position relative to the tectonic plate boundaries of the western Pacific. The thumbnail on the right below shows the view of the same location you'll see if you tilt your viewing direction and look north.



Vertical view, looking down.

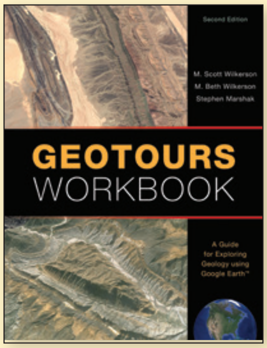


Inclined view, looking north.

Need More Help?

If you're having trouble, please visit digital.wwnorton.com/earth6. There you will find a video showing how to download and install Google Earth, additional instructions on how to find the *See for Yourself* sites, links to Google Earth videos describing basic functions, and links to any hardware and software requirements. Also, notes addressing Google Earth updates will be available at this site.

We also offer a separate book—the *Geotours Workbook,* Second Edition (ISBN 978-1-324-00096-9), by Scott Wilkerson, Beth Wilkerson, and Stephen Marshak—that identifies additional interesting geologic sites to visit, provides active-learning exercises linked to the sites, and explains how you can create your own virtual field trips.



Smartwork5 Online Activities

Smartwork5

Smartwork5 is Norton's tablet-friendly, online activity platform. Both the system and its physical geology content were designed with the feedback of hundreds of instructors, resulting in unparalleled ease of use for students and instructors alike.

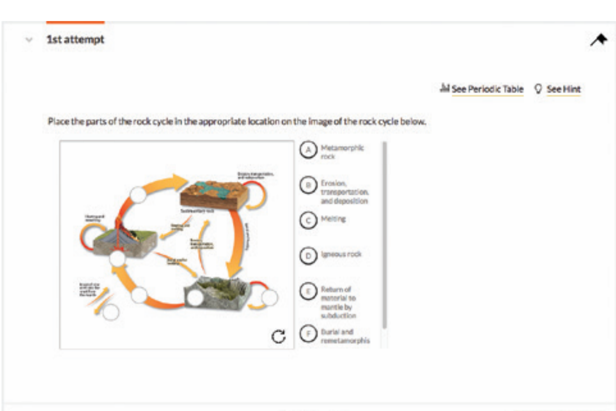
Smartwork5 features easy-to-deploy, highly visual assignments that provide students with answer-specific feedback. Students get the coaching they need to work through the assignments, while instructors get real-time assessment of student progress via automatic grading and item analysis. The question bank features a wide range of higher-order questions such as ranking, labeling, and sorting. All of the Narrative Art videos, animations, and interactive simulations are integrated directly into Smartwork5 questions—making them assignable. Smartwork5 also contains *What a Geologist Sees* questions that take students to sites not mentioned in the book, so they can apply their knowledge just as a geologist would. In addition, Smartwork5 offers reading quizzes for each chapter and *Geotours*-guided inquiry activities using Google Earth.

Based on instructor feedback, Smartwork5 offers three types of pre-made activity:

- Chapter **Reading Quizzes**, designed to help students prepare for lecture
- Chapter **Activities**, consisting of highly visual exercises covering all chapter Learning Objectives
- **Geotours Worksheets—**guided inquiry activities that use Google Earth

Smartwork5 is fully customizable, meaning that instructors can add or remove questions, create assignments, write their own questions, or modify ours. Easy and intuitive tools allow instructors to filter questions by chapter, section, question type, and learning objective.

SMARTWORK5 features a variety of question types to get students working hands-on with geologic concepts.



All Smartwork5 content is written by geology instructors. Our Sixth Edition Smartwork5 authors include Heather Lehto of Angelo State University, Tobin Hindle of Florida Atlantic University, Christine Clark of Eastern Michigan University, and Jacqueline Richard of Delgado Community College.

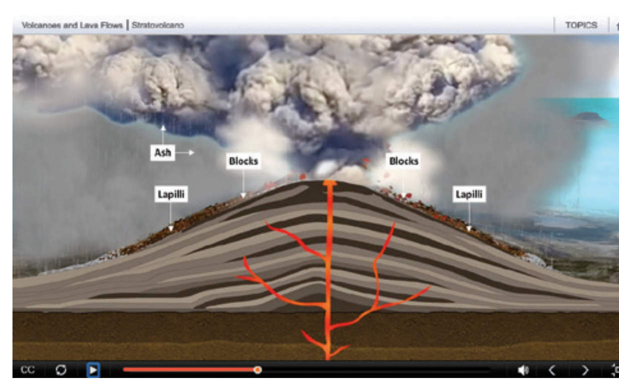
Media and Ancillaries

Animations, Simulations, and Videos

Earth: Portrait of a Planet, Sixth Edition, provides a rich collection of new animations, developed by Alex Glass of Duke University, working with Heather Cook of California State University, San Marcos. These illustrate geologic processes in a consistent style and with a 3-D perspective. Interactive simulations allow students to control variables and see the resulting output. The newest simulations are designed to help students understand basic terminology.

Narrative Art Videos, written and narrated by Stephen Marshak, bring both textbook art and supplementary field photos to life. And a robust suite of over 100 real-world video clips illustrate key processes, concepts, and natural phenomena.

ANIMATIONS illustrate geologic processes.



All the videos, animations, and interactive simulations are free, require no special software, and are available in a variety of settings to offer ultimate flexibility for instructors and students: on the Norton Digital Landing Page (digital.wwnorton.com/earth6); in LMS-compatible coursepacks; integrated into Smartwork5 questions; linked to the ebook; and as linked resources in the new Interactive Instructor's Guide that accompanies the text (iig.wwnorton.com/earth6/full).

Mobile-ready E-book

Earth Portrait of a Planet, Sixth Edition is available in a new format perfect for tablets and phones. Within the ebook, art expands for a closer look, links send you to geologic locations in Google Maps, animations and videos link out from each chapter, and pop-up key terms allow for quick review. It's also easy to highlight, take notes, and search the text.

The *Geotours Workbook*

Created by Scott Wilkerson, Beth Wilkerson, and Stephen Marshak, the *Geotours Workbook,* Second Edition, provides active-learning opportunities that take students on virtual field trips to see outstanding examples of geology at locations around the world, using Google Earth. Arranged by topic, the questions in the *Geotours Workbook* have been designed for auto-grading, and they are available as worksheets, both in print format (these come free with the book and include complete user instructions and advanced instruction) or electronically with automatic grading through *Smartwork5* or your campus LMS. The *Geotours Workbook* also provides instructions that will allow instructors or students to make their own geotours. Request a sample copy to preview each worksheet.

Lecture PowerPoints and Image Files

Norton provides a variety of electronic presentations of art and photographs in the book to enhance the classroom experience. These include:

- *Lecture Slides*—Designed for instant classroom use, these slides utilize photographs and line art from the book in a form that has been optimized for use in the PowerPoint environment. The art has been relabeled and resized for projection. Lecture Slides also include supplemental photographs. For the Sixth Edition, the lecture bullet PowerPoints were revised by Brian Zimmer of Appalachian State University, and accuracy-checked by Lalo Guerrero of Portland Community College.
- *Labeled and Unlabeled Image Files*—These include all art from the book, formatted as JPEGs, pre-pasted into PowerPoints. We offer one set in which all labeling has been stripped for use in quizzes and clicker questions, and one set in which the labeling has been retained. Individual JPEGs are also available for download.
- *Quarterly Update PowerPoints*—Norton offers a quarterly update service that provides new PowerPoint slides, with instructor support, covering recent geologic events. Monthly updates are authored by Paul Brandes.

Instructor's Manual and Test Bank

The *Instructor's Manual*, prepared by Robin Nagy of Houston Community College, and accuracy-checked by Kerry Workman-Ford of California State University, Fresno, is designed to help instructors prepare lectures and exams. It contains detailed Learning Objectives, Chapter Summaries, and complete answers to the end-of-chapter *Review Questions* and *On Further Thought Questions* for every chapter and interlude.

The *Test Bank*, written by Heather Cook of California State University, San Marcos, and Geoffrey Cook of University of California, San Diego, has been revised not only to correlate with this new Edition, but to provide greater, more rounded assessment than ever before. Expert accuracy checkers Angela Aranda of California State University, Fullerton, and Haraldur Karlsson of Texas Tech University have ensured that every question in the Test Bank is scientifically reliable and truly tests students' understanding of the most important topics in each chapter, so that the questions can be assigned with confidence.

Interactive Instructor's Guide—https://iig.wwnorton.com/earth6/full

New for the Sixth Edition, the Interactive Instructor's Guide is a dynamic, searchable, online resource that provides *all* instructor resources in one place. With content tagged by book chapter and section, learning objective, and keyword, instructors can find what they need, when they need it—whether a Real World Video, an in-class activity idea, or the Lecture Slides for the chapter.

LMS Coursepacks

Available at no cost to professors or students, *Norton Coursepacks* bring high-quality Norton digital media into a new or existing online course. *Coursepacks* contain ready-made content for your campus LMS. For *Earth: Portrait of a Planet*, Sixth Edition, content includes the full suite of animations, simulations, and videos keyed to core figures in each chapter; the Test Bank; reading quizzes authored by Cynthia Liutkus-Pierce of Appalachian State University and accuracy-checked by Karen Koy of Missouri Western State University; new European case studies; Geotour questions; vocabulary flashcards; and links to the ebook.

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Developing and revising this book is done in partnership with my wife, Kathy. She carries out the immense task

of pulling together content and writing changes introduced in my other books, *Essentials of Geology,* Fifth Edition, and *Earth Science*, First Edition, including suggestions from users and reviewers, to produce *Earth: Portrait of a Planet*, Sixth Edition. Kathy edits new text, cross-checks many sets of proofs, and manages the never-ending inflow and outflow of proofs that perpetually occupy our dining-room table. Without her efforts, the updating of *Earth: Portrait of a Planet* through the years would not be possible. We are grateful to our daughter, Emma, and our son, David, who provided valuable feedback and several of the photos—and who also served as scale in some of the photos. They allowed "the book" to become a member of our household, for more than two decades, and tolerated the overabundance of geo-stops on family trips.

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Moving a new edition of *Earth: Portrait of a Planet* from concept to completion involves a large team of professionals. The artists, Joanne Brummett and Stan Maddock, in Champaign, Illinois, have created beauty and enhanced pedagogy with the new illustrations that they have rendered for this Edition. Their work, along with the past work of other artists once anchored at Precision Graphics, set the bar for the quality of art in geology textbooks. Stan established the initial style of the book's art and developed innovative ways of visualizing geologic phenomena. Trish Marx has done a fantastic job with the Herculean task of finding, organizing, and crediting photographs and bringing the photo selection process into the 21st century. Lissi Sigillo creatively developed a clean and friendly page design. I am also grateful to Rob Bellinger, Cailin Barrett Bressack, Liz Vogt, Kim Yi, Marcus Van Harpen, Leah Clark, Francesca Olivo, Arielle Holstein, Gina Forsythe, and Kelly Smith for their innovative approach to ancillary and e-media development. Thanks also go to Marcus Van Harpen, Lizz Thabet, and Mateus Teixeira for their work on the tablet and mobile e-books, and to associate production director Benjamin Reynolds, who coordinated the back-and-forth between the publisher and various vendors and suppliers. Norma Sims-Roche has done an excellent job as copy editor for this Sixth Edition, and Associate Editor Rachel Goodman provided consistent editorial support and trouble-shooting throughout the process of making this book.

The six editions of this book and its cousin, *Essentials of Geology*, have benefited greatly from input by expert reviewers for specific chapters, by general reviewers of the entire book, and by comments from faculty and students who have used the book and were kind enough to contact the author or the publisher with suggestions and corrections. We gratefully acknowledge the contributions of the individuals listed below, who have provided invaluable input into this and past editions either through comments or reviews. I apologize if I've inadvertently left anyone off the list.

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Jamie Dustin Mitchem, California University of Pennsylvania
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Jeffrey Schaffer, Napa Valley Community College
Roy Schlische, Rutgers University
Sahlemedhin Sertsu, Bowie State University
Anne Sheehan, University of Colorado
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Stephen Marshak

About the Author

Stephen Marshak is a professor of geology at the University of Illinois, Urbana-Champaign, where he also serves as the Director of the School of Earth, Society, and Environment. He holds an A.B. from Cornell University, an M.S. from the University of Arizona, and a Ph.D. from Columbia University. Steve's research interests lie in structural geology and tectonics, and he has participated in field projects on a number of continents. Steve loves teaching and has won his college's and university's highest teaching awards. He also received the 2012 Neil Miner Award from the National Association of Geoscience Teachers (NAGT), for "exceptional contributions to the stimulation of interest in the Earth sciences." In addition to research papers and *Earth: Portrait of a Planet,* Steve has authored *Essentials of Geology*, and has co-authored *Earth Science; Laboratory Manual for Introductory Geology; Earth Structure: An Introduction to Structural Geology and Tectonics*, and *Basic Methods of Structural Geology*.

ANOTHER VIEW Geology students enjoying the view from outcrops in northern Scotland.

PRELUDE

And Just What Is Geology?

By the end of this prelude, you should be able to . . .

A. describe the scope and applications of geology.

B. explain the foundational themes of modern geologic study.

C. demonstrate how geologists employ the scientific method.

D. provide a basic definition of the theory of plate tectonics.

E. explain what geologists mean by the Earth System concept.

F. name the main layers of the Earth's interior.

Civilization exists by geological consent, subject to change without notice.

—Will Durant (American historian, 1885–1981)

P.1 In Search of Ideas

We arrived in the late-night darkness at a campsite in western Arizona. Here in the desert, so little rain falls over the course of a year that hardly any plants can survive, and rocks form ledges on many hills. Under the dry sky, there's no need for tents, so we could rest under the stars with our sleeping bags on a bed of sand. At dawn, the red rays of the first sunlight made the slope of the steep-sided hill near our campsite start to glow, and we could see our target, a prominent ledge of rusty-brown rock near the top of the hill. To reach it, though, we'd have to climb a steep slope littered with jagged boulders.

After a quick breakfast, we loaded our day packs with water bottles and granola bars, slathered on a layer of sunscreen, and set off toward the slope. It was the breezeless morning of what was going to be a truly hot day, and we wanted to gain elevation before the Sun rose too high in the sky. After a tiring hour finding our way through the boulder obstacle course, we reached the base of the ledge and decided to take a rest before our final ascent. But just as we leaned back to rest our backs against a rock, we heard an unnerving vibration. Somewhere nearby, too close for comfort, a rattlesnake shook an urgent warning. Rest would have to wait, and we scrambled up the ledge. It was the right choice, for the view from the top of the surrounding landscape was amazing **(Fig. P.1a)**. But the rocks beneath our feet were even more amazing. Close up, we could see curving ribbons of light and dark layers, cut by stripes of white quartz. The ledge preserved the story of a distant age in our planet's past when the rock we now stood on was kilometers below ground level and was able to flow like soft plastic, but ever so slowly **(Fig. P.1b)**. We now set to the task of figuring out what it all meant.

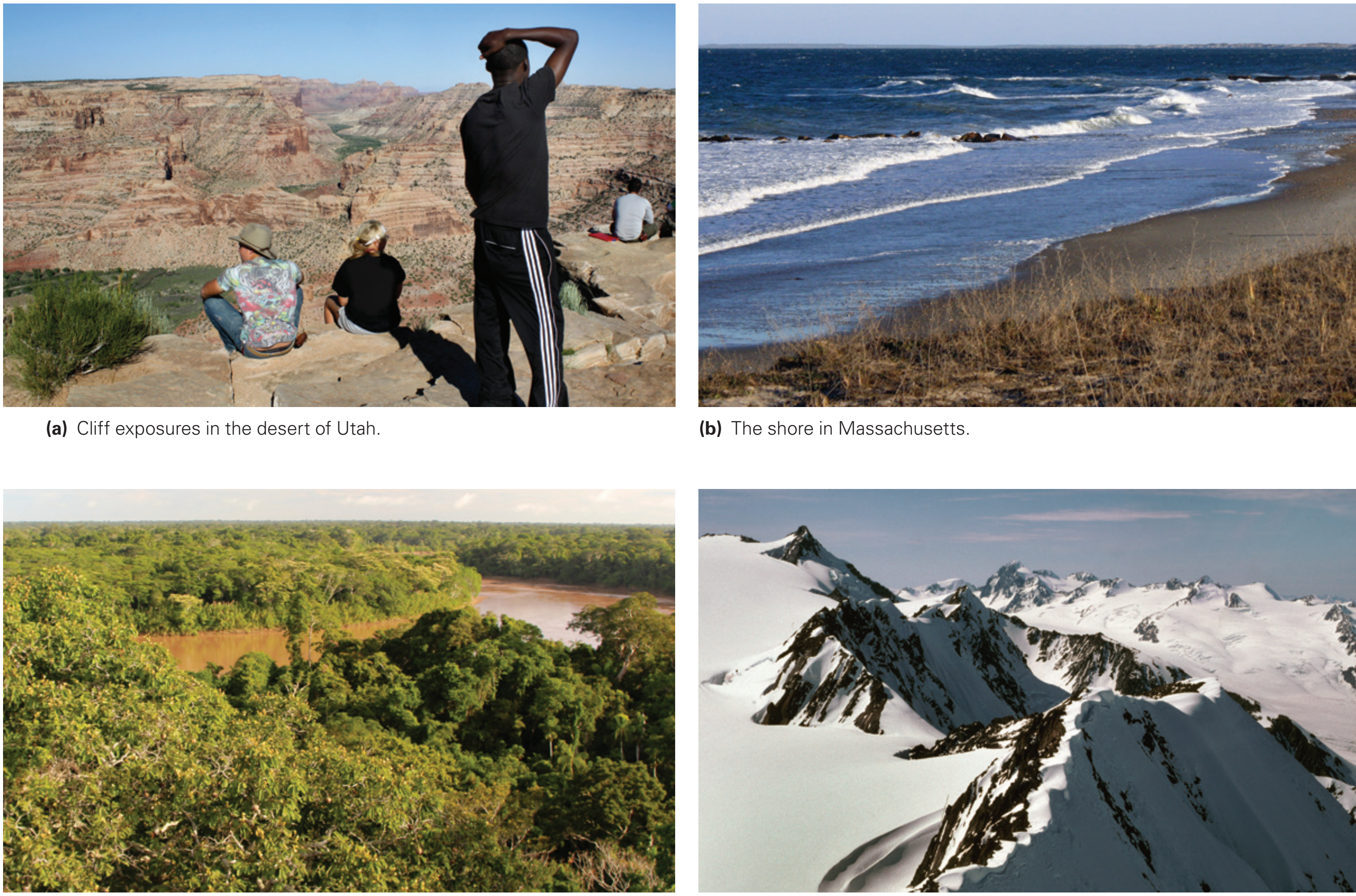
FIGURE P.1 Geologic exploration provides beautiful views and mysteries to solve.

(a) A view of the western Arizona desert is not just beautiful—it holds clues to the Earth's past and to the changes taking place today.

(b) The contortions of the rock layers speak of a time when the rock flowed like soft plastic.

◀ (facing page) Every beautiful vista has a geologic story to tell. The rocks we see here in the Maroon Bells, a group of mountains in Colorado, for example, are made of sand once buried deep beneath the Earth's surface. Immense forces uplifted these rocks kilometers into the sky.

FIGURE P.2 Geologists explore many environments.



(a) Cliff exposures in the desert of Utah.

(b) The shore in Massachusetts.

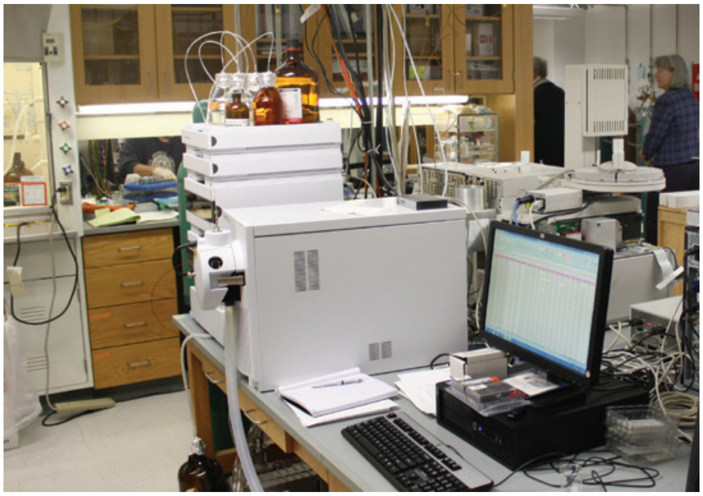
(c) A rainforest in Peru.

(d) Mountains in Alaska.

Geologists—scientists who study the Earth—do indeed explore remote deserts, such as the one pictured in Figure P.1. They also head to high mountains, damp rainforests, frigid glaciers, and deep canyons **(Fig. P.2)**. Such efforts can strike people in other professions as a strange way to make a living. This sentiment underlies a description by the Scottish poet Walter Scott (1771–1832) of geologists at work: "Some rin uphill and down dale, knapping the chucky stanes to pieces wi' hammers, like sae mony road-makers run daft—they say it is to see how the warld was made!" But Scott had it right—to see how the world was made, to see how it continues to evolve, to find its resources, to protect against its natural hazards, and to predict what its future may bring. These are the questions that have driven geologists to explore the Earth, on all continents and in all oceans, from the equator to the poles and everywhere in between.

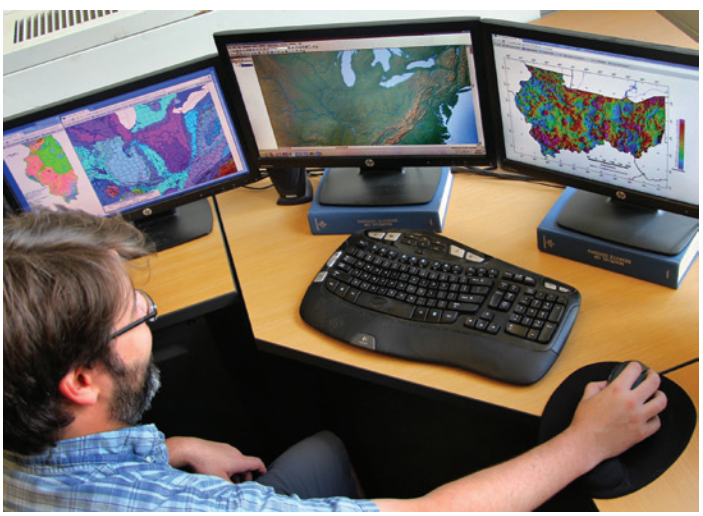
Geologic discovery continues today. But, while some geologists continue to work in the field with hammers and hand lenses, others have moved into laboratories that employ techniques of chemistry or sophisticated electronic instruments to analyze microscopic quantities of Earth materials **(Fig. P.3a, b)**. Still others use satellites to detect the motions of continents or the stability of volcanoes, high-speed computers to locate earthquakes or to analyze the flow of underground water, and scale models to simulate flow in rivers **(Fig. P.3c, d)**. For over two centuries, geologists have pored over the Earth in search of ideas to explain the processes that form and change our planet. In this Prelude, we look more closely at the questions geologists ask and have tried to answer. You'll see that the results of this work are not just of academic interest but have implications for society.

FIGURE P.3 Much of geologic study today takes place in the laboratory or in research facilities that use high-speed computers.

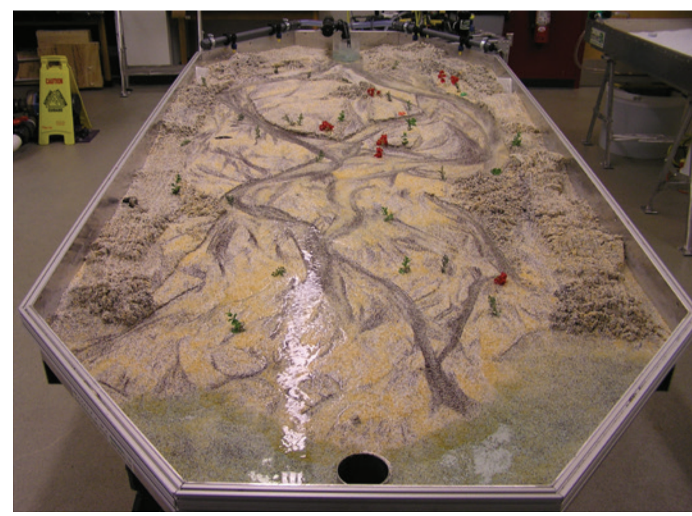


(a) Analytical equipment in a geology research laboratory.

(b) Laboratories provide an opportunity to carry out controlled experiments.



(c) A computer facility working with large amounts of data.



(d) A stream of water flowing over sand can simulate the evolution of a river.

P.2 Why Study Geology?

Geology (also called *geoscience*) is the study of the Earth. It encompasses studies that characterize the formation and composition of this planet, the causes of mountain building and ice ages, the record of life's evolution, and the history of climate change. Geology also addresses practical problems such as how to keep pollution out of groundwater, how to find oil and useful minerals, and how to avoid landslides. You can get a sense of the different kinds of problems that geologists work on by examining a list of the many subdisciplines of geology **(Table P.1)**.

Hundreds of thousands of people worldwide pursue careers in geology—mostly in energy, mining, water, engineering, and environmental companies. A smaller number work in universities or colleges, government-sponsored geological surveys, and research laboratories. Nevertheless, since most people reading this book will not become professional geologists, it's fair to ask the question, "Why should people, in general, study geology?"

First, geology may be one of the most practical subjects you can learn. When news reports begin with "Scientists say . . ." and then continue with "an earthquake occurred today off Japan," or "landslides will threaten the city," or "chemicals from a toxic waste dump will ruin the town's water supply," or "there's only a limited supply of oil left," or "the floods of

TABLE P.1 Principal Subdisciplines of Geology (Geoscience)

Name	Subject(s) of Study
Engineering geology	Aspects of geology relevant to understanding slope stability or to building tunnels, dams, mines, roads, or foundations
Environmental geology	Interactions between the environment and geologic materials, and the contamination of the near-surface realm of the Earth by pollutants
Geochemistry	Chemical composition and behavior of materials in the Earth, and chemical reactions in natural environments
Geochronology	The age (in years) of geologic materials, the Earth, and extraterrestrial objects
Geomorphology	Landscape formation and evolution
Geophysics	Physical characteristics of the Earth (such as the Earth's magnetic field and gravity field) and causes of forces that affect the Earth
Hydrogeology	Groundwater, its movement, and its reaction with rock and soil
Mineralogy	Physical properties, structure, and chemical behavior of minerals
Paleontology	Fossils and the evolution of life as preserved in the rock record
Petrology	Rocks and their formation
Sedimentology	Sediments and their deposition
Seismology	Earthquakes and the Earth's interior as revealed by earthquake waves
Stratigraphy	The succession of sedimentary rock layers and the record of Earth's history that they contain
Structural geology	Rock deformation (bending and breaking) in response to the application of force associated with mountain building
Tectonics	The origin and significance of regional-scale geologic features
Volcanology	Volcanic eruptions and their products, and volcanic hazards

the last few days are the worst on record," the scientists that the reports refer to are geologists. In fact, ask yourself the following questions, and you'll realize that geologic processes, phenomena, and materials play major roles in daily life:

- Do you live in a region threatened by landslides, volcanoes, earthquakes, or floods **(Fig. P.4a, b)**?
- Are you worried about the price of energy or about whether there will be a war in an oil-supplying country **(Fig. P.4c)**?
- Do you ever wonder where the copper in your home's wires comes from? Or the lithium in the battery of your cell phone?
- Have you seen fields of green crops surrounded by desert and wondered where the irrigation water comes from?
- Are you worried about the consequences of deforestation **(Fig. P.4d)**?
- Would you like to buy a dream house near a beach or a river?
- Are you concerned about how toxic waste can migrate underground into your town's well water?

Addressing these questions requires a basic understanding of geology. This knowledge may help you avoid building your home on a hazardous floodplain or fault zone, on an unstable slope, or along a rapidly eroding coast. With an understanding of groundwater, you may be able to find a good site for a well. With knowledge of the geologic controls on resource distribution, you may be able to invest more wisely in the resource industry or to understand the context of political choices regarding energy policy.

Second, the study of geology gives you an awareness of the planet that no other field can. As you will see, the Earth is a complicated world, where living organisms, oceans, atmosphere, and solid rock interact with one another in a great variety of ways. Geologic study reveals the Earth's antiquity (it's about 4.56 billion years old) and demonstrates how profoundly the planet has changed during its existence. What our ancestors considered to be the center of the Universe has become,

FIGURE P.4 Geology provides insight into natural hazards and resource exploration.

(a) Collapsed buildings in the aftermath of an earthquake.

(b) The natural power of a hurricane can level a beachside community.

(c) Coal is one of many resources that comes from the Earth.

(d) The human-generated power of a chain saw and a bulldozer can level a forest.

with the development of geologic perspective, our “island in space” today. And what was believed to be an unchanging orb originating at the same time as humanity has become a dynamic planet that not only existed long before people did, but continues to evolve.

Third, the study of geology puts the accomplishments and consequences of human civilization in a broader context. View the aftermath of a large earthquake, flood, or hurricane, and it’s clear that the might of natural geologic phenomena greatly exceeds the strength of human-made structures. But watch a bulldozer clear a swath of forest, a dynamite explosion remove the top of a hill, or a prairie field turn into a housing development, and it’s clear that people can also change the face of the Earth, often at rates exceeding those of natural geologic processes.

Finally, when you finish reading this book, your view of the world may be forever colored by geologic curiosity. If you walk in the mountains, you may remember that mountains rise and fall over time in response to forces that shape and reshape the Earth’s surface. If you hear about a natural disaster, you may think about the various phenomena that trigger such disasters. And as you drive past rock exposures along a highway, you won’t just see featureless masses of gray but will pick out layers and structures providing a record of the Earth’s amazing history.

P.3 Themes of This Book

A number of narrative themes appear—and reappear—throughout this text. These themes, listed below, can be viewed as the book’s overall take-home message.

- *Geology is a synthesis of many sciences:* The study of geology can help you understand physical science in general, for geology applies many of the basic concepts of physics and chemistry to the interpretation of visible phenomena. As you learn about the Earth, you’ll also be learning about the behavior of matter and energy, and about the nature of chemical reactions.

GEOLOGY AT A GLANCE

The Earth System

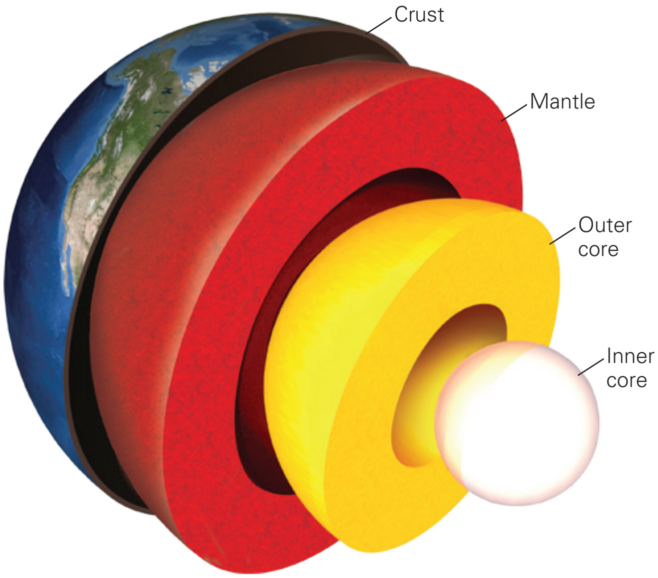
When you stand on the surface of the Earth, you can see the wondrous ways in which components of the Earth System interact. The geosphere consists of the solid part of our planet. You see it wherever you see exposed rock, sediment, or soil. Most of it lies underground, in the internal layers of our planet. The hydrosphere consists of all liquid water at or near the surface of the Earth. It fills oceans, lakes, underground pores, and occurs as gas in the atmosphere. The cryosphere consists of frozen water, mostly in glaciers. The biosphere consists of living organisms, from bacteria to whales. The atmosphere is the envelope of gas that encircles the planet. Flow in the air and sea transfer heat and water around the planet.

Internal energy rising from the interior and external energy coming to the Earth from the Sun keep the Earth System dynamic, so that materials cycle from component to component over time. Human society is having a growing impact on the Earth System, by extracting resources, building and farming on its surface, and emitting waste.

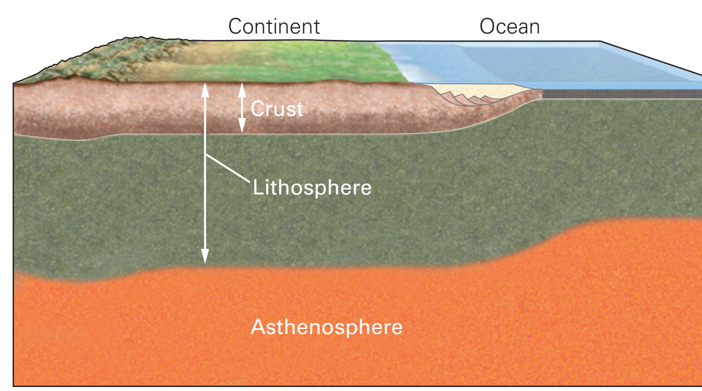
Jet stream
Moon
Cirrus clouds
Aurora
Wind system
Ice and snow
Coniferous forest
Evaporation
Volcanic islands
Industrial pollution
Cold surface current
Surface waters
Delta
Swamps
Warm surface current
Twilight zone
Abyssal zone
Whale
Seafloor
Giant squid
Bacteria and plankton
Deep-sea current
Black smokers

- *The Earth has an internal structure:* The Earth does not have a homogeneous interior, but rather consists of concentric layers. From center to surface, our planet has a *core*, *mantle*, and *crust*. We live on the surface of the crust, where it meets the atmosphere and the oceans **(Fig. P.5a)**.
- *The outer layer of the Earth consists of moving plates:* In the 1960s, geologists recognized that the crust, together with the uppermost part of the underlying mantle, forms a 100- to 150-km-thick semi-rigid shell called the **lithosphere**. Distinct boundaries separate this shell into discrete pieces, called **plates**, which move very slowly relative to one another over a softer part of the mantle called the **asthenosphere** **(Fig. P.5b, c)**. The theory that describes this movement and its consequences is called the **theory of plate tectonics**, and it serves as the foundation for understanding most geologic phenomena. Plate movements and interactions produce earthquakes, volcanoes, and mountain ranges, and cause the map of the Earth's surface to change very slowly over time.
- *We can picture the Earth as a complex system:* The Earth is not static, but rather can be pictured as a dynamic entity whose components move and change. Our planet's interior, solid surface, oceans, atmosphere, and life all interact with one another in many ways to yield the land, oceans, and air in which we and other organisms can live. Geologists refer to this interconnected web of interacting materials and processes as the **Earth System** (**Geology at a Glance**, pp. 6–7). Within the Earth System, certain materials cycle among different types of rock, or among

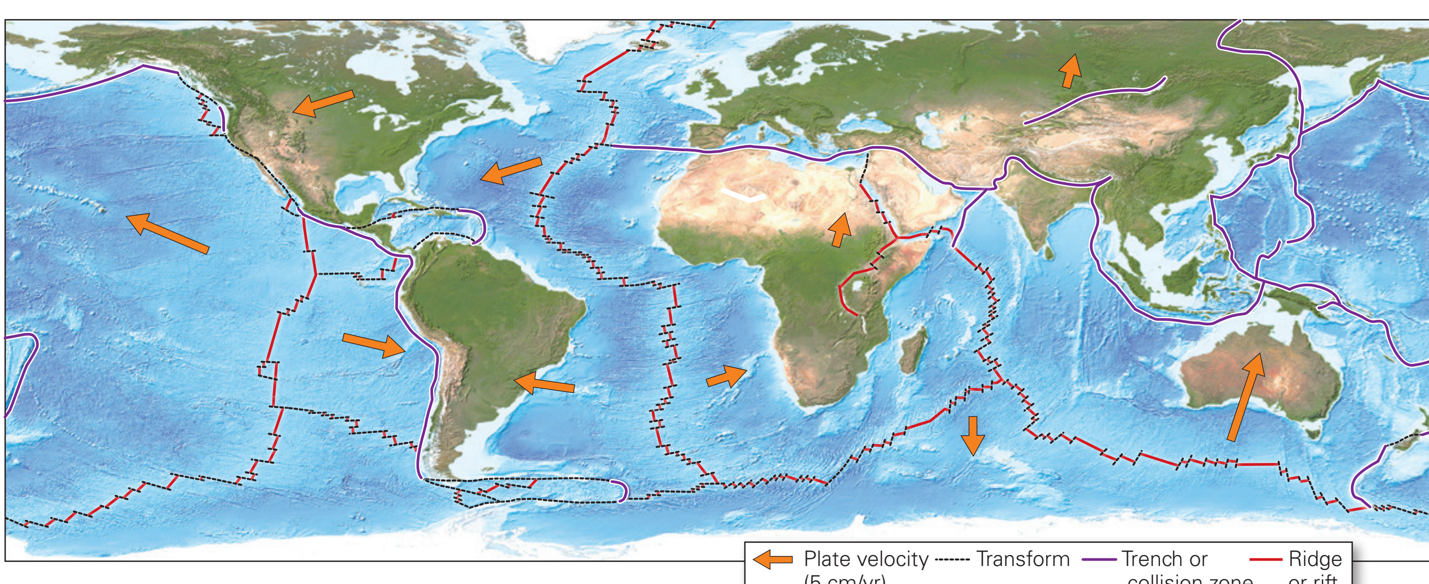
FIGURE P.5 The Earth's interior and the theory of plate tectonics.



(a) Simplistically, the interior of the Earth can be pictured as a set of concentric shells.



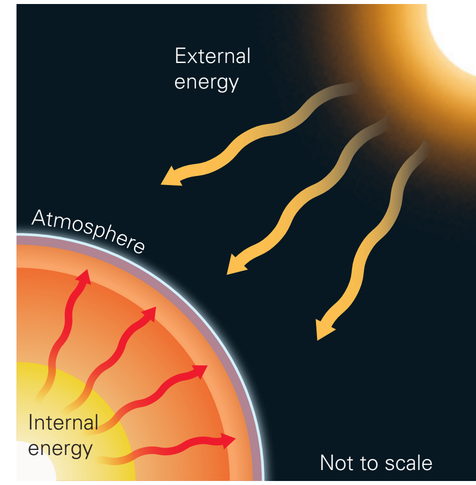
(b) The crust and the uppermost part of the mantle together constitute the relatively rigid lithosphere. The asthenosphere lies beneath the lithosphere.



(c) A simplified map of the Earth's plates. The arrows indicate the direction each plate is moving, and the length of the arrow indicates plate velocity (the longer the arrow, the faster the motion)

(a) In this scenic view in Switzerland, we see many aspects of the Earth System—air, water, ice, rock, life, and human activity.

FIGURE P.6 The Earth System and its energy source.



(b) The difference between internal and external energy in the Earth System.

rock, sea, air, and life **(Fig. P.6a)**. Over time, the distribution of these materials among various components of the Earth System can change, as can the characteristics of the components.

- *The Earth is a planet:* Despite the uniqueness of the Earth System, we can think of the Earth as a planet, formed like the other planets of the Solar System. But because of the way the Earth System operates, our planet differs from other planets by having plate tectonics, an oxygen-rich atmosphere and a liquid-water ocean, and abundant life.
- *Internal and external processes drive geologic phenomena:* **Internal processes** are those driven by heat from inside the Earth. Plate movement is an example. Because plate movements cause mountain building, earthquakes, and volcanoes, we consider all of these phenomena internal processes **(Fig. P.6b)**. **External processes** are those driven by energy coming to the Earth from the Sun. The heat produced by this energy drives the movement of air and water, which grinds and sculpts the Earth's surface and transports the debris to new locations, where it accumulates. As we'll see, **gravity**—the pull that one mass exerts on another—plays an important role in both internal and external processes. The interaction between internal and external processes forms the mountains, canyons, beaches, and plains of our planet.
- *The Earth is very old:* Geologic data indicate that the Earth formed 4.56 billion years ago—plenty of time for geologic processes to generate and destroy landscapes, for life forms to evolve, and for the map of the planet to change. For example, plate movement at rates of only a few centimeters per year can move a continent thousands of kilometers if those movements continue for hundreds of millions of years. There's time enough to build mountains and time enough to grind them down, many times over. The Earth has a history, and it extends far into the past, long before human ancestors appeared.
- *The geologic time scale divides the Earth's history into intervals:* To refer to specific portions of geologic time, geologists developed the **geologic time scale (Fig. P.7)**. The last 541 million years comprise the *Phanerozoic Eon*, and all time before that falls into the *Precambrian*. The Precambrian can be further divided into three main intervals named, from oldest to youngest, the *Hadean*, the *Archean*, and the *Proterozoic Eons*. The Phanerozoic Eon, in turn, can be divided into three main intervals named, from oldest to youngest, the *Paleozoic*, the *Mesozoic*, and the *Cenozoic Eras*.
- *Geologic phenomena affect society:* Volcanoes, earthquakes, landslides, floods, groundwater, energy sources, and mineral reserves are of vital interest to every inhabitant of this planet. Therefore, throughout this book we emphasize the linkages among geology, the environment, and society.
- *Physical aspects of the Earth System interact with life processes:* All life on this planet depends on physical features such as the minerals in soil; the temperature, humidity, and composition of the atmosphere; and the flow of surface and subsurface water. And life in turn affects and alters physical features. For example, the oxygen in the Earth's atmosphere comes from photosynthesis, a life activity in