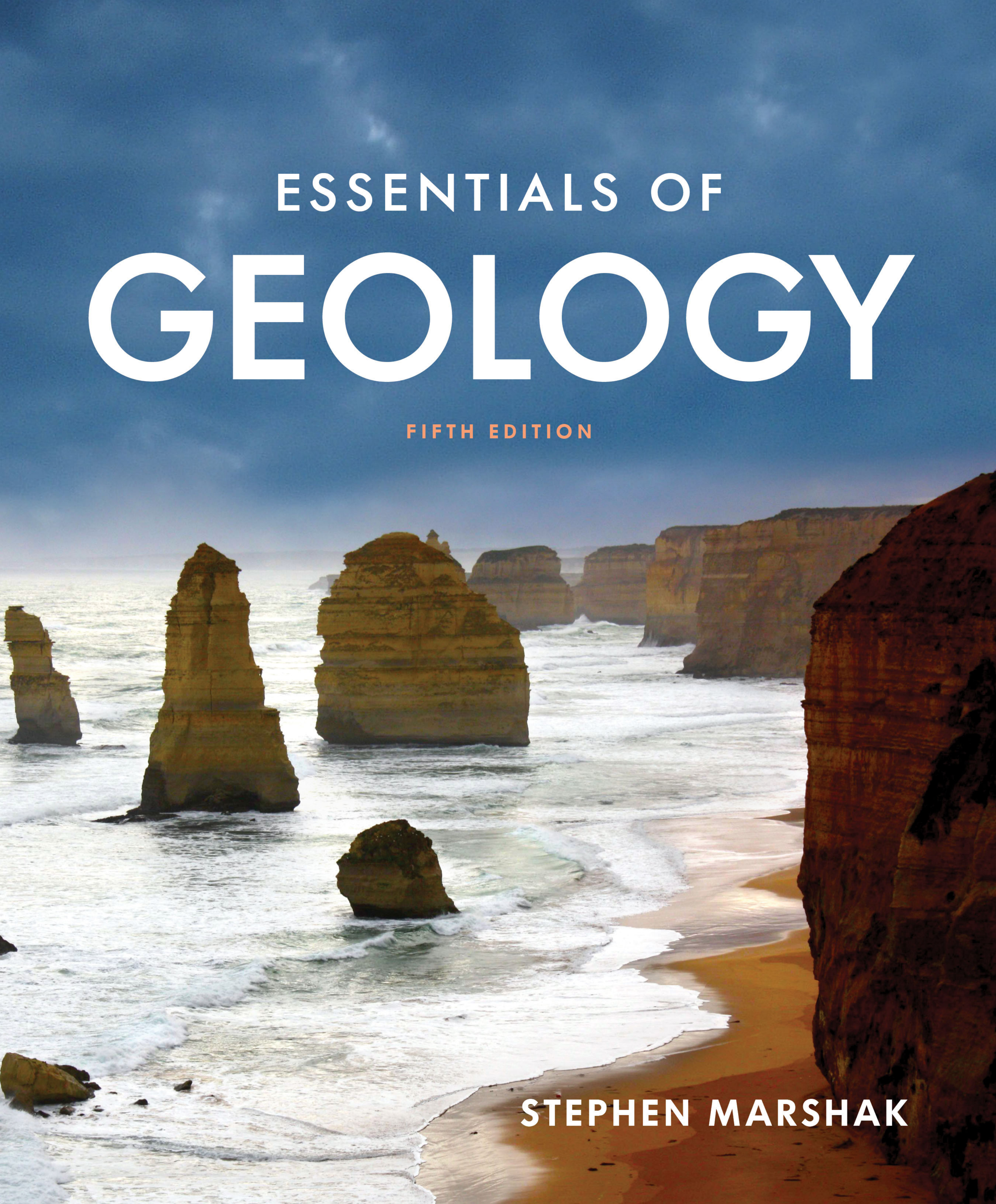


ESSENTIALS OF GEOLOGY

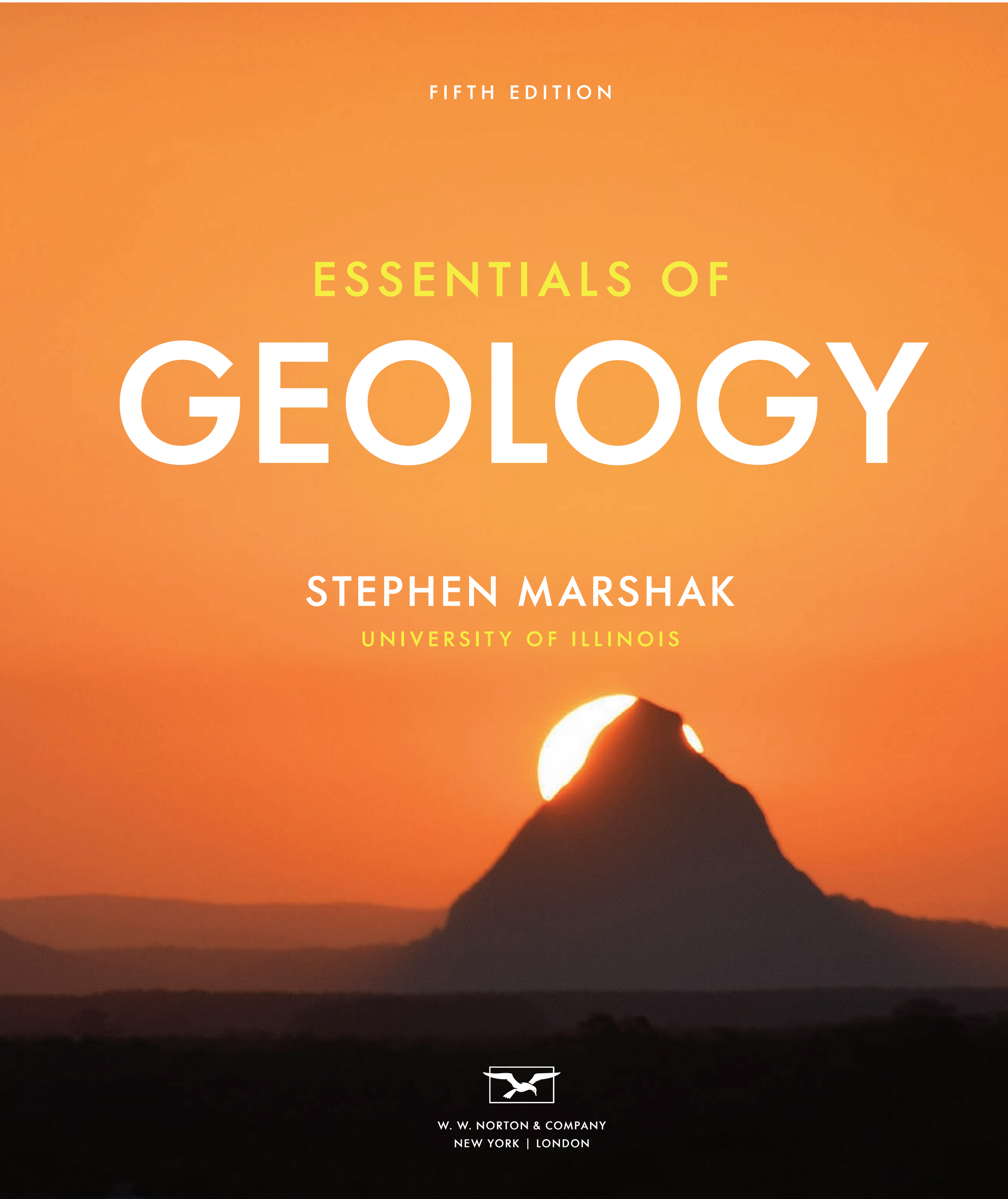
FIFTH EDITION

STEPHEN MARSHAK

ESSENTIALS OF

GEOLOGY

FIFTH EDITION



FIFTH EDITION

ESSENTIALS OF GEOLOGY

STEPHEN MARSHAK
UNIVERSITY OF ILLINOIS

W. W. NORTON & COMPANY
NEW YORK | LONDON

W. W. Norton & Company has been independent since its founding in 1923, when William Warder Norton and Mary D. Herter Norton first published lectures delivered at the People's Institute, the adult education division of New York City's Cooper Union. The firm soon expanded its program beyond the Institute, publishing books by celebrated academics from America and abroad. By mid-century, the two major pillars of Norton's publishing program—trade books and college texts—were firmly established. In the 1950s, the Norton family transferred control of the company to its employees, and today—with a staff of four hundred and a comparable number of trade, college, and professional titles published each year—W. W. Norton & Company stands as the largest and oldest publishing house owned wholly by its employees.

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Title page photo: In 1770, Captain James Cook named these 500 m-high hills, here seen at sunset on the east coast of Australia, the Glass House Mountains. Cook thought that they resembled glass furnaces in Yorkshire. In fact, they are remnants of geologic furnaces. Their shape developed when erosion of volcanoes that had erupted 26 million years ago left behind hard rock that solidified from melt within and just below the volcanoes. (Photo courtesy of Stephen Marshak.)

DEDICATION

—In memory of Jack Repcheck—

friend, mentor, and editor,

whose perpetual enthusiasm

permeates the pages of this book.

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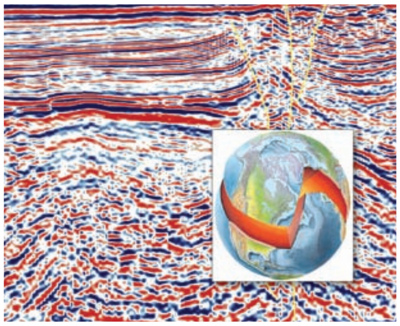
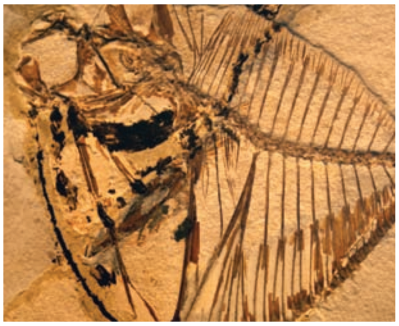
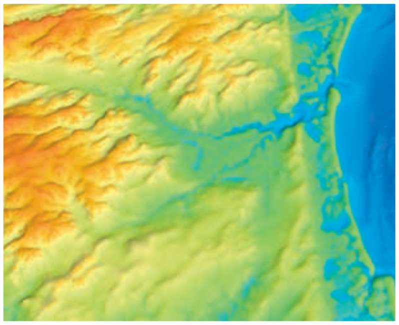






INTERLUDE F

CHAPTER 13

Preface

NARRATIVE THEMES

Why do earthquakes, volcanoes, floods, and landslides happen? What causes mountains to rise? How do beautiful landscapes develop? Do climate and life change 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? Can 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 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 Earth. The second idea, called the *Earth System concept,* emphasizes that our planet's water, land, atmosphere, and living inhabitants are dynamically interconnected. In the Earth System, materials constantly cycle among various living and nonliving reservoirs on, above, and within the planet. We have come to realize that the history of life is intimately linked to the history of the physical Earth.

Essentials of Geology, Fifth Edition, offers an introduction to the study of our planet that employs both the theory of plate tectonics and the concept of the Earth System throughout the book, to weave together a number of narrative themes, including:

1. The solid Earth, the oceans, the atmosphere, and life interact in complex ways, yielding a unique planet, unlike any other in the Solar System.
2. Most geologic processes reflect the interactions among plates.
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 features continue to be destroyed.
4. The Earth is very old—about 4.57 billion years have passed since its birth. During this time the surface, subsurface, and atmosphere of the planet have changed, and life has evolved.
5. Internal processes (driven by the Earth's internal 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 natural hazards such as earthquakes, volcanoes, landslides, and floods, and in some cases can reduce the danger that these hazards pose.
7. Energy and mineral resources come from the Earth and form in response to geologic phenomena. Geologic study can help locate these resources and mitigate the consequences of their use.
8. Physical features of the Earth are linked to life processes, and vice versa.
9. Science comes from observation; people make scientific discoveries.
10. Geology utilizes ideas from physics, chemistry, and biology, so the study of geology provides an excellent means to improve science literacy.

These narrative themes serve as the *take-home message* of this book, a message that students will remember long after finishing an introductory geology course. In effect, these themes provide a mental framework on which students can organize and connect ideas, and develop a modern, coherent image of our planet.

PEDAGOGICAL APPROACH

Students learn best from textbooks when they can actively engage with a combination of narrative text and narrative art. Some students respond more to words, which help them to organize information, provide answers to questions, fill in the essential steps that link ideas together, and develop a personal context for understanding information. Some students respond more to narrative art—art designed to tell a story—for visual images help students comprehend and remember processes. And some respond to question-and-answer-based active learning, an approach through which students can in effect "practice" their knowledge in real time. *Essentials of Geology*, Fifth Edition, supports all three of these learning approaches.

The text and ancillary educational package of this book have been crafted to engage students in its narrative style, the art has been configured to tell a story, the chapters are laid out to help students internalize key principles, and the online videos, animations, and activities have been designed to increase student interest and involvement, as well as to provide them with active feedback. For example, *Did You Ever Wonder* panels prompt students to connect new information to their existing knowledge base by asking geology-related questions that they have probably already thought about. A *Take-Home Message* panel at the end of each section helps students solidify key themes before proceeding to the next section. Questions at the end of each chapter not only test basic knowledge, but also stimulate critical thinking. Animations and videos support each chapter and are designed to work hand in hand with the text. New student assessment tools that work in your school's learning management system (LMS), including Smartwork5 online homework, help students prepare for class with dynamic visual questions. Finally, the *See for Yourself* and *Geotour* features guide students on virtual field trips, via *Google Earth*™, to locales around the globe where they can apply their newly acquired knowledge to the interpretation of real-world geologic features.

ORGANIZATION

Topics covered in this book have been arranged so that students can build their knowledge of geology on a foundation of overarching principles. The book starts by considering how the Earth formed, and how it is structured, overall, from its surface to its center. With this basic background, students can delve into plate tectonics, the grand unifying theory of geology. Plate tectonics appears early in the book, so that students can use the theory as a foundation from which they can interpret and link ideas presented in subsequent chapters. 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 and problems occurring at or near the Earth's surface, from the unstable slopes of hills, down the course of rivers, to the shores of the sea, and beyond. This section concludes with a topic of growing concern in society—global change, particularly climate change.

Although we have arranged the sequence of chapters to provide a pedagogically consistent narrative, each chapter is self-contained, and we reiterate relevant material where necessary. As a result, instructors can choose their own strategies for teaching geology, and they can resequence chapters if useful for their own course's design.

SPECIAL AND UPDATED FEATURES FOR THIS EDITION

Narrative Art and *What a Geologist Sees*

To help students visualize topics, we have lavishly illustrated this book by creating figures and selecting photographs that provide a realistic context for interpreting geologic features without overwhelming students with extraneous detail. In this edition, many drawings and photographs have been integrated into *narrative art* that has been laid out, labeled, and annotated to tell a story—the figures are drawn to teach! Subcaptions are positioned adjacent to the relevant parts of a figure, labels point out key features, and balloons provide additional detail. Where relevant, we've arranged subparts of figures to convey time progression. Color schemes in drawings tie directly to those of relevant photos, so that students can easily visualize the relationships among drawings and photos. In some examples, annotated sketches labeled *What a Geologist Sees* accompany photographs. These "WAGS" help students confirm that they actually see the specific features that the photograph was intended to show.

Narrative Art Videos, Animations, and Simulations

The Fifth Edition of *Essentials of Geology* provides a rich collection of over fifty new animations and videos to illustrate geologic processes and course concepts. Animations and simulations utilize a consistent style applying a new 3-D perspective. Many allow students to control and simulate aspects of a geologic process. In a brand-new set of *narrative art video*s, the author enhances explanations of core concepts in the text by describing the processes displayed in animated versions of the book's figures. We provide these resources to students, at the book's student website, through the Marshak YouTube channel, or through LMS coursepacks. They are available to instructors through an easy-to-use USB-compatible flash drive, and at the instructor resource center.

Featured Paintings: *Geology at a Glance*

In addition to individual figures, renowned British artist Gary Hincks has created spectacular two-page annotated paintings, called *Geology at a Glance*. The Fifth Edition features a brand-new painting that captures the history of the Earth, displaying stages in the evolution of land and life over time, to scale. All Hincks paintings integrate key concepts introduced in the chapters and visually emphasize the relationships among components of the Earth System. And, they provide students with a way to review a subject . . . *at a glance*.

New Coverage of Current Topics

To ensure that *Essentials of Geology*, Fifth Edition, reflects the latest research discoveries and helps students understand geologic events that have been featured in recent news headlines, we have updated many topics throughout the book. For example, the extensively revised resources chapter explains how new technologies—such as directional drilling and hydraulic fracturing—have been game changers in the interpretation of global energy reserves, by making so-called "unconventional reserves" accessible. The book utilizes new discoveries from EarthScope projects, as well as updates from the latest IPCC report on climate change. *Essentials of Geology*, Fifth Edition, also discusses lessons learned from natural disasters such as Hurricane Sandy, Typhoon Haiyan, the Oso landslide, and the Tōhoku tsunami.

Assessment That Works in Your School's LMS

Monitoring whether students are prepared for class and understand the chapter material is a constant challenge. We have designed two tools that help you and that work directly in your school's learning management system—free Norton Coursepacks and the upcoming update of Norton's automated system, Smartwork5. Developed with substantial input from instructors and students, these tools allow students to receive the coaching they need in order to work through their assignments, while instructors get real-time assessment of student progress with automatic grading and item analysis. The questions in these products were developed with the help of the author, Stephen Marshak, in order to work seamlessly with the text.

Built-In Review Features

Each chapter begins with *Learning Objectives* that frame the chapter's major concepts, and every section ends with a *Take-Home Message*, a brief summary to help readers identify and remember the highlights of that section before moving on to the next. *Did You Ever Wonder* questions occur throughout to help show how the book's narrative and figures may address questions that you've already asked about the Earth. Each chapter then concludes with an integrated *Chapter Review*, designed to pull together summary points, key terms, basic review questions, critical thinking questions (*On Further Thought*), and highlights of available free student media, into a visually compact, two-page, easy-to-follow layout.

Interludes

The book contains several Interludes. These "mini-chapters" focus on self-contained key topics that are not broad enough to require an entire chapter. Arranging some content into Interludes not only keeps chapters reasonable in length, but also provides instructors with additional flexibility to sequence topics within a course. Interludes in the Fifth Edition contain dedicated summary sections, structured like those in the numbered chapters.

Discussion of Societal Issues

We address geology's practical applications in several chapters, providing students with an opportunity to learn about energy resources, mineral resources, global change, and natural disasters. *Science and Society* features, provided for free on the open student website and in Norton's LMS coursepacks, challenge students to apply material that they learn in *Essentials of Geology*, Fifth Edition to the interpretation of news articles and publicly available geologic data.

Student Website

Free for students, this site contains all the animations, simulations, and videos developed for this text and highlighted in the chapter summaries. Students will also find vocabulary flashcards, *Science and Society* features that challenge students to use course concepts in analyzing news articles, real-time geologic data, and information on how best to utilize the *Google Earth*™ materials provided for this book. This support includes a video designed to help with start-up, all the book's *See For Yourself* sites in one downloadable file, instructions to enter latitude and longitude coordinates for each site, and links to Google tutorials and information on updates. Students can access the student site at *digital.wwnorton.com/essgeo5*.

MEDIA AND ANCILLARY MATERIALS FOR INSTRUCTORS

Assessment That Works in Your School's 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. Working within your school's LMS, and without additional login, Norton Coursepacks offer a selection of rich visual and media-based questions, as well as updated Reading Quizzes for each chapter, featuring art from the text. Instructors can also provide on-line access to all the videos and animations developed for *Essentials of Geology*, Fifth Edition. Additional content includes *Science and Society* features and questions, *Geotour* questions, and links to the ebook (for students) and our test bank (for instructors). Coursepacks were prepared with the consultation of the author and other instructors, especially Cindy Liutkus-Pierce and Brian Zimmer of Appalachian State.

See for Yourself

USING *GOOGLE EARTH*™

Visiting Field Sites Identified in the Text

There's no better way to appreciate geology than to see it first-hand in the field, but 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, you'll probably see examples of only a few geologic settings. Fortunately, *Google Earth*™ makes it possible for you to fly to spectacular geologic field sites anywhere in the world in a matter of seconds—you can take a virtual field trip electronically. Throughout the chapter, you will find *See For Yourself* panels identifying geologic sites that you can explore on your own personal 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 whether *Google Earth*™ is installed on your personal computer, smartphone, or tablet. If not, please download the software from **earth.google.com** or the app from the Apple or Android app store.
2. Find a site in the *See For Yourself* panel that you're interested in visiting. In addition to a thumbnail photo and very brief description of the site (highlighting what you will see at the site), we provide the latitude and longitude of the site, in degrees, minutes, and seconds.
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 specify the coordinates in the book as follows:

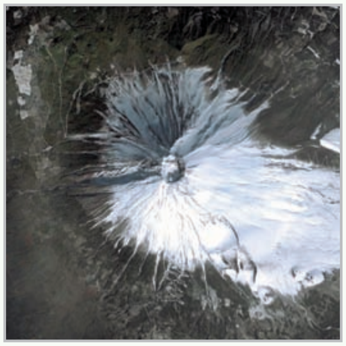
    LATITUDE 35°21′41.78″N
    LONGITUDE 138°43′50.74″E

Type these coordinates into the search window as:

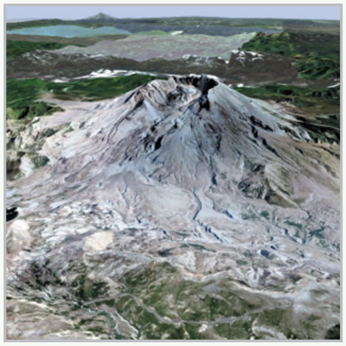
35 21 41.78N, 138 43 50.74E

Note that the degree (°), minute (′), and second (″) symbols are left as blank spaces.

When you click ENTER or RETURN, your device will bring you to the viewpoint right above Mt. Fuji illustrated by the thumbnail on the left. Note that you can use the tools built into *Google Earth*™ to vary the elevation, tilt, orientation, and position of your viewpoint. The thumbnail on the right shows the view you'll see of the same location if you tilt your viewing direction and look north.



View Looking Down.

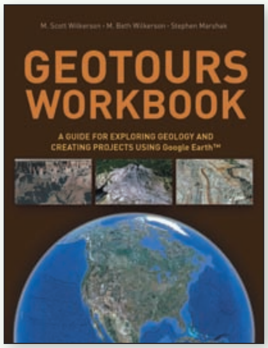


View Looking North.

NEED MORE HELP?

If you have any trouble operating *Google Earth™*, please visit digital.wwnorton.com/essgeo5 and navigate to the student site to find a video showing you how to download and install *Google Earth*™, as well as more detailed 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. Notes addressing important *Google Earth*™ updates will be available at this site.

To provide additional opportunities to study geology using *Google Earth*™, we also offer a separate book—the *Geotours Workbook* (ISBN 978-0-393-91891-5)—that identifies even more interesting geologic sites to visit. The *Geotours Workbook* provides active-learning exercises linked to the sites and explains how you can create your own virtual field trips.



New Smartwork5 Online Tutorial and Assessment System. The new Smartwork5 online assessment available for use with *Essentials of Geology*, Fifth Edition features visual assignments developed with the eye of the author, with focused feedback. Because students learn best when they can interact with art as well as with text, Smartwork5 includes drag-and-drop figure-based questions, animation- and video-based questions, and *What a Geologist Sees* photo interpretations. Smartwork5 also provides questions based on real field examples, via the *Geotours Workbook*, and helps students check their knowledge as they go by working with reading-based questions and pre-made and easy-to-assign reading quizzes. Designed to be intuitive and easy to use for both students and instructors, Smartwork5 makes it a snap to assign, assess, and report on student performance, and to keep the class on track. Smartwork5 now works with tablet and mobile environments, and also has single sign-on capability with your institution's learning management system

Smartwork5 is available for free with most newly purchased print or electronic versions of the text. Immediate online access can also be purchased at digital.wwnorton.com/essgeo5. Select the option to buy a registration code before you create your account. Instructors can request their own Smartwork5 course at wwnorton.com/instructors.

Art Files and PowerPoints

The following visual resources are available from wwnorton.com/instructors, or through this book's instructor USB drive.

- *Enhanced Art Lecture PowerPoints*—Designed for instant classroom use, these slides utilize photographs and line art from the book in a format that has been optimized for use in the PowerPoint environment. The art has been relabeled and resized for projection formats. *Enhanced Art PowerPoints* also include supplemental photographs courtesy of Ron Parker of Fronterra Geosciences. Author Brian Zimmer of Appalachian State has also included new *Think-Pair-Share* slides to encourage classroom discussion, as well as *Takeaway Points* slides to summarize key concepts.
- *Labeled and Unlabeled Art PowerPoints*—These PowerPoints include all art from the book. We offer one set from which all labeling has been stripped and one set in which labeling remains.
- *Art JPEGs*—We provide a complete file of individual JPEGs for art and photographs used in the book.
- *Clicker questions*—Designed for use with any classroom signaling device, these sets also contain *Think-Pair-Share* questions designed for work in small groups.
- *Update PowerPoints*—W. W. Norton offers a semester-by-semester update service that provides new PowerPoint slides, with instructor support, covering recent geologic events.

New Animations, Simulations, and Videos. As described earlier, this extensive set of material has been completely revised and updated for quality and consistency working with the text's author and Alex Glass of Duke University. These materials are free and available at the student site, on the Marshak YouTube channel, in Norton Coursepacks, and through instructor formats including the new USB drive. In addition, working with Melissa Hudley of the University of North Carolina, Chapel Hill; Heather Lehto of Angelo State University; and Meghan Lindsey of the University of South Florida, our DVD, coursepacks and instructor support website contain a selection of streaming videos of geologic processes including content developed by IRIS. All animations and videos are ready to go and perfect for classroom or online use.

Norton Instructor USB Flash Drive. The Instructor USB drive offers a wealth of easy-to-use multimedia resources, all structured around the text. Resources include all PowerPoint art files, animations, and videos described earlier in the Preface, and electronic versions of the Instructor's Manual, Test Bank, and ExamView test-generation software. Further resources include clicker questions, as well as supporting files for using *Google Earth*™.

Instructor's Manual and Test Bank. The Instructor's Manual, prepared by John Werner of Seminole State College of Florida, is designed to help instructors prepare lectures and exams. It contains detailed *Learning Objectives, Chapter Summaries*, and complete answers to end-of-chapter Review and *On Further Thought* questions for every chapter and interlude. New to this edition are animation and video descriptions for these Norton resources, including suggestions for classroom implementation and two discussion questions per multimedia asset.

The Test Bank, revised by Heather Lehto of Angelo State University and carefully reviewed by Dylan Blumentritt of SUNY Potsdam, has been rewritten not only to correlate to the new edition of the text, but to provide greater, more rounded assessment than ever before. During the course of this revision, at least four geologists have reviewed and improved on each question, making sure that it is scientifically reliable and truly tests students' understanding of the most important topics in each chapter. Each chapter now features new short-answer questions that test student critical thinking and knowledge-application skills. These supplements are available on the Instructor USB drive and are also downloadable from wwnorton.com/instructors.

Instructor's Website—wwnorton.com/instructors. Online access is available for a rich array of resources: Test Bank, Instructor's Manual, PowerPoints, JPEGs, *Google Earth*™ file of sites from the text, art from the text, animations, simulations, videos, and WebCT- and Blackboard-ready content.

The Google Earth™ Geotours Workbook. Created by Scott Wilkerson, Beth Wilkerson, and Stephen Marshak, *Geotours* are active-learning opportunities that take students on virtual field trips to see outstanding examples of geology at localities around the world. They are available as Worksheets, both in print format (these come free with the book and include complete user instructions and advanced instruction) and electronically with auto-grading through Smartwork5 or your campus LMS. Request a sample copy to preview each worksheet.

See for Yourself Google Earth™ Sample Site File. Users who simply want access to sample field sites for classroom presentations or distribution to students can download the sites from the book's *See for Yourself* panels. This single download is available at the Norton instructor download site as well as from the student site.

Ebook. The *Essentials of Geology,* Fifth Edition ebook is available at digital.wwnorton.com/essgeo5. It contains live links to animations, simulations, and videos, as well as *Google Earth™* sites. When a student purchases ebooks at this site, Smartwork5 is available for free. The Norton ebook reader works on all computers and mobile devices and includes intuitive highlighting, note taking, and bookmarking features.

ACKNOWLEDGMENTS

Essentials of Geology, and its parent book, *Earth: Portrait of a Planet*, would not have come into existence without the inspiration and strong support of Jack Repcheck. As acquisitions editor for the first three editions, Jack proposed a number of the features that attracted readers to the book in the first place, and was a constant source of encouragement and support throughout the long, long process of writing, illustrating, and revising. Sadly, Jack passed away in October 2015. He will be greatly missed by all authors who had the good fortune to work with him over his immensely productive career.

I am very grateful for the assistance of many people in bringing *Essentials of Geology* from the concept stage to the shelf, and for helping to provide the momentum needed to bring this revision to completion. First and foremost, I wish to thank my wife, Kathy, who served as in-home project manager for this book. Kathy helped to construct the manuscript based on prior editions of this book and its parent, *Earth: Portrait of a Planet*; coordinated manuscript and proof traffic between our household and the publisher; maintained schedule, standards, and consistency; and served as an invaluable extra set of eyes. This book would not have appeared without Kathy. I also wish to thank my daughter, Emma, and my son, David, for their willingness to adopt "the book" as a member of our household when they were growing up, and to endure the overabundance of geo-photo stops on family trips. Emma helped develop the concept of narrative art used in the book, provided feedback about how the book works from a student's perspective, and provided several of the book's photos.

I am very grateful to all the staff of W. W. Norton & Company for their incredible efforts during the development of my books over the past two decades. It has been a privilege to work with an employee-owned company that is willing to work so closely with its authors. Many thanks to senior editor Eric Svendsen, who injected new enthusiasm and ideas into the project. Eric's experience and skill have guided the book in new directions and have helped connect the project to new trends in science pedagogy and book design. Thom Foley, as always, has been an incredible project manager. Thom handles the complicated process of assembling chapter proofs and figures into the final book, and puts in extra hours to meet deadline after deadline, all while remaining incredibly calm. Thom invested untold hours in sorting out composition and design issues—it's thanks to Thom that this edition made it to the shelf on schedule. I also greatly appreciate the efforts of Rob Bellinger for his innovative approach to ancillary development and for overseeing the development of the coursepack and Smartwork5 supplements; Sunny Hwang for her expertise and work as the new developmental editor for this project; Stephanie Romeo for her expert and thoughtful editing of the photo collection and permissions; Ben Reynolds for coordinating the back-and-forth between the publisher and various suppliers; Marcus Van Harpen and Kim Yi for their dedicated and creative production work on the media components, including the ebook and Smartwork5; Jake Schindel, who has so ably assumed the mantle of marketing manager for the book; Caitlin Barrett-Bressack and Tori Reuter for creatively handling the ancillaries and Smartwork5; Rachel Goodman for expertly performing all the tasks that come with a project of this complexity; Liz Vogt for assisting Rob with everything emedia; and Connie Parks for her excellent copyediting work. I also wish to thank Susan Gaustad, the outstanding developmental editor of the First Edition, who helped refine the prose style of the book.

Production of the illustrations has involved many people over many years. I am particularly indebted to Stan Maddock, an amazingly talented artist who helped to create the style of the figures from the very first, and who has kept up with constantly evolving graphics technology so the book's illustrations remain at the cutting edge. I am grateful to all the artists and compositors involved in this project.

It has been great fun to interact with Gary Hincks, who painted the incredible two-page spreads, in part using his own designs and geologic insights. Some of Gary's paintings originally appeared in *Earth Story* (BBC Worldwide, 1998) and were based on illustrations conceived with Simon Lamb and Felicity Maxwell. Others were developed specifically for *Earth: Portrait of a Planet* and *Essentials of Geology*. Some of the chapter-opening quotes were found in *Language of the Earth*, compiled by F. T. Rhodes and R. O. Stone (Pergamon, 1981).

The five editions of this book and of its parent, *Earth: Portrait of a Planet*, 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 me or the publisher. In particular, in this edition I would like to thank Michael Rygel of SUNY-Potsdam and Geoffrey and Heather Cook, who greatly helped with the process of updating Smartwork5. Kurt Wilkie of Washington State University continues

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I apologize if I inadvertently left anyone off this list.

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Stephen Marshak

Geology, perhaps more than any other department of natural philosophy, is a science of contemplation. It demands only an enquiring mind and senses alive to the facts almost everywhere presented in nature.

—Sir Humphry Davy (British scientist, 1778–1829)

ABOUT THE AUTHOR

STEPHEN MARSHAK is a professor of geology at the University of Illinois, Urbana-Champaign, where he is also 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 in structural geology and tectonics have taken him into the field on several continents. He loves teaching and has won his college's and university's highest teaching awards, as well as the Neil Miner Award of the National Association of Geoscience Teachers "for exceptional contributions to the stimulation of interest in the earth sciences." In addition to research papers and *Essentials of Geology*, Steve has authored *Earth: Portrait of a Planet* and has co-authored *Laboratory Manual for Introductory Geology*; *Earth Structure: An Introduction to Structural Geology and Tectonics*; and *Basic Methods of Structural Geology*.

ESSENTIALS OF

GEOLOGY

FIFTH EDITION

LEARNING OBJECTIVES

1.

2.

3.

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PRELUDE

P.1

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 crop out on many hills. Under the dry sky, there's no need for tents, so we could sleep 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 that formed a shelf at 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 break before ascending the final cliff. But just as we leaned to rest our backs against a rock, we heard an unnerving vibration. Somewhere nearby, too close for comfort, a

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

WILL DURANT

(American writer, historian, and philosopher, 1885–1981)

rattlesnake shook an urgent warning with its tail. 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.

Geologists—scientists who study the Earth—explore many areas, including remote deserts, 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 the Scottish poet Walter Scott's (1771–1832) description of geologists at work: "Some rin uphill and down dale, knappin' the chucky stones to pieces like sa' many roadmakers run daft. They say it is to see how the warld was made!" Indeed—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 everything in between.

Geologic discovery continues today, and involves a variety of techniques. While some geologists continue to work in the field with hammers and hand lenses, others have moved into laboratories where they employ sophisticated electronic instruments to analyze microscopic quantities of Earth materials or detect the configuration of layers underground, use satellites to detect the motions of continents or the stability of volcanoes, and use high-speed computers to locate earthquakes or analyze the flow of underground water. 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 at the questions geologists ask and have tried to answer. You'll see that many of these answers are not just of academic interest but have implications for society as a whole.

P.2 The Nature of Geology

Geology, or geoscience, is the study of the Earth. Not only do geologists address fundamental questions such as the formation and composition of our planet, the causes of earthquakes and ice ages, and the evolution of life, but they also address practical problems such as how to keep pollution out of groundwater, how to find oil and minerals, and how to avoid landslides.

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.

FIGURE P.2 Field study in many environments.

(a) A desert cliff in Utah.

(b) A rainforest in Peru.

(c) Mountains in Alaska.

(d) The shore in Massachusetts.

The fascination of geology attracts many to careers in this science. Tens of thousands of geologists work for energy, mining, water, engineering, and environmental companies, while a smaller number work in universities, government geological surveys, and research laboratories. Nevertheless, since most of the students reading this book will not become professional geologists, it's fair to ask the question, "Why should people, in general, study geology?"

Did you ever wonder...
will an earthquake happen near where you live?

First, geology may be one of the most practical subjects you can learn. When a news report begins, "Scientists say," and then continues, "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 the last few days are the worst on record," the scientists that the report refers to are geologists. In fact, ask yourself the following questions, and you'll realize that geologic phenomena and materials play major roles in daily life:

- Do you live in a region threatened by landslides, volcanoes, earthquakes, or floods (**Fig. P.3**)?
- Are you worried about the price of energy or about whether there will be a war in an oil-supplying country?

FIGURE P.3 Human-made cities cannot withstand the vibrations of a large eathquake. These apartment buildings collapsed during an earthquake in Turkey.

- Do you ever wonder about 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?
- Would you like to buy a dream house on a beach or near a river?
- Are you following news stories about how toxic waste can migrate underground into your town's water supply?

Clearly, all citizens of the 21st century, not just professional geologists, need to make decisions and understand news reports addressing Earth-related issues. A basic understanding of geology will help you do so.

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 entity, where living organisms, oceans, atmosphere, and solid rock interact with one another in a great variety of ways. Geologic study reveals Earth's antiquity and demonstrates how the planet has changed profoundly during its existence. What our ancestors considered to be the center of the Universe has become, 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 existed long before people did and 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 evolve into a housing development, and it's clear that people can change the face of the Earth at rates often exceeding those of natural geologic processes.

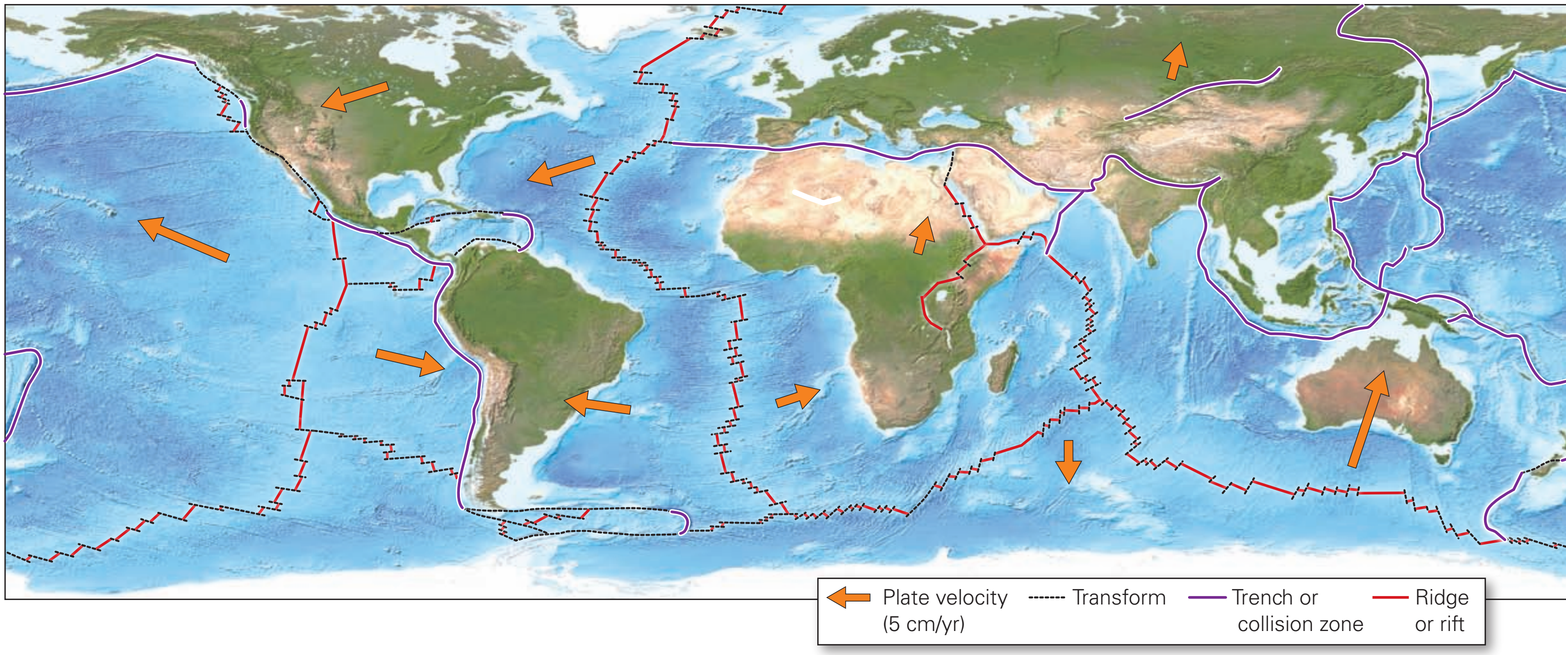
Finally, when you finish reading this book, your view of the world may be forever colored by geologic curiosity. If you walk in the mountains, you will think of the many forces that shape and reshape the Earth's surface. If you hear about a natural disaster, you will have insight into the processes that brought it about. And if you go on a road trip, the rock exposures along the highway will no longer be gray, faceless cliffs, but will present complex puzzles of texture and color telling a story of the Earth's long 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 this book's overall take-home message.

- *Studying geology helps you understand physical science in general:* Geology incorporates many of the basic concepts of physics and chemistry because Earth materials are a form of matter, and energy drives geologic processes. Thus, studying geology can help you develop a better grasp of key ideas in physical science. Those readers who pursue teaching careers in elementary or secondary education will find that geological examples can help students develop STEM (science-technology-engineering-math) learning skills.
- *The Earth has an internal structure:* The Earth is not a homogeneous ball, but rather it consists of concentric layers. From center to surface, Earth has a **core**, **mantle**, and **crust**. We live on the surface of the crust, where it meets the atmosphere and the oceans.
- *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**. Large cracks separate this shell into discrete pieces, called **plates**, which move very slowly relative to one another (**Fig. P.4**). 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 yield earthquakes, volcanoes, and mountain ranges, and cause the map of Earth's surface to change very slowly over time.
- *We can picture the Earth as a complex system with many interconnected realms:* The Earth is not static, but rather

FIGURE P.4 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).



it is a dynamic entity whose components can move and change over time. 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 species of organisms can live. Geologists refer to this interconnected web of interacting realms of materials and processes as the **Earth System**. Within the Earth System, certain materials cycle among rock, sea, and air, and among all of these entities and life. Over time, the distribution of these materials among various components of the Earth System can change.

- *The Earth is a planet:* Despite the uniqueness of the Earth System, the Earth is a planet, formed like the other planets of the Solar System. But because of the way the Earth System operates, our planet differs from others by having plate tectonics, an oxygen-rich atmosphere, liquid-water ocean, and abundant life.
- *The Earth is very old:* Geologic data indicate that the Earth formed 4.54 billion years ago—plenty of time for geologic processes to build mountains and grind them down many times over, for life forms to evolve and go extinct, and for the map of the planet to change. Even 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.

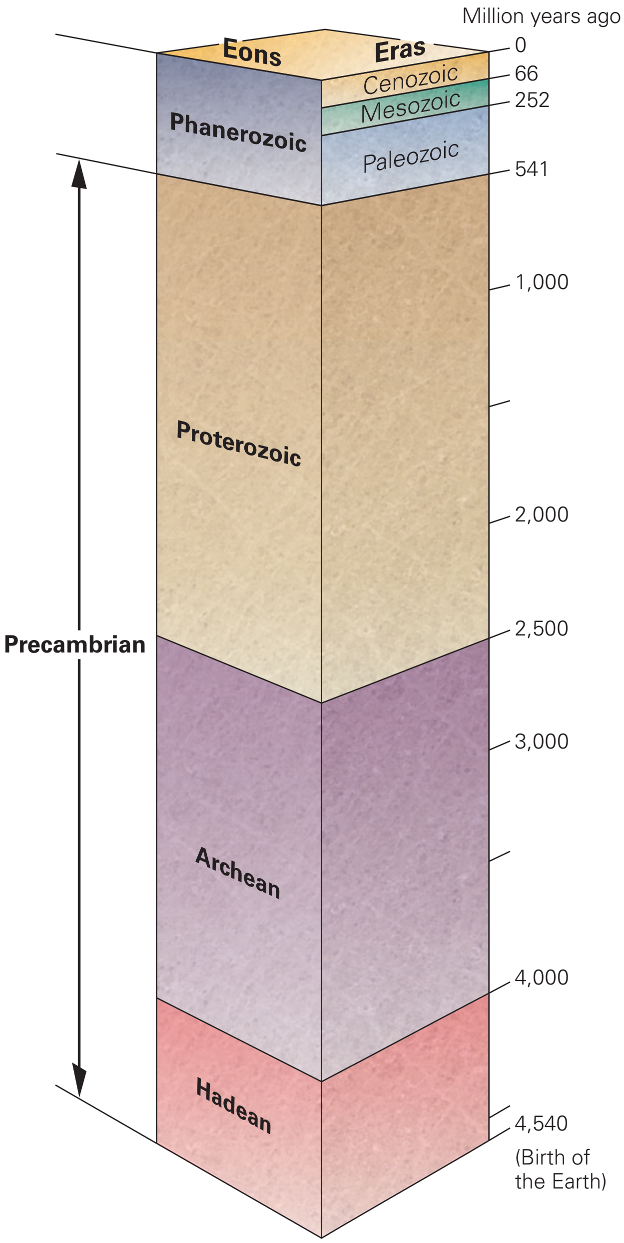
Did you ever wonder...

if a map of the Earth's surface today looks like a map of the surface 200 million years ago?

The Earth has a history, and it extends far into the past. **Geologic time** represents the duration of this history.

- *The geologic time scale divides Earth's history into intervals:* To refer to specific portions of geologic time, geologists developed the **geologic time scale** (**Fig. P.5**). The last 541 million years comprise the *Phanerozoic Eon*, and all time before that makes up 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*.
- *Internal and external processes drive geologic phenomena: Internal processes* are 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 to be manifestations of internal processes. *External processes* are 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. The interaction between internal and external processes forms and shapes the mountains, canyons, beaches, and plains of our planet. As we'll see, **gravity**—the pull that one mass exerts on another—plays an important role in both internal and external processes.

FIGURE P.5 The geologic time scale.



(a) The scale has been divided into eons and eras.

One thousand years ago = 1 **Ka**
(Ka stands for kilo-annum)

One million years ago = 1 **Ma**
(Ma stands for mega-annum)

One billion years ago = 1 **Ga**
(Ga stands for giga-annum)

(b) Abbreviations for time units.

- *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 link to life processes:* All life on this planet depends on such physical features as the composition of 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 plants. This oxygen in turn permits complex animals to survive and controls chemical reactions among air, water, and rock. Without the physical Earth, life could not exist; but without life, this planet's surface might have become a frozen wasteland, like that of Mars, or a cloud-enshrouded oven, like that of Venus.
- *The Earth has changed dramatically in many ways over geologic time and continues to change:* The landscape that you see outside your window today is not what you would have seen a thousand, a million, or a billion years ago. Over Earth history, the planet's surface, composition of the atmosphere, and sea level have all changed. Also, continents move relative to one another. Change continues today, and aspects of the Earth System are changing faster than ever before because of human activity.
- *Most of the resources that we use come from geologic materials:* Modern society uses vast quantities of oil, gas, coal, metal, concrete, clay, fertilizer, and other materials. Most of these come from the solid Earth (**Fig. P.6**).

FIGURE P.6 Workers excavate limestone in a quarry near Chicago. This rock commonly consists of shells and shell fragments, and can be used in the production of concrete.

BOX P.1 CONSIDER THIS...

The Scientific Method

Sometime during the past 200 million years, a large block of rock or metal, which had been orbiting the Sun, slammed into our planet. It made contact at a site in what is now the central United States, a landscape of flat cornfields. The impact of this block, a *meteorite*, released more energy than a nuclear bomb—a cloud of shattered rock and dust blasted skyward, and once-horizontal layers of rock from deep below the ground sprang upward and tilted on end beneath the gaping crater left by the impact. When the event was over, the land surface looked radically different—a layer of debris surrounded and partially filled the crater at the impact site. Later in Earth history, running water and blowing wind wore down this jagged scar and carried away the debris. Then, about 15,000 years ago, sand, gravel, and mud carried by a vast sheet of ice, a glacier, buried what remained, hiding it entirely from view (**Fig. BxP.1**). Wow! So much history beneath a cornfield. How do we know this? It takes scientific investigation.

The movies often portray science as a dangerous tool, capable of creating Frankenstein's monster, and scientists as nerdy characters with thick glasses and poor taste in clothes. In reality, **science** is simply the use of observation, experiment, and calculation to explain how nature operates, and scientists are people who study and try to understand natural phenomena. Scientists guide their work using the **scientific method**, an idealized thought process for systematically analyzing scientific problems in a way that leads to verifiable results. Let's see how geologists employed the scientific method to come up with the meteorite-impact story.

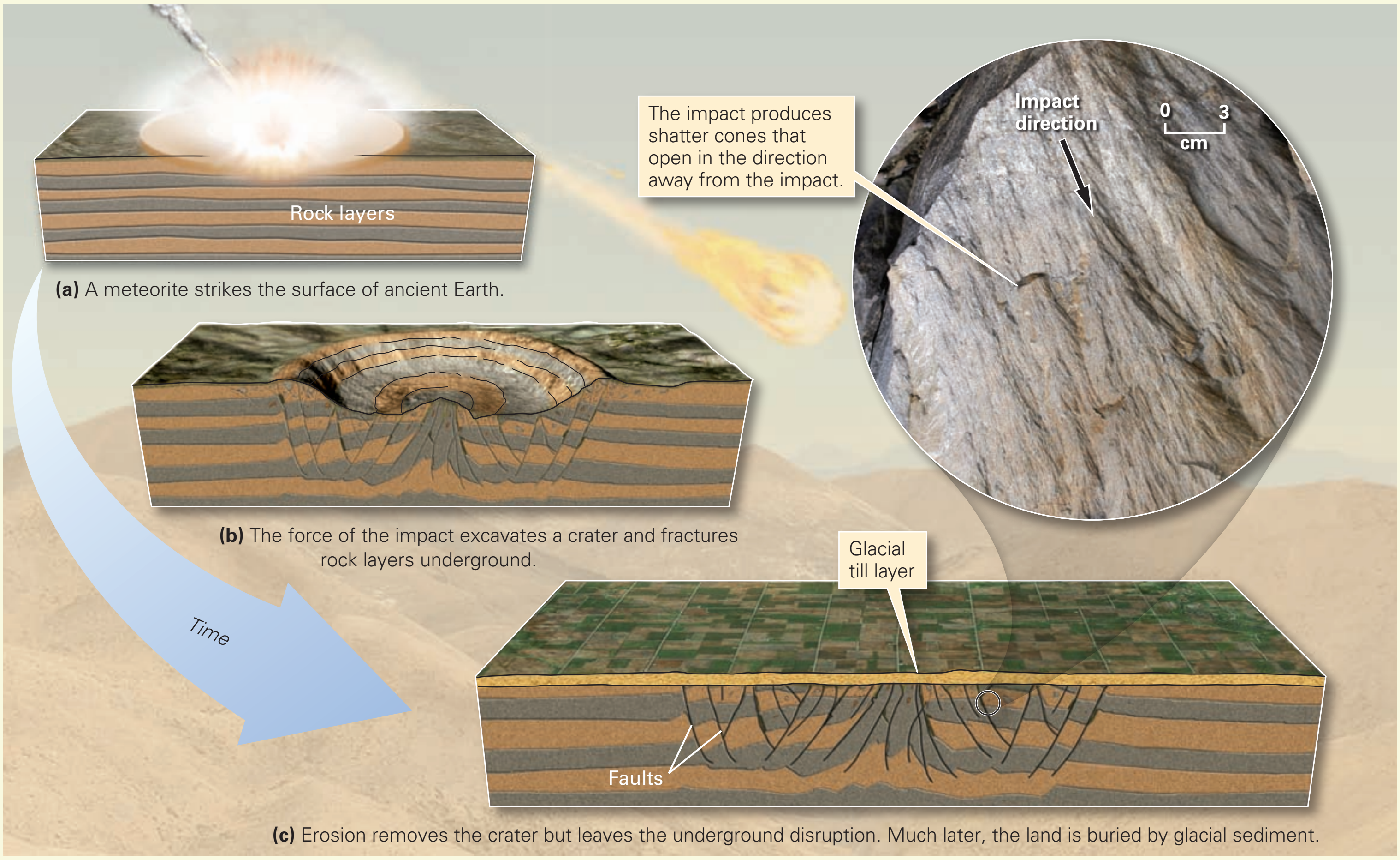
- *Recognizing the problem:* Any scientific project, like any detective story, begins by identifying a mystery. The cornfield mystery came to light when water drillers discovered that limestone, a rock typically made of shell fragments, lies just below the 15,000-year-old glacial sediment. In surrounding regions, the rock beneath the glacial sediment consists instead of sandstone, a rock made of cemented-together sand grains. Since limestone can be used to build roads, make cement, and produce the agricultural lime used in treating soil, workers stripped off the glacial sediment and dug a quarry to excavate the limestone. They were amazed to find that rock layers exposed in the quarry were tilted steeply and had been shattered by large cracks. In the surrounding regions, all rock layers are horizontal like the layers in a birthday cake, the limestone layer lies underneath the sandstone, and the rocks contain relatively few cracks. When curious geologists came to investigate, they soon realized that the geologic features of the land just beneath the cornfield presented a problem to be solved. What phenomena had brought limestone up close to the Earth's surface, had tilted the layering in the rocks, and had shattered the rocks?
- *Collecting data:* The scientific method proceeds with the collection of observations or clues that point to an answer. Geologists studied the quarry and determined the age of its rocks, measured the orientation of the rock layers, and documented (made a written or photographic record of) the fractures that broke up the rocks.
- *Proposing hypotheses.* A scientific **hypothesis** is merely a possible explanation, involving only natural processes, that can explain a set of observations. Scientists propose hypotheses during or after their initial data collection. In this example, the geologists working in the quarry came up with two alternative hypotheses: either the features in this region resulted from a volcanic explosion, or they were caused by a meteorite impact.
- *Testing hypotheses.* Since a hypothesis is just an idea that can be either right or wrong, scientists try to put hypotheses through a series of tests to see if they work. The geologists at the quarry compared their field observations with published observations made at other sites of volcanic explosions and meteorite impacts, and they studied the results of experiments designed to simulate such events. If the geologic features visible in the quarry were the result of volcanism, the quarry should contain rocks formed by the freezing of molten rock erupted by a volcano. But no such rocks were found. If, however, the features were produced by an impact, the rocks should contain **shatter cones**, tiny cracks that fan out from a point. Shatter cones can be overlooked, so the geologists returned to the quarry specifically to search for them and found them in abundance. The impact hypothesis passed the test!

Note that we said "idealized" thought process. Sometimes serendipity works into the process, and scientists make discoveries by chance. Also, because we can't travel through time, we can't always completely test all geologic hypotheses.

Theories are scientific ideas supported by an abundance of evidence; they have passed many tests and have failed none. Scientists are much more confident in the correctness of a theory than of a hypothesis. Continued study in the quarry eventually yielded so much evidence for impact that the impact hypothesis came to be viewed as a theory. Scientists continue to test theories over a long time. Successful theories withstand these tests and are supported by so many observations that

(*continued*)

FIGURE BxP.1 An ancient meteorite impact excavates a crater and permanently changes rock beneath the surface.



(a) A meteorite strikes the surface of ancient Earth.

(b) The force of the impact excavates a crater and fractures rock layers underground.

(c) Erosion removes the crater but leaves the underground disruption. Much later, the land is buried by glacial sediment.

they become part of a discipline's foundation. However, some theories may eventually be disproved and replaced by better ones.

In a few cases, scientists have been able to devise concise statements that completely describe a specific relationship or phenomenon. Such statements are called **scientific laws**. Scientific laws are not the same as scientific theories, as the former do not provide an explanation for a phenomenon, while the latter do. For example, the *law* of gravity, a simple equation that explains how objects accelerate (speed up) when subjected to gravitational force, does not explain why gravity exists. In contrast, the *theory of evolution* does explain why evolution occurs, by providing a testable mechanism for why the assemblages of life on Earth change over time.

> *Science comes from observation, and people make scientific discoveries:* Science does not consist of subjective guesses or arbitrary dogmas, but rather of a consistent set of objective statements resulting from the application of the scientific method (**Box P.1**). Every scientific idea must be tested thoroughly and should be used only when supported by documented observations. Further, scientific ideas do not appear out of nowhere; they are the result of human efforts. Wherever possible, this book shows where geologic ideas came from, and tries to answer the question, "How do we know that?"

As you read this book, please keep these themes in mind. Don't view geology as a list of words to memorize, but rather as an interconnected set of concepts to digest. Most of all, enjoy yourself as you learn about what may be the most fascinating planet in the Universe. It certainly is to humans!

Prelude Review

Prelude Summary

- Geologists are scientists who study the Earth. They search for the answers to the mysteries of our home planet, from why volcanoes explode to where we can find diamonds.
- Geologic study can involve field exploration, laboratory experiments, high-tech measurements, and calculations with computers.
- Geologic research not only provides answers to academic questions such as how the Earth formed, but also addresses practical problems like how to find resources and to avoid landslides. Many people pursue careers as geologists.
- A set of themes underlies geologic thinking. Key concepts are that the Earth's outer shell consists of moving plates whose interactions produce earthquakes, volcanoes, and mountains; that the Earth is very old; and that interacting realms of material on the planet comprise the "Earth System."

Guide Terms

core (p. 4)
crust (p. 4)
Earth System (p. 5)
geologic time scale (p. 5)
geologist (p. 2)
geology (p. 2)
gravity (p. 5)
hypothesis (p. 7)
lithosphere (p. 4)
mantle (p. 4)
plate (p. 4)
science (p. 7)
scientific law (p. 8)
scientific method (p. 7)
shatter cone (p. 7)
theory (p. 7)
theory of plate tectonics (p. 4)

Review Questions

1. What are some of the practical applications of geology?
2. Explain the difference between internal processes and external processes.
3. How would the Earth's atmosphere differ if life didn't exist?
4. Explain the difference between a hypothesis and a theory, in the context of science.
5. What are the sources of data that geologists can use to understand the Earth?
6. What are the major subdivisions of geologic time? Which time unit is longer, the Precambrian or the Paleozoic?