CHERNICOFF

GEOLOGY

GEOLOGY

An Introduction to Physical Geology

Second Edition

Stanley Chernicoff
University of Washington, Seattle

Houghton Mifflin Company Boston New York

Editor-in-Chief: Kathi Prancan
Senior Associate Sponsor: Susan Warne
Senior Project Editor: Chere Bemelmans
Editorial Assistant: Joy Park
Senior Production/Design Coordinator: Jill Haber
Associate Production/Design Coordinator: Jodi O'Rourke
Manufacturing Manager: Florence Cadran
Marketing Manager: Penelope Hoblyn

Cover Design: Walter Kopec.

Cover Image: *A Miracle of Nature* by Thomas Moran, 1913, oil on canvas, 20⅛″ × 30⅛″.
Private Collection/SuperStock.

Photo credits begin on page A-31.

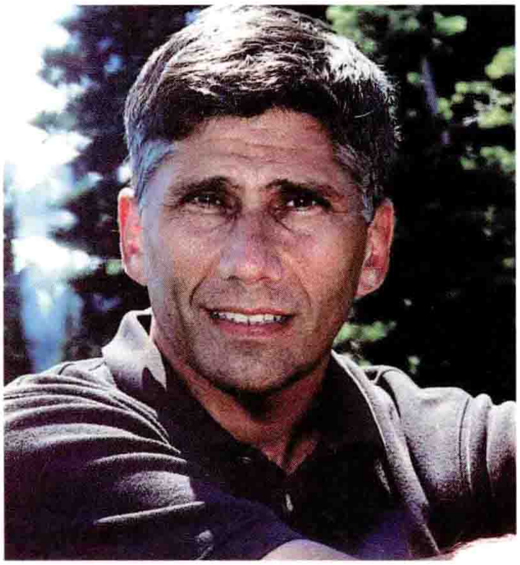
Printed in the U.S.A.

Library of Congress Catalog Card Number: 98-72010

ISBN: 0-395-92351-4

123456789-VH-02 01 00 99 98

About the Author



Born in Brooklyn, New York, Stan Chernicoff began his academic career as a political science major at Brooklyn College of the City University of New York. On graduation, he intended to enter law school and pursue a career in constitutional law. He had, however, the good fortune to take geology as his last requirement for graduation in the spring of his senior year, and he was so thoroughly captivated by it that his plans were forever changed.

After an intensive post-baccalaureate program of physics, calculus, chemistry, and geology, Stan entered the University of Minnesota–Twin Cities, where he received his doctorate in Glacial and Quaternary Geology under the guidance of one of North America's preeminent glacial geologists, Dr. H. E. Wright. Stan launched his career as a purveyor of geological knowledge as a senior graduate student teaching physical geology to hundreds of bright Minnesotans.

Stan has been a member of the faculty of the Department of Geological Sciences at the University of Washington in Seattle since 1981, where he has won several teaching awards. At Washington, he has taught Physical Geology, the Great Ice Ages, and the Geology of the Pacific Northwest to more than 20,000 students, and he has trained hundreds of graduate teaching assistants in the art of bringing geology alive for non-science majors. Stan studies the glacial history of the Puget Sound region and pursues his true passion, coaching his sons and their buddies in soccer, baseball, and basketball. He lives in Seattle with his wife, Dr. Julie Stein, a professor of archaeology, and their two sons, Matthew (the midfielder, second baseman, two-guard) and David (the striker, second baseman, point guard).

Preface

The introductory course in physical geology, taken predominantly by non-science majors, may be the only science course some students will take during their college years. What a wonderful opportunity this provides us to introduce students to the field we love and show them how fascinating and useful it is. Indeed, much of what students will learn in their Physical Geology course will be recalled throughout their lives, as they travel across this and other continents, dig in backyards, walk along a beach, or sit by a mountain stream. For this reason, our book team—author, illustrators, photo researchers, and editors—have expended the best of our abilities to craft an exciting, stimulating, and enduring introduction to the field.

The Book's Goal

The book's goal is basic—to teach what everyone should know about geology in a way that will engage and stimulate. The book embodies the view that this is perhaps the most useful college-level science class a non-science major can take—one that we believe all students should take. Physical geology can show students the essence of how science and scientists work at the same time as it nurtures their interest in understanding, appreciating, and protecting their surroundings. In this course they can learn to prepare for any number of geologic and environmental threats, and see how our Earth can continue providing all of our needs for food, shelter, and material well-being as long as we don't squander these resources.

Content and Organization

The unifying themes of plate tectonics, environmental geology and natural resources, and planetary geology are introduced in Chapter 1 and discussed in their proper context within nearly every chapter. Chapter 1 also presents the important groups of rocks, the rock cycle, and geological time—building a foundation for the succeeding chapters. Chapters 1 through 8 introduce the basics—minerals, rocks, and time—to prepare the reader for the in-depth discussions of structural geology, geophysics, and tectonics that follow in Chapters 9 through 12. After the Earth's first-order features—ocean basins, continents, and mountain systems—have been discussed, the processes that sculpt these large-scale features are addressed. Chapters 13 through 19 present the principal geomorphic processes of mass movement, streams, groundwater, glacial flow, arid region and eolian processes, and coastal evolution. Chapter 16, Caves and Karst, is a brief chapter covering material that is usually embedded in or appended to groundwater chapters. Because caves are among the natural settings that many students visit, and because karst environments are particularly sensitive to environmental damage, we have expanded the discussion as a separate chapter. The final chapter, Human Use of the Earth's Resources, ties together earlier discussions from throughout the book. It reinforces principles that relate to the origins of resources, especially energy-producing ones, and stresses our responsibility to manage them wisely.

New to the Second Edition of *Geology*

A second edition is a wonderful opportunity to build on the first:

- To weave in the latest discoveries in the geosciences.
- To offer up-to-the-minute examples of exciting geological processes, such as the most recent volcanic eruptions and earthquakes.
- To rethink how concepts have been presented in the first edition—to clarify and illustrate them more effectively.

This—the second edition of *Geology*—attempts to accomplish all of these goals, all to ensure that our students have the very best introductory experience with our science. Toward these ends, the following is just a sampling of the new and exciting areas that this edition of *Geology* explores:

- An expanded discussion of the proposed origin of the Moon from a collision between the Earth and a Mars-sized impactor.
- A discussion of Hawai'i's next island, Loihi.
- Iceland's spectacular subglacial eruption of 1996 and its resulting outburst floods.
- Updates on recent and ongoing eruptions in the Caribbean (Montserrat), Mexico City, and New Zealand.
- Dealing with "VOG"—Hawai'i's volcanic smog.
- An expanded discussion of weathering on Mars—with evidence from Pathfinder.
- New insights into the origin of life on Earth.
- A new section on using cosmogenic isotopes to date the Earth's surface.
- The moment magnitude scale—an alternative to the Richter Scale.
- The tsunami of 1700—evidence of catastrophic earthquakes in the Pacific Northwest.
- Monitoring nuclear testing with seismology.
- An expanded discussion of seismic tomography and its wide-ranging uses in deep-Earth studies.
- Using the global positioning system to track plate motion.
- Reconstructing Rodinia and other pre-Pangaea supercontinents.
- Evidence of massive submarine landslides from the flanks of K'ilauea.
- The artificial floods of Glen Canyon, 1997.
- Studies of the groundwater of Yucca Mountain, our proposed nuclear-waste repository.
- Heinrich events and North Atlantic Deep Water circulation and their effects on global glaciation.
- The glaciation of Europa.
- Global warming, sea level, and coastal destruction.

These topics and many more constitute a substantial effort to ensure that a new edition of *Geology* brings new ideas to its readers.

This edition of *Geology* also benefits significantly from a change in text design. The new two-column format has enabled the book's designers to offer much-enlarged photos and illustrations—a concern from the first edition. More than two hundred new photos have been selected (under the outstanding direction of Photo Researcher Townsend P. Dickinson) that illustrate most vividly the processes described in the text.

The Artwork

The drawings in this book are unique. Ramesh Venkatakrishnan is an experienced and respected geology professor and consultant. He is also a highly gifted artist. His drawings evolved along with the earliest drafts of the manuscript, sometimes leading the way for the text discussions. We have worked together since we were graduate teaching assistants at the University of Minnesota–Twin Cities. The desire to illuminate what we want introductory students to know about the Earth is shared by both of us.

As you will see when you leaf through this book, the art explains, describes, stimulates, and teaches. It is not schematic; it shows how the Earth and its geological features actually look. It is also not static; it shows geological processes in action, allowing students to see how geological features evolve through time. Every effort has been made to illustrate accurately a wide range of geological and geomorphic settings, including vegetation and wildlife, weathering patterns, even the shadows cast by the Sun at various latitudes. The artistic style is consistent throughout, so that students may become familiar with the appearance of some features even before reading about them in subsequent chapters. For example, the stream drainage patterns appearing on volcanoes in Chapter 4, Volcanoes and Volcanism, set the stage for the discussion of drainage patterns in Chapter 14, Streams and Floods. The colors used and the map symbols keyed to various rock types follow international conventions and are consistent throughout.

The second edition builds on the strengths of the art program of the first. The images in this edition have been enhanced digitally by renowned geology illustrators George Kelvin and John Woolsey to sharpen their focus, deepen their colors, and lend additional clarity and simplicity to their subjects.

Pedagogy

Nearly every chapter contains one or more Highlights—in-depth discussions of topics of popular interest that provide a broader view of the relevance of geology. In many cases, the Highlights comprise a late-breaking story that also shows the reader that the Earth's geology and its effects on us are changing daily.

To help readers learn and retain the important principles, every chapter ends with a Summary, a narrative discussion that recalls all of the important chapter concepts. Key terms, which are in boldface type in the chapter, are listed at the chapter's end and also appear in boldface in the Summary. Also at the end of every chapter are two question sets: *Questions for Review* helps students retain the facts presented, and *For Further Thought* challenges readers to think more deeply about the implications of the material studied.

The author and illustrators have tried to introduce readers to world geology. This book emphasizes, however, the geology of North America (including the offshore state, Hawai'i), while acknowledging that geological processes do not stop at national boundaries or at the continent's coasts. Wherever data are available—from the distribution of coal to the survey of seismic hazards—we have tried to show our readers as much of this continent, and beyond, as feasible. Photos and examples have been selected from throughout the United States and Canada and from many other regions of the world.

The metric system is used for all numerical units, with their English equivalents in parentheses, so that U.S. students can become more familiar with the units of measurement used by virtually every other country in the world.

The Supplements Package

Geology is accompanied by an array of materials to enhance teaching and learning.

Students who wish additional help mastering the text can use the Study Guide by W. Carl Shellenberger (Montana State University—Northern). For each chapter, the Guided Study section helps students focus on and review in writing the key ideas of each section of the chapter as they read. The Chapter Review, arranged by section and composed of fill-in statements, enables them to see if they have retained the ideas and terminology introduced in the chapter. The Practice Tests and the Challenge Test, which consist of multiple-choice, true/false, and brief essay questions, test their mastery of the material. All answers are accompanied by page references for easy review.

The Instructor's Resource Manual by Chip Fox (Texas A&M University—Commerce) features an outline lecture guide with teaching suggestions embedded in it and student activities and classroom demonstrations. Answers to the end-of-chapter questions in the textbook are also provided. Also included is a comprehensive Test Bank, compiled by Chip Fox, that contains more than one thousand questions. There are at least 40 multiple-choice questions per chapter, classified as either factual or conceptual/analytical. There are also ten short essay questions, complete with answers, for each chapter. A computerized version of the Test Bank is available in both IBM and Macintosh formats.

Also available with this edition is the *Geology Laboratory Manual* by James D. Myers, James E. McClurg, and Charles L. Angevine of the University of Wyoming. This inexpensive manual is closely tied to the text and offers twenty physical geology labs on topics such as maps, plate tectonics, sedimentary and metamorphic rocks, streams, and groundwater. Each lab contains multiple activities to develop and hone students' geological skills. Worksheets are designed to be torn from the manual and submitted for grading.

More than 130 of the text's diagrams and photographs are available for classroom use as full-color slides or transparencies.

The book is supported further by its award-winning website, GEOLOGYLINK (found at www.geologylink.com), maintained and updated regularly by its webmaster, Rob Viens of the University of Washington. This site will tell you what of geological import has happened overnight while you slept. It also contains expanded discussions of "hot topics" in the field of geology and an exhaustive encyclopedia of links to all things geological. For the second edition of *Geology* GEOLOGYLINK contains chapter quizzes and tutorials as well as an on-line version of the *Peterson Field Guide to Rocks and Minerals* by Frederick Pough. These outstanding teaching and learning aids help the student learn physical geology through multimedia technology, study physical geology in a stimulating, yet thoughtful way, and master the principles of physical geology.

Acknowledgments

Some remarkably talented, dedicated people have helped me accomplish far more than I could have done alone. A "committee" of top-flight geologists has been assembled who have dramatically clarified definitions and explanations, eliminated ambiguities, corrected factual errors and fuzzy logic, and, in general, helped the author hone the manuscript in countless ways and helped the illustrator select what to show and how best to do it. Special thanks must go to Kurt Hollocher of Union College and L. B. Gillett of SUNY-Plattsburgh for their extremely insightful critiques of the first edition. In addition, for their constructive criticism at various stages along the way, we wish to thank these excellent reviewers:

From the first edition of *Geology:*

Gail M. Ashley, *Rutgers University, Piscataway*

David M. Best, *Northern Arizona University*

David P. Bucke, Jr., *University of Vermont*

Michael E. Campana, *University of New Mexico*

Joseph V. Chernosky, Jr., *University of Maine, Orono*

G. Michael Clark, *University of Tennessee, Knoxville*

W. R. Danner, *University of British Columbia*

Paul Frederick Edinger, *Coker College (South Carolina)*

Robert L. Eves, *Southern Utah University*

Stanley C. Finney, *California State University, Long Beach*

Roberto Garza, *San Antonio College*

Charles W. Hickox, *Emory University*

Kenneth M. Hinkel, *University of Cincinnati*

Darrel Hoff, *Luther College (Iowa)*

David T. King, Jr., *Auburn University*

Peter T. Kolesar, *Utah State University*

Albert M. Kudo, *University of New Mexico*

Martin B. Lagoe, *University of Texas, Austin*

Lauretta A. Miller, *Fairleigh Dickinson University*

Robert E. Nelson, *Colby College (Maine)*

David M. Patrick, *University of Southern Mississippi*

Terry L. Pavlis, *University of New Orleans*

John J. Renton, *West Virginia University*

Vernon P. Scott, *Oklahoma State University*

Dorothy Stout, *Cypress College (California)*

Daniel A. Sundeen, *University of Southern Mississippi*

Allan M. Thompson, *University of Delaware*

Charles P. Thornton, *Pennsylvania State University*

From the Second Edition of *Geology:*

William W. Atkinson, *University of Colorado, Boulder*

Joseph Chernosky, *University of Maine, Orono*

Cassandra Coombs, *College of Charleston*

Peter Copeland, *University of Houston*

Katherine Giles, *New Mexico State University*

L. B. Gillett, *SUNY-Plattsburgh*

Kurt Hollocher, *Union College*

Kathleen Johnson, *University of New Orleans*

Judith Kusnick, *Cal-State Sacramento*

Bart Martin, *Ohio Wesleyan University*

Ronald Nusbaum, *College of Charleston*

Meg Riesenberg

Roger Stewart, *University of Idaho*

Donna L. Whitney, *University of Minnesota*

I would also like to thank William A. Smith (Charleston Southern State University) for his sharp eye in reviewing the art for accuracy.

At Houghton Mifflin, developmental editors Virginia Joyner and Marjorie Anderson, working under oppressive time constraints, performed the arduous task of reining in the author's long-windedness with extraordinary grace and intelligence and brought organization wherever they found disorder. Senior Associate Sponsor Sue Warne, Senior Project Editor Chere Bemelmans, Art Editor Charlotte Miller, Copyeditor Jill Hobbs, and Editorial Assistant Joy Park polished each chapter of prose and every rough sketch, working with all the elements of the book until they formed a coherent whole. Photo research was handled masterfully by Photo Researchers Townsend P. Dickinson and Mardi Welch Dickenson. The book's pleasing appearance was created under the supervision of Senior Production/Design Coordinator Jill Haber, Associate Production/Design Coordinator Jodi O'Rourke, and Layout Designer Penny Peters. I very much appreciate Editor-in-Chief Kathi Prancan's support and behind-the-scenes hard work and Marketing Manager Penny Hoblyn's energetic marketing support. Thanks are due also to Associate Editor Marianne Stepanian, who coordinated and edited the supplements.

Finally, I also wish to acknowledge with deep appreciation the role of Ron Pullins (formerly of Little, Brown and now of Focus Publishing) and Worth Publisher's Kerry Baruth who championed the cause of *Geology* with their respective companies during its early gestation.

After they leave our classrooms, students may well forget specific facts and terminology of geology, but they will still retain the general impressions and attitudes they formed during our course. We hope that our words and illustrations will help advance the goals of those teaching this course and contribute to their classes. We have used our teaching experiences to craft a textbook that we think our own students will learn from and enjoy. We hope your students will, too. We invite your comments; please send them to the author, whose e-mail address is sechern@u.washington.edu.

Stan Chernicoff

To the Student

Geology is the scientific study of the structure and origin of the Earth, and the processes that have formed it over time. This book was created to bring you some of the excitement of that study through words and illustrations. Over the years, I have derived much pleasure from introducing geology to thousands of my own students at the Universities of Washington and Minnesota. I have also been a student and understand that some topics will be more interesting to you than others. I have worked to make every aspect of the book as fascinating and useful to you as possible.

Unlike some subjects you might study, your Physical Geology course is not over after the final exam. Wherever you live or travel, geology is far more than just the scenery—although your appreciation for the landscape will be much enhanced by a basic knowledge of geology. When you drink from a kitchen tap, dig in garden soil, see a forest—or see it being cut down for a construction project—geology has a role. If you gaze at a waterfall, swim in coastal currents, endure an earthquake—or read about those who did—you will understand more about the experience after taking this course. As you will learn, geology is everywhere—in the products you buy, the food you eat, the quality of your environment. The materials and processes encountered in the study of geology supply all of our needs for shelter, food, and warmth. This course will help you understand why earthquakes occur in some places and not in others, where we should build our homes and businesses to avoid floods and landslides, where we can find safe drinking water, and more. Knowledge of geology can also help make us better citizens as we learn how to prevent further damage to our environment and clean up some of our past mistakes.

You will also learn about more distant matters: the age of the Earth, how the planet has changed over its long lifetime, and how some of its creatures have changed along with it. You will explore some geological ideas about our Moon and the planets with which we share our solar system. Highlight boxes in each chapter provide additional information about particularly interesting topics. These include some of the geo-news events you've heard or read about in recent months.

The language geologists use helps us describe natural phenomena with precision and accuracy. We have minimized the new terminology you will need to learn, but to do well in the course you will still need to master some technical terms. We have also included some of their etymology (mostly Latin) so you can learn from where these unusual terms derive. The key terms are in bold type when introduced. They are also listed at the end of each chapter and defined in the glossary at the end of the book.

The drawings in this book are unique, showing you how the Earth really looks both on and below the surface. As you read and examine each illustration, you will find that the words, the photographs, and the drawings are all important—they are expressly designed to give you a full picture of geology. The text and illustrations, the key terms, and even the chapter summaries work together to help you learn the concepts and terms. When you read the summary, ask yourself if you know these key points; can you cite examples beyond those given in the brief summary?

Each chapter also includes two sets of questions, one testing your retention of the facts and one challenging you to think more deeply about some of their implications. Test yourself, and then go back and reread any material you are not sure you understand.

Finally, with the advancements in communications and multimedia technology, we have crafted two additional means by which you can learn an amazing amount about the Earth and, in doing so, strongly enhance your prospects for "doing well" in your geology course. The first—GEOLOGYLINK (available at www.geologylink.com), the text's web site—is a remarkable device for keeping you up-to-date regarding all things geological. Visiting the site for a few minutes each morning will prepare you well for geology class; in fact, you'll probably be more current than your professor regarding the major geo-events of the day. Use this resource and dazzle your professors and friends with your geo-knowledge. In addition to the latest information on geologic events, GEOLOGYLINK contains quizzes and tutorials on the major concepts in the course as well as an on-line version of the *Field Guide to Rocks and Minerals* by Frederick Pough.

The second teaching aid is the *Geology* CD-ROM that accompanies this book. This tool is designed to help you master the principles of physical geology and test your mastery of them. I strongly encourage you to spend time with both of these wonderful educational tools; they are ideal learning companions to the textbook.

As the author of this book, I hope you will enjoy it and gain an appreciation for geology that will enrich your life. This book has been written, illustrated, and designed to compel you to keep it on your bookshelf (although a few of you may actually choose to sell it to "Used Books"). It is our hope that 5, 10, or 20 years from now, when you see something that sparks your geological curiosity, you'll use your old geology book as a reference. If you have any comments, complaints, or compliments, please send them to me or to Houghton Mifflin. My e-mail address is sechern@u.washington.edu.

Features of

GEOLOGY,

Second Edition

The rich detail and technical accuracy of the illustrations help convey complex concepts to introductory students.

Photos are often paired with art to emphasize a point.

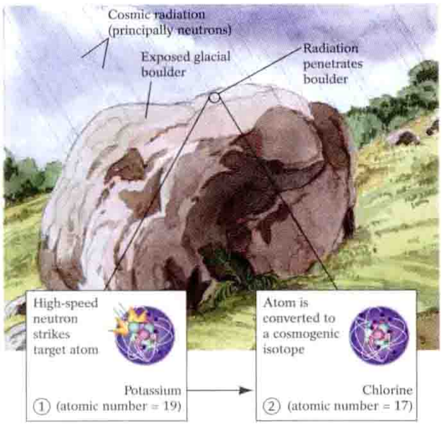


Figure 8-30 As soon as it is exposed, any surface rock begins to be bombarded with cosmic radiation. This converts target atoms into radioactive "cosmogenic" isotopes whose decay rate can then be measured to determine the time of initial exposure.

This method measures *cosmogenic* isotopes, those produ[...] in extremely small quantities at the surfaces of newly [...] posed rocks and other surface materials from cosmic-[...] bombardment.

Intergalactic cosmic radiation, predominantly in [...] form of neutrons, constantly bombards the Earth at p[...] nomenal speeds. (Countless numbers of these particles [...] passing through your body as you read this passage.) Th[...] neutrons strike the rocks and soils at the Earth's surface, p[...] etrating to a maximum depth of 2 to 3 meters (7 to 10 fe[...] before being absorbed. As these high-speed neutrons hit t[...] get elements in rocks and soils—such as oxygen, silicon, a[...] minum, iron, magnesium, calcium, and potassium—th[...] knock other atomic particles from the nuclei of these e[...] ments, converting these elements into new "cosmogenic" [...] dioactive isotopes (Fig. 8-30). Silicon, magnesium, iron, a[...] aluminum, for example, are typically converted to *berylliu[...] 10;* potassium, calcium, and chlorine become *chlorine-*[...]

The atoms of these radioactive substances, like ot[...] radioactive atoms, immediately begin to decay. Unlike in [...] case of non-cosmogenic isotopes, whose number of par[...] atoms is fixed (such as uranium in the Earth's crust), [...] atoms of these cosmogenic isotopes are constantly being p[...] duced, even as others decay. Thus a simple parent–daugh[...] decay relationship does not apply to these isotopes. Inste[...] we must know and then subtract their production rates a[...] accurately determine their decay rate, or half-life. Much [...] orous testing and study have revealed that chlorine-36 ha[...] half-life of roughly 300,000 years; beryllium-10's half-life[...]

Figure 8-31 This massive basaltic boulder was plucked from the Columbia River basalt flows of eastern Washington by a moving glacier about 15,000 years ago. Since the moment it melted from the ice, it has been bombarded by cosmic radiation; its time of initial exposure can be determined by surface-exposure dating.

approximately 1.5 million years. Knowing these half-lives enables geologists to date newly exposed surface boulders (Fig. 8-31) whose ages fall between the ranges of carbon-14 dating and other isotope-dating schemes.

Of course, any new dating method faces technical challenges. The first involves the extremely small amounts of these cosmogenic isotopes present in the rocks. During the

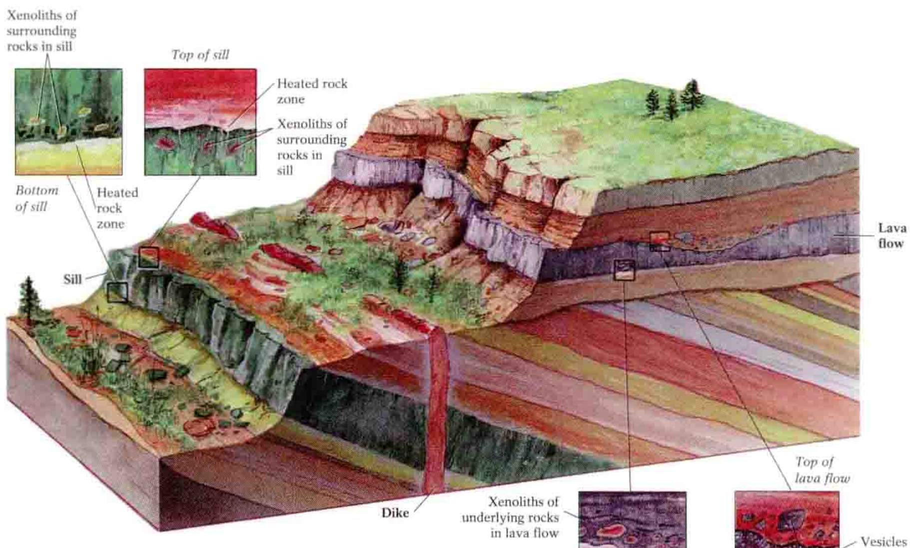


Figure 3-20 Sills and lava flows have differing relationships to the rocks surrounding them. Because sills result from magma intruding preexisting rock layers, rocks *both above and below* a sill show evidence of heating by the magma. Only the rock *below* a lava flow is affected, as overlying layers are not deposited until after the flow has solidified. In addition, because they occur at the surface, lava flows show evidence of having been exposed to air, whereas sills do not.

1. Look at the adjacent surfaces of the surrounding rocks. When lava is extruded, there are no overlying rocks and only the rocks *beneath* it will show evidence of heating. When hot magma intrudes between two layers of rock to form a sill, it heats the adjacent surfaces of *both* layers before cooling.
2. Look at the top and bottom surfaces of the igneous layer. Both surfaces of a sill will contain fragments of the surrounding rock that were pried loose as magma intruded, whereas only the bottom of a lava flow incorporates preexisting rock.
3. Look at the top surface of the igneous layer. Because the top of a lava flow is exposed to the air for some time before being overlain by other lava or sediment, its gases are free to escape. Consequently, the surface of a lava flow is often pockmarked by cavities called *vesicles* that were formerly occupied by escaping gas bubbles. The tops of most sills, which were never exposed to the air, display few, if any, vesicles.
4. Look for signs of weathering (discussed in Chapter 5). The upper surface of a lava flow would appear somewhat weathered from its exposure to the atmosphere before being overlain, whereas a sill would not show signs of weathering because it was never exposed.

Batholiths and Other Large Plutons

Large concordant plutons are commonly several kilometers thick and tens or even hundreds of kilometers across. They may be mushroom-shaped or saucer-shaped, close to the surface or deep beneath it.

When thick, viscous magma intrudes between two parallel layers of rock and lifts the overlying one, it cools to form a mushroom-shaped or domed concordant pluton, or **laccolith** (from the Greek *lakkos*, or "reservoir") (see Fig. 3-17). Laccoliths tend to form at relatively shallow depths, where there is little pressure to keep the overlying rock in place. Many are granitic, formed from felsic magma that flows so slowly that it tends to bulge upward instead of spreading

Artwork shows geologic features in a naturalistic context, to give students a sense of how these features actually look.

Highlight 4-3 Fire and Ice: Iceland's Subglacial Eruption of 1996

On September 29, 1996, an earthquake shook the ground beneath the 600-meter (2000-foot)-thick Vatnajökull icecap of southeastern Iceland. Vatnajökull, covering 8300 square kilometers (3200 square miles), is the largest glacier in Europe. The quake signaled the onset of a fissure eruption emanating from Iceland's Bardarbunga and Grimvötn volcanic centers. On the morning of October 1, scientists discovered a deep subsidence basin in the glacier's surface, close to the location of a major subglacial eruption in 1938. Throughout the day, the basin grew and three additional basins opened. The development of these aligned basins indicated that intensive melting was occurring at the base of the glacier along a 5- to 6-kilometer (3- to 4-mile)-long fissure. By October 2, steam rising from the glacier's surface indicated that the eruption had broken through the ice. Over the next several days, a steam column rose to more than 10 kilometers (6 miles), the surface fissure extended roughly the same distance, and black ash was being thrown intermittently into the air to heights of 300 to 500 meters (1000–1600 feet) (Fig. 4-26).

The greatest danger from a subglacial eruption is a *jokulhlaup,* or outburst flood. These floods occur when a great volume of subglacial meltwater, draining through subglacial tunnels, finds an outlet at the glacier's margin and discharges catastrophically (Fig. 4-27). Vatnajökull, overlying a segment of the mid-Atlantic ridge in southeastern Iceland, has been the source of numerous jokulhlaups in the past. By October 12, Vatnajökull's surface had risen 15 to 20 meters (50 to 65 feet) directly above the Grimsvötn caldera. This change suggested that meltwater from the eruption was flowing into and filling the 10-kilometer (6-mile)-diameter caldera. Engineers, anticipating a flood of monumental proportions, worked around the clock to reinforce dikes and cut diversionary channels to steer the expected torrents away from Iceland's main, island-ringing road, about 50 kilometers (30 miles) south of the icecap.

The long, unnerving wait for the jokulhlaup ended on November 5, when Iceland's largest flood in 60 years burst from the edge of the icecap. For two days, the flow formed the second-largest river in the world, destroying three bridges, severing vital telephone lines, and, despite valiant efforts, washing away Iceland's south-coast road. Such are the rigors of life in Iceland—the self-proclaimed Land of Fire and Ice.

Figure 4-26 Steam and ash rising from the subsidence basin on the surface of the Vatnajökull icecap, directly above the subglacial Grimvötn volcano.

Highlight boxes introduce high-interest topics, often recent geologic events.

Subglacial Eruptions When polar regions coincide with zones of volcanic activity, two of geology's most pronounced extremes—fire *and* ice—collaborate in spectacular geological

ıts. For example, in areas where large ice sheets overlie anically active fissures, hot mafic lava periodically erupts ɪath the ice, melting vast amounts of it and producing strophic outbursts of meltwater. One such drama captid geologists for six weeks in the autumn of 1996 when olcano erupted beneath a massive icecap in Iceland hlight 4-3).

oclastic Eruptions

oclastic eruptions, usually involving viscous, gas-rich magmas, vary from moderately to spectacularly explosive and tend to produce a great deal of solid volcanic fragments. Moderately explosive eruptions on the Italian island of Stromboli in the eastern Mediterranean occur almost continuously. A

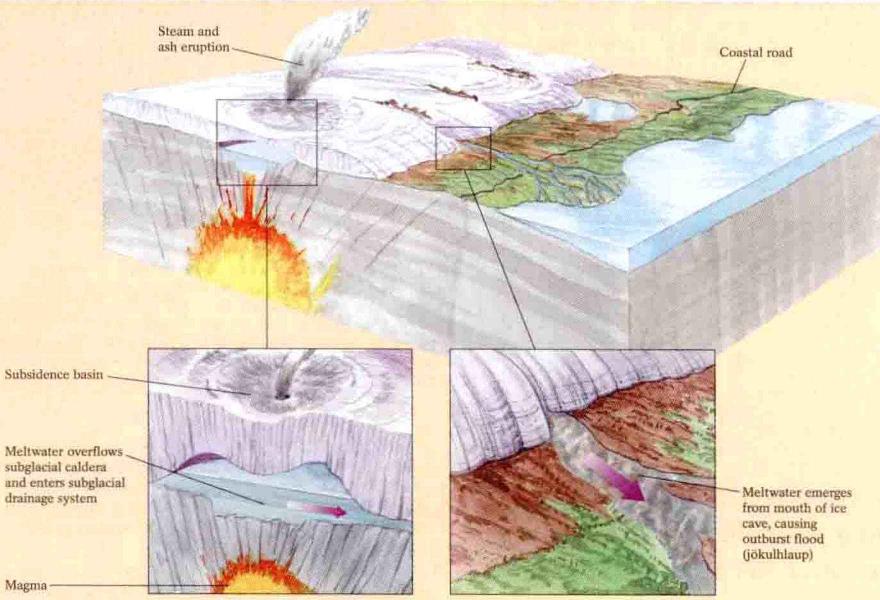


Figure 4-27 Muddy meltwater bursts catastrophically from the margin of the Vatnajökull icecap, producing an outburst flood, or jokulhlaup.

Every chapter has been updated to include fascinating developments and significant discoveries of the last 3 years.

Chapter Summary

Geology is the scientific study of the Earth. Geologists, like other scientists, systematically collect data derived from experiments and observations. They analyze and interpret their findings and develop **hypotheses** to explain how the forces of nature work. The hypotheses that are consistently supported by further study and investigation may be elevated to the status of a widely accepted explanation, or **theory.** A theory that withstands rigorous testing over a long period of time may be declared a **scientific law.** In order to be accepted, all scientific investigations must conform to these **scientific methods.** The hypotheses that have undergone such scrutiny include two that attempted to explain the evolution of the Earth's geologic features. **Catastrophism,** which was popular until the mid-eighteenth century, held that the Earth had evolved through a series of immense worldwide upheavals; **uniformitarianism,** proposed that the Earth has evolved slowly and gradually by small-scale processes that can still be seen operating. Today scientists recognize the effects of both slow processes and catastrophic events in the evolution of the Earth.

The present universe began with the "Big Bang" roughly 12 billion years ago. The Sun, which is a star, formed about 5 billion years ago from the collapse of a gas cloud, the center of which heated up as particles drawn inward by gravity collided and produced nuclear reactions. As the out region of the gas cloud cooled, the Earth and other plane developed (the Earth about 4.6 billion years ago) by accr tion of colliding masses of matter, some perhaps as large the planet Mars. Earth's collision with one such mass m have spawned the Moon.

During the Earth's first few tens of millions of years existence, the impact of these accreted masses along with t heat produced by radioactive decay warmed its interior u til the accumulated heat was sufficient to melt much of t planet's constituents. This period of internal heating caus the Earth to become layered, or differentiated. We base mu of our knowledge about the origin of the Earth's interior la ers on the study of **chondrules,** small nuggets of rocky m terial found in many meteorites that are believed to droplets of matter that condensed directly from the origin solar nebula. By comparing the composition of the Earth crust today to that of these chondrules, we note that t Earth's crust is quite deficient in iron. The early period heating must have caused the Earth's densest elements, p marily iron, to sink toward its interior while its lightest el ments rose and became concentrated closer to its surfac

Today, the Earth has three principal concentric laye of different densities: the thin, least dense outer layer, call the **crust;** a thick, denser underlying layer, called the **mantl** and a much smaller **core,** which is the most dense of Earth layers. Over the last 4 billion years, the Earth has cool slowly from its initial higher temperatures. Enough heat remains in its interior to generate currents of flowing mantle rock that have kept the outer portion of the Earth mobile. The Earth's **lithosphere,** a composite layer made up of the crust and the outermost segment of the mantle, is solid and brittle and forms large rocky plates; these plates move along at the Earth's surface atop the warm, flowing **asthenosphere** beneath them.

Time plays an important role in the evolution of the Earth's geologic features and materials. The Earth is believed to be about 4.6 billion years. Over such a vast amount of time, many gradual geological changes can take place that occur too slowly to be perceived on a human time scale. The Earth's three principal types of rocks undergo such changes, actually turning from one type into another, depending on the environmental forces acting on them. **Rocks,** which are defined as naturally occurring aggregates of inorganic materials **(minerals),** are categorized according to the way in which they form. The three basic rock groups are **igneous rocks,** which solidify from molten material; **sedimentary rocks,** which are compacted and cemented aggregates of fragments of preexisting rocks of any type; and **metamorphic rocks,** which form from any type of rock when its chemical composition is altered by heat, pressure, or chemical reactions in the Earth's interior. The continual transformation of the Earth's rocks from one type into another over time is called the **rock cycle.**

End-of-chapter summaries present an overview of the content in narrative form to help students review.

which evidence of life began to be abundantly preserved as fossils in rocks. The Phanerozoic Eon is divided into the **Paleozoic** ("ancient life") **Era, Mesozoic** ("middle life") **Era,** and **Cenozoic** ("recent life") **Era;** the Paleozoic was dominated by marine invertebrates (such as primitive clams, snails, and corals), and later fish and amphibians, and the Mesozoic and Cenozoic were dominated by reptiles (such as dinosaurs) and mammals, respectively.

Key Terms

geochronology (p. 207)
historical geology (p. 208)
relative dating (p. 208)
absolute dating (p. 209)
principle of uniformitarianism (p. 209)
principle of original horizontality (p. 210)
principle of superposition (p. 210)
principle of cross-cutting relationships (p. 210)
principle of inclusions (p. 210)
fossils (p. 212)
principle of faunal succession (p. 212)
index fossils (p. 213)
unconformities (p. 213)
correlation (p. 217)
parent isotope (p. 220)
daughter isotope (p. 220)
radiometric dating (p. 221)
half-life (p. 222)
uranium–thorium–lead dating (p. 225)
potassium–argon dating (p. 225)
rubidium–strontium dating (p. 225)
carbon-14 dating (p. 225)
fission tracks (p. 227)
dendrochronology (p. 227)
varves (p. 227)
lichenometry (p. 229)
geologic time scale (p. 232)
Paleozoic Era (p. 233)
Mesozoic Era (p. 233)
Cenozoic Era (p. 234)

Questions for Review

1. Briefly explain the difference between relative and absolute dating.

2. Discuss three of the basic principles that serve as the foundation of relative dating.

3. What qualifies a species to become an index fossil? How are index fossils used in the correlation of sedimentary rock strata?

4. Sketch and label two different types of unconformities.

5. Name three parent–daughter radiometric dating systems, and give the half-lives of each parent isotope, as well as the rocks or sediments that are most likely to be dated by each.

6. Briefly discuss two potential problems that may diminish the reliability of an isotopically derived date.

7. Briefly explain how carbon-14 enters the cells of living organisms.

8. Select three absolute-dating methods. Describe their basic principles, and the materials that can be dated by each technique.

9. Using the geologic time scale, state when each of the following great events in Earth history occurred: the origin of the world's iron ores; the first appearance of a protective atmosphere; the origin of flowering plants; the origin of birds; the age of reptiles; the current ice age.

10. If the oldest rocks found on Earth are less than 4.0 billion years old, what evidence suggests that the Earth is actually 4.6 billion years old?

For Further Thought

1. Why are obsidian and basalt more susceptible to the development of hydration and weathering rinds than granite and andesites?

2. Look at Figure 8-13 on page 216, the geologic profile of the Grand Canyon. The Cambrian Tapeats Sandstone lies unconformably above several different bodies of rock. Identify two different types of unconformities that separate the Tapeats Sandstone from the underlying rocks.

3. Using the various dating methods discussed in Chapter 8, derive the sequence of events that produced the hypothetical landscape below. (Go slowly, and don't jump to premature conclusions. Consider all the principles that we've discussed.) Which of the layers might be dated absolutely?

4. Although geologists claim that "the present is the key to the past" (the principle of uniformitarianism), the Earth has certainly changed throughout its 4.6-billion-year history. Think of two geological processes that operate differently today than they did in the past, and discuss how they vary.

5. Suppose you decided not to accept the 4.6-billion-year age of the Earth that geologists have determined (primarily from the ages of Moon rocks and meteorites and the evolution of lead isotopes on Earth). Devise an alternative strategy for determining the age of the Earth, assuming that you have unlimited funds.

The Key Term list is a tool for quick review and gives the page number for the full discussion, for students who need to reread the material. (The terms also appear in the glossary.)

Questions for Review help students review the factual content of the chapter, and For Further Thought questions encourage them to think critically about the implications of the information they have learned.

Contents in Brief

Contents