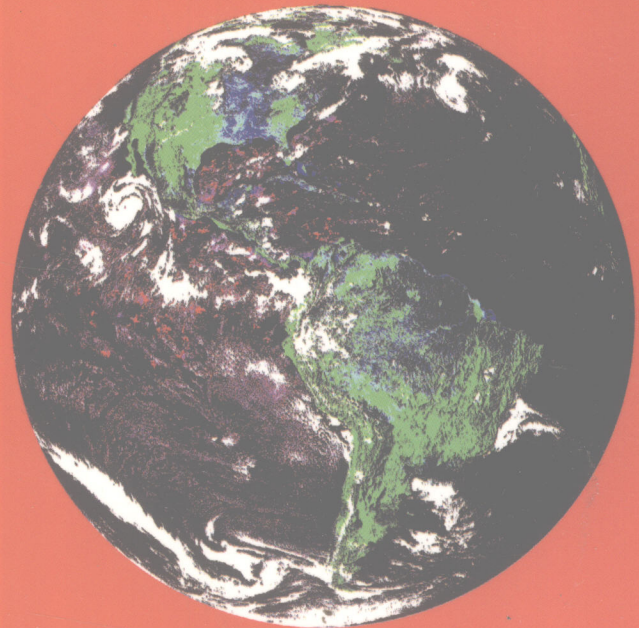
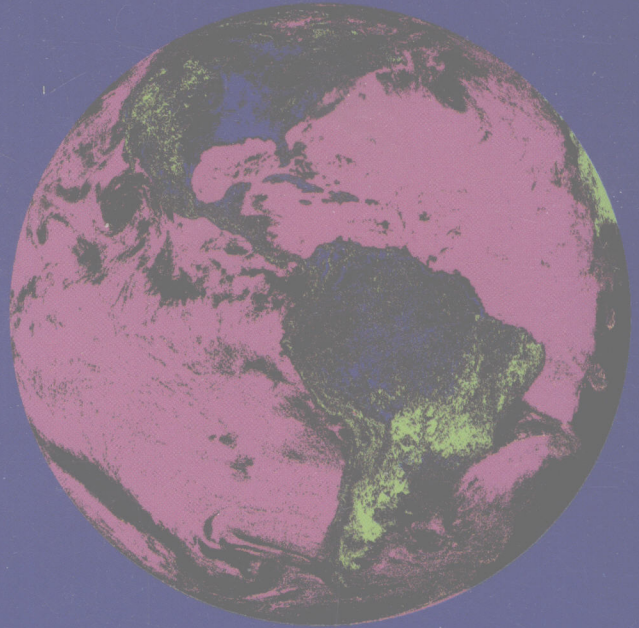
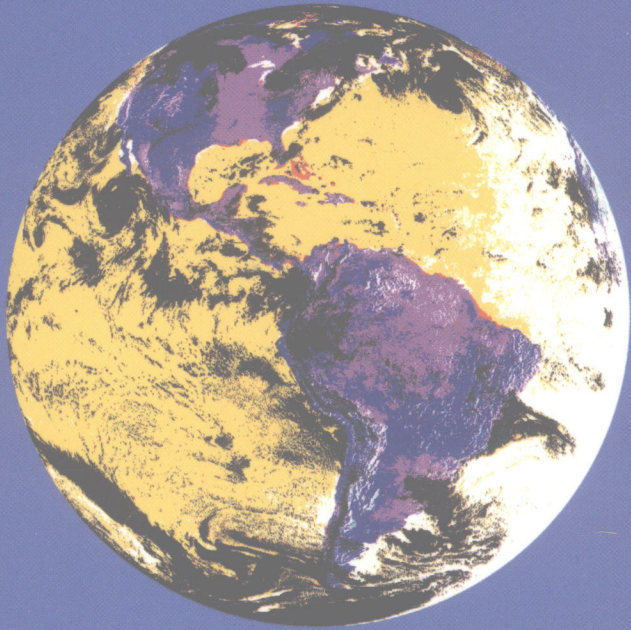


EARTH

PORTRAIT OF A PLANET



STEPHEN MARSHAK



Earth

Portrait of a Planet

STEPHEN MARSHAK

University of Illinois

With contributions from

Donald Prothero

Occidental College



W. W. NORTON & COMPANY

NEW YORK LONDON

Copyright © 2001 by W. W. Norton & Company, Inc.

All rights reserved.

Printed in the United States of America.

First Edition

The text of this book is composed in Stone Serif, with the display set in Frutiger.

Composition by TSI Graphics

Manufacturing by Courier

Editor: Jack Repcheck

Developmental editor: Susan Gaustad

Director of manufacturing: Roy Tedoff

Photography editors: Ruth Mandel, Neil Ryder Hoos, Sarah Chamberlin

Project editors: JoAnn Simony, Kim Yi

Layout artists: JoAnn Simony, Roberta Flechner, Cathy Lombardi

Editorial assistant: Garrett Michaels

Book designer: Joan Greenfield

Library of Congress Cataloging-in-Publication Data

Marshak, Stephen, 1955–

Earth : portrait of a planet / by Stephen Marshak ; with contributions by Donald Prothero.

p. cm.

Includes bibliographical references and index.

ISBN 0-393-97423-5 (pbk.)

1. Geology. I. Prothero, Donald R. II. Title.

QE26.2.M365 2001

550—dc21

00-048031

W. W. Norton & Company, Inc., 500 Fifth Avenue, New York, N.Y. 10110

www.wwnorton.com

W. W. Norton & Company Ltd., Castle House, 75/76 Wells Street, London W1T 3QT

5 6 7 8 9 0

TO THE
THE ASIA FOUNDATION
DISTRIBUTED BY
CHANGHAI INTERNATIONAL
UNIVERSITY LIBRARY
UNIVERSITY LIBRARY
UNIVERSITY LIBRARY

The modern science of geology (or geoscience), the study of the Earth, began in the late eighteenth century. So in comparison with other sciences, geology is a young subject. But over the past two centuries, thousands of geologists have provided answers to a wide range of questions: Why do earthquakes and volcanoes happen? What causes mountains to rise? How is the ocean floor different from the land surface? Where do rocks form, and what are they made of? How do Earth's varied landscapes develop and change through time? How has the climate changed through time? When did our planet form, and by what process? Has the map of Earth's surface remained the same through time? What do fossils tell us about the evolution of life? Where do we dig to find valuable ore, and where do we drill to find oil? How does the land react with air and water? Indeed, a look at almost any natural feature leads to a new question, and new questions fuel the need for new research. Thus, geoscience remains an active and exciting field today.

Before the mid-twentieth century, geoscientists studied each of the questions listed above on its own, without considering its relation to other issues. But since 1960, there have been two "paradigm-shifting" advances that have unified thinking about the Earth and its features. The first, called the theory of plate tectonics, shows that the Earth's outer shell, rather than being static, consists of discrete plates that constantly move very slowly, so that the map of our planet constantly changes. We now understand that plate interactions cause earthquakes and volcanoes, build mountains, provide gases for the atmosphere, and affect the distribution of life on Earth. The second advance, called the concept of Earth systems science, emphasizes that the planet's water, land, atmosphere, and living inhabitants are dynamically interconnected. Earth materials constantly cycle among various living and nonliving reservoirs on, above, and within the planet, and the history of life is intimately linked to the history of the physical Earth.

Earth: Portrait of a Planet is an introduction to geology that weaves the theory of plate tectonics and the concept of Earth systems science into its narrative from the beginning, and thus strives to create a modern, coherent image—a portrait—of our planet. This book will help students understand the origin of the Earth and its internal structure, the processes that cause plates to move and the consequences of this movement, the origin of Earth's diverse landscapes (from deserts to glaciers to coasts), the materials that make up the Earth (including the resources they contain), the envelope of air and water that surrounds and interacts with the solid Earth, the long history of the Earth, and the ways in which the planet changes through time. In addition, stu-

dents will acquire the background they need to address such practical issues as investing in property, as they learn about the hazards posed by earthquakes, unstable slopes, and floods. And they will gain the knowledge to understand political issues such as global warming and nuclear-waste disposal.

NARRATIVE THEMES

Although students will learn plenty of geological terminology in this book, to develop a more complete understanding of the Earth, they must go beyond vocabulary and be aware of fundamental concepts, or narrative themes, that explain how the Earth works. These themes provide a Peg-Board on which to hang observations and ideas, and allow students to make connections between them. Several narrative themes (discussed more fully in the Prelude) are emphasized throughout the text.

1. The Earth is a complex system in which the solid Earth, the oceans, the atmosphere, and life are interconnected to yield a planet unique in the solar system.
2. Most geological processes can be understood in the context of plate tectonics theory.
3. The Earth is a planet, formed like other planets from dust and gas, but a constantly changing one.
4. The Earth is very old—about 4.6 billion years old. During this time, the map of the planet and its surface features have changed, and life has evolved.
5. Internal processes (driven by Earth's internal heat) and external processes (driven by heat from the Sun) interact at the Earth's surface to create our landscapes.
6. Natural hazards—earthquakes, volcanoes, landslides, floods—and processes such as the depletion of oil and gas reserves are of vital interest to us all.
7. Physical features of the Earth are linked to life processes.
8. Science comes from observation, and people make scientific discoveries.
9. The study of geology can increase science literacy in such areas as chemistry and physics.

ORGANIZATION

The topics covered in this book have been arranged so that students can build their knowledge of geology on a

foundation of basic concepts. Thus, the book starts with cosmology and the formation of the Earth, and then introduces the architecture of our planet, from surface to center. With this background, we can delve into plate tectonics theory. Plate tectonics appears early, a departure from standard practice in introductory geology texts, so that students can relate all subsequent chapters to this concept. Knowing about plate tectonics, for example, helps students understand the next suite of chapters on minerals, rocks, and the rock cycle. A knowledge of plate tectonics and rocks together then provides a basis for learning about volcanoes, earthquakes, and mountains. And with this background, we can see how the map of the Earth and the life on it have changed through the vast expanse of geologic time, and how energy and mineral resources have developed.

The final part of the book addresses 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 also includes a summary of atmospheric science and concludes with a topic of growing concern in society—global change, particularly climate change.

SPECIAL FEATURES

Broad Application

Earth: Portrait of a Planet provides complete coverage of topics used in a traditional physical geology or introduction to geology course. But, recognizing that many instructors cover aspects of historical geology and Earth systems science as well, the book also provides chapters that address Earth history, the atmosphere, the oceans, and global change.

Flexible Organization

Though the sequence of chapters was chosen for a reason, this book is designed to be flexible enough for instructors to choose their own strategies for teaching geology. Thus, each chapter is largely self-contained, reiterating relevant material or at least referring to other chapters where certain topics can be reviewed. This apparent redundancy is intentional, for geology is a nonlinear subject: the individual topics are so interrelated that there is not always a single best way to order them.

Societal Issues

Geology's practical applications are addressed in chapters on energy resources, mineral resources, global change, and

mass wasting. Further, chapters on earthquakes, volcanoes, and landscapes highlight geological hazards. And students are encouraged to apply their geological understanding to environmental issues, where relevant.

Boxed Inserts

Throughout the text, boxes expand on specific topics by giving further scientific background, additional detail, or related information that's just plain interesting.

Detailed Illustrations

It's hard to understand features of the Earth system without being able to see them. To help students visualize topics, this book is lavishly illustrated, with figures that attempt to give a realistic context for a geologic feature without overwhelming students with extraneous detail. The talented artists who worked on the book have "pushed the envelope" of modern computer graphics, and the result is the most realistic pedagogical art ever provided by a geoscience text.

Photographs from around the world have been assembled for this book. Where appropriate, they are accompanied by annotated sketches labeled "What a geologist sees," to help students discover what the photos show.

Featured Paintings

In addition to individual figures, British painter Gary Hincks has provided spectacular two-page spreads for most chapters. These paintings illustrate key concepts introduced in the chapters and visually emphasize the relationships between components of the Earth system.

SUPPLEMENTS

For Instructors

1. Norton Media Library with PowerPoint Slides

Included on this CD-ROM (dual platform) are approximately 100 photographs, 300 state-of-the-art illustrations from the text, and 49 unique and dynamic Flash animations. Developed by Stephen Marshak in collaboration with Precision Graphics, and by Declan DePáor, these animations illustrate key geologic principles that are difficult to convey through static images. Some examples:

- Transform faulting
- Plate boundaries
- Hot-spot volcanoes
- Subduction
- Rifting
- Mineral growth
- The formation of oceanic crust
- The formation of cross beds
- Transgression and regression
- Types of faults
- Seismic-wave motion
- How a seismograph works
- Types of unconformity
- Folding
- Geologic history
- Oil formation and trapping
- The evolution of a meandering stream
- Glacial advance and retreat
- Milankovitch cycles

Designed for lecture display or student use, these animations can be enlarged to full-screen view, and feature VCR-like controls that allow you to pause, fast-forward, or rewind for more effective use in the classroom.

2. *Overhead Transparency Set*

The text illustrations are featured in a complete set of transparency acetates.

3. *Test-Item File*

Prepared by Stephen Marshak, Terry Engelder of Pennsylvania State University, and John Werner of the University of Illinois, this test bank contains over 1,200 multiple-choice and true-false test questions. It is available in printed form or in Norton TestMaker (MicroTest III), a flexible electronic testing system for IBM-compatible or Macintosh computers. The computerized test-item file includes approximately 700 additional multiple-choice and true-false questions from the Study Guide.

4. *Instructor's Resource Manual*

This manual, prepared by John Werner, contains useful material to assist instructors as they prepare their lectures.

For Students

1. *Portrait of a Planet Website*

This resource features nearly fifty interactive animations of dynamic processes, with an emphasis on plate tectonics, geologic hazards, and Earth systems science concepts. Overviews, key terms and definitions, crossword puzzles, and multiple-choice quizzes test students' understanding of chapter content. Biweekly *Earth Science News* updates from Newswise.com and specially commissioned articles by science writer Elisabeth Mason help them to apply their knowledge and further highlight the relevancy and inherent interest of geologic concepts.

2. *Portrait of a Planet CD-ROM*

Selected contents from the student website are also available on a free CD-ROM packaged with every copy of the text.

3. *Study Guide*

Written by Rita Leafgren of the University of Northern Colorado, this thorough review provides summaries and study advice for each chapter, recall and matching exercises,

short-answer questions, figure-labeling exercises, and practice tests.

ACKNOWLEDGMENTS

I am very grateful for the assistance of many people in bringing this book from the concept stage to the shelf. First and foremost, I wish to thank my family. My wife Kathy helped throughout in the overwhelming task of keeping track of text and figures. In addition, she edited text, copied drafts, and provided invaluable advice. My daughter Emma spent many nights helping to organize figures, and my son David helped me keep the project in perspective. During the early stages, I benefited greatly from discussions with Philip Sandberg, who contributed ideas that helped establish the organization and tone of the book. Donald Prothero assisted at a later stage by contributing text and editorial comments, and providing end-of-chapter questions and suggested readings. I also wish to thank Fernando Alkmim, who helped me figure out the best way to explain some of the complex topics in the book.

The publisher, W. W. Norton, has been incredibly supportive and generous in their investment in this project. I am particularly grateful to the editorial staff. Steve Mosberg helped lay out the basic framework of the book and provided valuable suggestions for content, and Rick Mixter refined the framework and set it on track to its final form. Jack Repcheck bulldozed aside obstacles to bring the project to completion, has been a constant source of encouragement, and has provided numerous innovative ideas that have strengthened the book. Susan Gaustad has been an outstanding copy editor, who has come up with wonderful suggestions for wordings. Susan's sharp eye caught many of those little errors that are so easy to miss. April Lange expertly coordinated the development of ancillaries, particularly the CD-ROM. Ruth Mandel and, later, Neil Hoos and Sarah Chamberlin have been outstanding photo researchers, incorporating my own photographs and locating spectacular photos from contributors. JoAnn Simony ably managed the Herculean task of overseeing production for the book.

The illustrations have involved many artists. Precision Graphics, of Champaign, Illinois, has done a phenomenal job of producing overwhelming volumes of high-quality figures on short notice. Joanne Bales of PG has been particularly helpful in working out the details of figure design with me and in coordinating the artists who worked on the book. Stan Maddock helped create the style of the figures, and produced a great many of them. George Kelvin drew a number of the figures in the earlier chapters. And Gary Hincks has produced the incredible two-page spreads, in part using his own designs and geological insight.

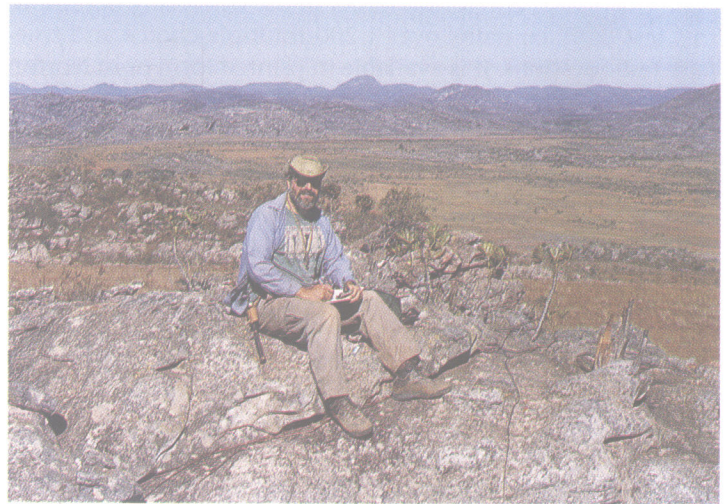
I also much appreciate insightful reviews or discussions of the manuscript by the following geologists. The careful comments by Barbara Tewksbury were particularly valuable.

Jack C. Allen, Bucknell University
David W. Andersen, San Jose State University
Philip Astwood, University of South Carolina
Keith Bell, Carleton University
Mary Lou Bevier, University of British Columbia
George S. Clark, University of Manitoba
Patrick M. Colgan, Northeastern University
John W. Creasy, Bates College
Robert T. Dodd, State University of New York at Stony Brook
James E. Evans, Bowling Green State University
William D. Gosnold, University of North Dakota
Bryce M. Hand, Syracuse University

Donna M. Jurdy, Northwestern University
Robert Lawrence, Oregon State University
John A. Madsen, University of Delaware
Charlie Onasch, Bowling Green State University
Lisa M. Pratt, Indiana University
Bob Reynolds, Central Oregon Community College
Kevin G. Stewart, University of North Carolina at Chapel Hill
Barbara Tewksbury, Hamilton College
Thomas M. Tharp, Purdue University
Kathryn Thorbjarnarson, San Diego State University
Robert T. Todd, SUNY Stony Brook
Jon Tso, Radford University
William E. Sanford, Colorado State University
Alan Whittington, University of Illinois
Lorraine W. Wolf, Auburn University
Christopher J. Woltemade, Shippensburg University

ABOUT THE AUTHOR

Stephen Marshak is currently professor and head of the Department of Geology at the University of Illinois, Urbana-Champaign. He holds an A.B. from Cornell University, an M.S. from the University of Arizona, and a Ph.D. from Columbia University (Lamont-Doherty Earth Observatory). Steve's research interests lie in the fields of structural geology and tectonics. He has served as chair of the Division of Structural Geology and Tectonics of the Geological Society of America, and as a member of the National Science Foundation Panel for Tectonics. Over the years, he has had the opportunity to explore geology in the field on several continents. Recently, his work has focused on understanding the development of mountain belts, particularly in the ancient crust of Brazil (the accompanying photograph was taken in Serra do Espinhaço). Steve has been on the faculty of the University of Illinois since 1983, teaching courses in introductory geology, structural geology, tectonics, field geology, and petroleum geology, and has won the university's highest teaching award. He shares authorship on two previous books: *Basic Methods of Structural Geology* and *Earth Structure: An Introduction to Structural Geology and Tectonics*.



THANKS!

I greatly appreciate your selection of this book as your entrée into the science of geology. This is a first edition, and as such can certainly benefit from input by users. I welcome your comments, especially if you find text or figures that are in error or not clear. Please contact me at: smarshak@uiuc.edu.

Stephen Marshak

B R I E F C O N T E N T S

	Preface		xiii
	Prelude	<i>And Just What Is Geology?</i>	3
<hr/>			
PART I OUR ISLAND IN SPACE	Chapter 1	<i>Cosmology and the Birth of Earth</i>	15
	Chapter 2	<i>Journey to the Center of the Earth</i>	35
	Chapter 3	<i>Drifting Continents and Spreading Seas</i>	51
	Chapter 4	<i>The Way the Earth Works: Plate Tectonics</i>	77
<hr/>			
PART II EARTH MATERIALS	Chapter 5	<i>Patterns in Nature: Minerals</i>	109
	Interlude A	<i>Rock Groups</i>	129
	Chapter 6	<i>Up from the Inferno: Magma and Igneous Rocks</i>	137
	Chapter 7	<i>A Surface Veneer: Sediments and Sedimentary Rocks</i>	163
	Chapter 8	<i>Change in the Solid State: Metamorphic Rocks</i>	203
	Interlude B	<i>The Rock Cycle</i>	227
<hr/>			
PART III TECTONIC ACTIVITY OF A DYNAMIC PLANET	Chapter 9	<i>The Wrath of Vulcan: Volcanic Eruptions</i>	237
	Chapter 10	<i>A Violent Pulse: Earthquakes</i>	269
	Interlude C	<i>Seeing Inside the Earth</i>	308
	Chapter 11	<i>Crags, Cracks, and Crumples: Crustal Deformation and Mountain Building</i>	319
<hr/>			
PART IV HISTORY BEFORE HISTORY	Interlude D	<i>Memories of Past Life: Fossils and Evolution</i>	352
	Chapter 12	<i>Deep Time: How Old Is Old?</i>	365
	Chapter 13	<i>A Biography of Earth</i>	395
<hr/>			
PART V EARTH RESOURCES	Chapter 14	<i>Squeezing Power from a Stone: Energy Resources</i>	427
	Chapter 15	<i>Riches in Rock: Mineral Resources</i>	453
<hr/>			
PART VI PROCESSES AND PROBLEMS AT THE EARTH'S SURFACE	Interlude E	<i>Ever-Changing Landscapes and the Hydrologic Cycle</i>	472
	Chapter 16	<i>Unsafe Ground: Landslides and Other Mass Movements</i>	481
	Chapter 17	<i>Streams and Floods: The Geology of Running Water</i>	507
	Chapter 18	<i>Restless Realm: Oceans and Coasts</i>	545
	Chapter 19	<i>A Hidden Reserve: Groundwater</i>	581
	Chapter 20	<i>An Envelope of Gas: Earth's Atmosphere and Climate</i>	611
	Chapter 21	<i>Dry Regions: The Geology of Deserts</i>	645
	Chapter 22	<i>Amazing Ice: Glaciers and Ice Ages</i>	667
	Chapter 23	<i>Global Change in the Earth System</i>	707
<hr/>			
	Metric Conversion Chart		736
	Appendix A	<i>Scientific Background: Matter and Energy</i>	A-1
	Appendix B	<i>Flow Charts for Identifying Minerals</i>	B-1
	Glossary		G-1
	Index		I-1

PREFACE

Prelude

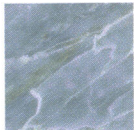
And Just What Is Geology? 3

In Search of Ideas 3

The Nature of Geology 5

Themes of This Book 6

SCIENCE TOOLBOX: *The Scientific Method* 9



PART I

Our Island in Space

Chapter 1

Cosmology and the Birth of Earth 15

Introduction 15

An Evolving Image of the Earth and Space 15

A Sense of Scale 18

THE REST OF THE STORY: *Earth's Rotation* 18

SCIENCE TOOLBOX: *The Parallax Method* 20

The Modern Image of the Universe 21

Forming the Universe 21

SCIENCE TOOLBOX: *Transmitting Energy by Waves* 22

Growing Solar Systems out of Chaos 25

We Are All Made of Stardust 25

Featured painting: The Birth of the Earth-Moon System 26–27

End-of-chapter material 31

Chapter 2

Journey to the Center of the Earth 35

Introduction 35

Welcome to the Neighborhood 35

The Atmosphere 37

Land and Oceans 38

What Is the Earth Made Of? 40

Discovering That the Earth Has Layers 41

Featured painting: The Interior of the Earth 42–43

What Are the Layers Made Of? 45

THE REST OF THE STORY: *Meteorites* 47

The Lithosphere and Asthenosphere 48

End-of-chapter material 48

xiii

Chapter 3

Drifting Continents and Spreading Seas 51

Introduction 51

Wegener's Evidence for Continental Drift 52

Paleomagnetism and Apparent Polar-Wander Paths 56

SCIENCE TOOLBOX:

The Fundamentals of Magnetism 57

THE REST OF THE STORY:

Generating Earth's Magnetic Field 58

THE REST OF THE STORY: *Finding Paleopoles* 61

Setting the Stage for the Discovery of Sea-Floor Spreading 63

Harry Hess and His "Essay in Geopoetry" 66

Marine Magnetic Anomalies: Evidence for Sea-Floor Spreading 66

Featured painting: Paleomagnetism 68–69

Deep-Sea Drilling: Further Evidence 73

End-of-chapter material 74

Chapter 4

The Way the Earth Works: Plate Tectonics 77

Introduction 77

What Do We Mean by Plate Tectonics? 78

SCIENCE TOOLBOX:

Archimedes' Principle of Buoyancy 79

Featured painting: The Theory of Plate Tectonics 80–81

Divergent Plate Boundaries and Sea-Floor Spreading 84

Convergent Plate Boundaries and Subduction 87

Transform Plate Boundaries 89

Special Locations in the Plate Mosaic 91

THE HUMAN ANGLE:

So You Want to See a Plate Boundary? 93

The Birth and Death of Plate Boundaries 97

What Drives Plate Motion? 99

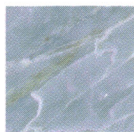
The Velocity of Plate Motions 101

THE REST OF THE STORY:

Does Plate Tectonics Occur on Other Planets? 101

The Dynamic Planet 102

End-of-chapter material 103



PART II Earth Materials

Chapter 5

Patterns in Nature: Minerals 109

Introduction 109

What Is a Mineral? 111

SCIENCE TOOLBOX:

Some Basic Definitions from Chemistry 112

Beauty in Patterns: Crystals and Their Structure 113

How Do You Tell One Mineral from Another? 118

Organizing Our Knowledge: Mineral Classification 121

Something Precious—Gems! 123

THE REST OF THE STORY:

Where Do Diamonds Come From? 125

End-of-chapter material 127

Interlude A

Rock Groups 129

Introduction 129

What Is Rock? 129

Rock Occurrences 130

The Basis of Rock Classification 131

Studying Rock 134

Chapter 6

Up from the Inferno: Magma and Igneous Rocks 137

Introduction 137

The Formation of Magma 139

Featured painting: The Formation of Igneous Rocks 140–41

What Is Magma Made Of? 142

THE REST OF THE STORY:

Understanding Decompression Melting 142

THE REST OF THE STORY: *Bowen's Reaction Series* 145

The Movement of Magma and Lava 146

Extrusive versus Intrusive Environments 147

Transforming Magma into Rock 152

Igneous Rock Textures 152

Classifying Igneous Rocks 154

Where Does Igneous Activity Occur, and Why? 155

End-of-chapter material 159

Chapter 7

A Surface Veneer: Sediments and Sedimentary Rocks 163

Introduction 163

Weathering: The Formation of Sediment 165

Soil: Derived from Sediment at the Earth's Surface 172

Introducing Sedimentary Rocks 176

Clastic Sedimentary Rocks 176

Biochemical and Organic Sedimentary Rocks:

Byproducts of Life 179

Chemical Sedimentary Rocks 183

Sedimentary Structures 186

Sedimentary Environments 188

Featured painting: The Formation of Sedimentary Rocks 192–93

Sedimentary Basins 196

End-of-chapter material 199

Chapter 8

Change in the Solid State: Metamorphic Rocks 203

Introduction 203

What Is a Metamorphic Rock? 204

Causes and Consequences of Metamorphism 205

SCIENCE TOOLBOX: *Diffusion* 206

Types of Metamorphic Rocks 210

Grades of Metamorphism 214

THE REST OF THE STORY: *Metamorphic Facies* 217

Featured painting: Environments of Metamorphism 218–19

Environments of Metamorphism 220

THE HUMAN ANGLE: *Pottery Making—
an Analogue for Thermal Metamorphism* 222

Where Do You Find Metamorphic Rocks? 224

End-of-chapter material 224

Interlude B

The Rock Cycle 227

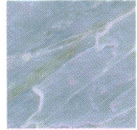
Introduction 227

A Case Study 228

Featured painting: Rock-Forming Environments and the Rock Cycle 230–31

Rates of Movement Through the Rock Cycle 232

What Drives the Rock Cycle? 232



PART III *Tectonic Activity of a Dynamic Planet*

Chapter 9

The Wrath of Vulcan: Volcanic Eruptions 237

- Introduction 237
- The Products of Volcanic Eruptions 238
- The Architecture and Shape of Volcanoes 244
- Eruptive Styles: Will It Flow, or Will It Blow? 247
- Featured painting: *Volcano* 248–49

THE HUMAN ANGLE:

Volcanic Explosions to Remember 250

- Hot-Spot Eruptions 252
- Eruptions Along Mid-Ocean Ridges 255
- Eruptions Along Convergent Boundaries 256
- Eruptions in Continental Rifts 256
- Volcanoes in the Landscape 257
- Beware: Volcanoes Are Hazards! 257
- Protection from Vulcan's Wrath 260
- Volcanoes and Climate 263
- Volcanoes and Civilization 264
- Volcanoes on Other Planets 265
- End-of-chapter material 266

Chapter 10

A Violent Pulse: Earthquakes 269

- Introduction 269
- Faults and the Generation of Earthquakes 270
- Featured painting: *Faulting in the Crust* 276–77

THE REST OF THE STORY: *Moonquakes* 279

- Seismic Waves 279
- Measuring and Locating Earthquakes 281
- Where and Why Do Earthquakes Occur? 288
- Damage from Earthquakes 293
- Predicting "The Big One" 300
- Earthquake Engineering and Zoning 304
- End-of-chapter material 306

Interlude C

Seeing Inside the Earth 308

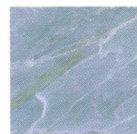
- Introduction 308
- The Movement of Seismic Waves Through the Earth 308

- The Reflection and Refraction of Wave Energy 310
- Discovering the Crust-Mantle Boundary 310
- Defining the Structure of the Mantle 311
- The Core-Mantle Boundary (the P-Wave Shadow Zone) 312
- The Nature of the Core (the S-Wave Shadow Zone) 313
- Fine-Tuning Our Image of the Earth's Layers 314
- An Integrated View of the Earth 316

Chapter 11

Crags, Cracks, and Crumples: Crustal Deformation and Mountain Building 319

- Introduction 319
- Mountain Belts and the Concept of Orogeny 321
- Rock Deformation in the Earth's Crust 321
- Joints: Natural Cracks in Rocks 325
- THE REST OF THE STORY:
Describing the Orientation of Structures 326
- Faults: Fractures on Which Sliding Has Occurred 327
- Folds: Curving Rock Layers 330
- Tectonic Foliation in Rocks 334
- Rock Formation During Orogeny 334
- Uplift and the Formation of Mountain Topography 336
- Causes of Mountain Building 339
- Cratons and the Deformation Within Them 341
- Featured painting: *The Collision of India with Asia* 342–43
- Life Story of a Mountain Range: An Example 345
- Measuring Mountain Building in Progress 346
- End-of-chapter material 346



PART IV *History Before History*

Interlude D

Memories of Past Life: Fossils and Evolution 352

- The Discovery of Fossils 352
- Fossilization 353
- Classifying Life 358
- Classifying Fossils 359
- The Fossil Record 361
- Evolution and Extinction 362

Chapter 12

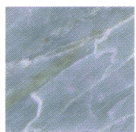
***Deep Time: How Old Is Old?* 365**

- Introduction 365
- Time: A Human Obsession 366
- The Concept of Geologic Time 366
- Physical Principles for Defining Relative Age 370
- Adding Fossils to the Story: Fossil Succession 371
- Unconformities: Gaps in the Record 372
- Stratigraphic Formations and Their Correlation 374
- The Geologic Column 377
- Featured painting: The Record in Rocks: Reconstructing Geologic History* 378–79
- Numerical Age and the Radiometric Clock 383
- THE REST OF THE STORY: *Carbon-14 Dating* 386**
- Adding Numerical Ages to the Geologic Column: Dating Periods 388
- The Age of the Earth 389
- Picturing Geologic Time 391
- End-of-chapter material 392

Chapter 13

***A Biography of Earth* 395**

- Introduction 395
- Methods for Studying the Past 396
- The Hadean Eon: Hell on Earth 397
- The Archean Eon: The Birth of the Crust, the Oceans, and Life 399
- The Proterozoic Eon: Transition to the Modern World 401
- Featured painting: The Evolution of Life* 404–5
- The Phanerozoic Eon: Life Diversifies, and Today's Continents Form 406
- The Paleozoic Era: From Rodinia to Pangaea 406
- The Mesozoic Era: When Dinosaurs Ruled 411
- SCIENCE TOOLBOX: *Stratigraphic Sequences and Sea-Level Change* 416**
- The Cenozoic Era: The Final Stretch to the Present 418
- Into the Future 421
- End-of-chapter material 422



PART V
Earth Resources

Chapter 14

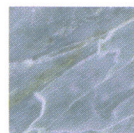
***Squeezing Power from a Stone: Energy Resources* 427**

- Introduction 427
- Sources of Energy in the Earth System 428
- Oil and Gas 430
- Making an Oil Reserve 432
- THE REST OF THE STORY: *Types of Oil Traps* 435**
- Oil Exploration and Production 436
- THE HUMAN ANGLE: *Spindletop* 436**
- Natural Gas 438
- Coal: Energy from the Swamps of the Past 439
- Finding and Mining Coal 442
- Nuclear Power 444
- Geothermal Energy 447
- Hydroelectric Power 447
- Energy Choices, Energy Problems 448
- End-of-chapter material 450

Chapter 15

***Riches in Rock: Mineral Resources* 453**

- Introduction 453
- Metals and Their Discovery 454
- Ores, Ore Minerals, and Ore Deposits 456
- Ore-Mineral Exploration and Production 461
- Nonmetallic Mineral Resources 463
- THE HUMAN ANGLE: *The Sidewalks of New York* 465**
- Global Mineral Needs, Reserves, and Politics 466
- End-of-chapter material 468



PART VI
Processes and Problems at the Earth's Surface

Interlude E

***Ever-Changing Landscapes and the Hydrologic Cycle* 472**

- Introduction 472
- The Battle Between Uplift and Erosion 472
- Featured painting: The Hydrologic Cycle* 476–77
- Factors Controlling Landscape Development 478
- The Hydrologic Cycle 479

Chapter 16

***Unsafe Ground: Landslides and Other Mass Movements* 481**

- Introduction 481
- Types of Mass Movement 482
- Setting the Stage for Mass Movements 489

- Featured painting: Mass Movement* 490–91
 Fingers on the Trigger: Factors Causing Slope Failure 494
 Plate Tectonics and Mass Movements 498
THE HUMAN ANGLE: *Los Angeles, a Mobile Society* 499
 How Can We Protect Against Mass-Movement Disasters? 500
 End-of-chapter material 504

Chapter 17***Streams and Floods: The Geology of Running Water*** 507

- Introduction 507
 Draining the Land 508
 Discharge and Turbulence 513
GEOLOGY YOU CAN SEE:
Badlands National Park 516
 The Work of Running Water 518
 How Streams Change Along Their Length 521
 Streams and Their Deposits in the Landscape 522
Featured painting: River Systems 530–31
 The Evolution of Drainage 532
 Raging Waters 534
 Rivers: A Vanishing Resource? 540
 End-of-chapter material 541

Chapter 18***Restless Realm: Oceans and Coasts*** 545

- Introduction 545
 Landscapes Beneath the Sea 547
 Ocean Water 551
 Currents: Rivers in the Sea 553
SCIENCE TOOLBOX: *The Coriolis Effect* 555
 The Tides Go Out . . . the Tides Come In . . . 559
 Wave Action 559
 Where Land Meets Sea: Coastal Landforms 562
 Causes of Coastal Variability 572
 Coastal Problems and Solutions 573
 End-of-chapter material 577

Chapter 19***A Hidden Reserve: Groundwater*** 581

- Introduction 581
 Where Does Groundwater Reside? 582
 Permeability: The Ease of Flow 584
 The Water Table 585
 Groundwater Flow: From Recharge to Discharge 587

- The Chemistry of Groundwater 589
 Tapping the Groundwater Supply 590

THE HUMAN ANGLE: *Oases* 593

- Hot Springs and Geysers 594
 Groundwater Usage Problems 596
 Caves and Karst: A Spelunker's Paradise 601
Featured painting: Caves and Karst Landscape 602–3
 End-of-chapter material 608

Chapter 20***An Envelope of Gas: Earth's Atmosphere and Climate*** 611

- Introduction 611
 The Formation of the Atmosphere 612
 The Atmosphere in Perspective 613
 Wind and Global Circulation in the Atmosphere 616
THE HUMAN ANGLE: *Why Is the Sky Blue?* 618
THE REST OF THE STORY:
The Earth's Tilt: The Cause of Seasons 620
 Weather and Its Causes 624
 Storms: Nature's Fury 628
 Global Climate 637
 End-of-chapter material 641

Chapter 21***Dry Regions: The Geology of Deserts*** 645

- Introduction 645
 What Is a Desert? 645
 Types of Deserts 646
 Weathering and Erosional Processes in Deserts 649
 Depositional Environments in Deserts 653
 Desert Landscapes 655
THE REST OF THE STORY: *Uluru (Ayers Rock)* 658
 Life in the Desert 659
Featured painting: The Desert Realm 660–61
 Deserts in the Modern Era: Desertification 663
 End-of-chapter material 665

Chapter 22***Amazing Ice: Glaciers and Ice Ages*** 667

- Introduction 667
 Ice: A Rock Made from Water 669
 The Nature of Glaciers 669
 Carving and Carrying by Ice 676
 Deposition Associated with Glaciation 681
Featured painting: Glaciers and Glacial Landforms 686–87

THE HUMAN ANGLE: *So You Want to See a Glacier?* 688

Other Consequences of Continental Glaciation 688

THE REST OF THE STORY:

The Great Missoula Flood 692

Periglacial Environments 692

The Pleistocene Ice Age 694

Ice Ages: The Causes 698

Will There Be Another Glacial Advance? 701

End-of-chapter material 702

Chapter 23

Global Change in the Earth System 707

Introduction 707

Unidirectional Changes 708

THE REST OF THE STORY: *The Goldilocks Effect* 709

Physical Cycles 710

Biogeochemical Cycles 712

Featured painting: *The Earth System* 714–15

Global Climate Change 717

THE HUMAN ANGLE:

Global Climate Change and the Birth of Legends 720

THE REST OF THE STORY:

The Faint Young Sun Paradox 722

Anthropogenic Changes in the Earth System 726

The Future of the Earth: A Scenario 732

End-of-chapter material 733

Metric Conversion Chart 736

Appendix A Scientific Background: Matter and Energy A-1

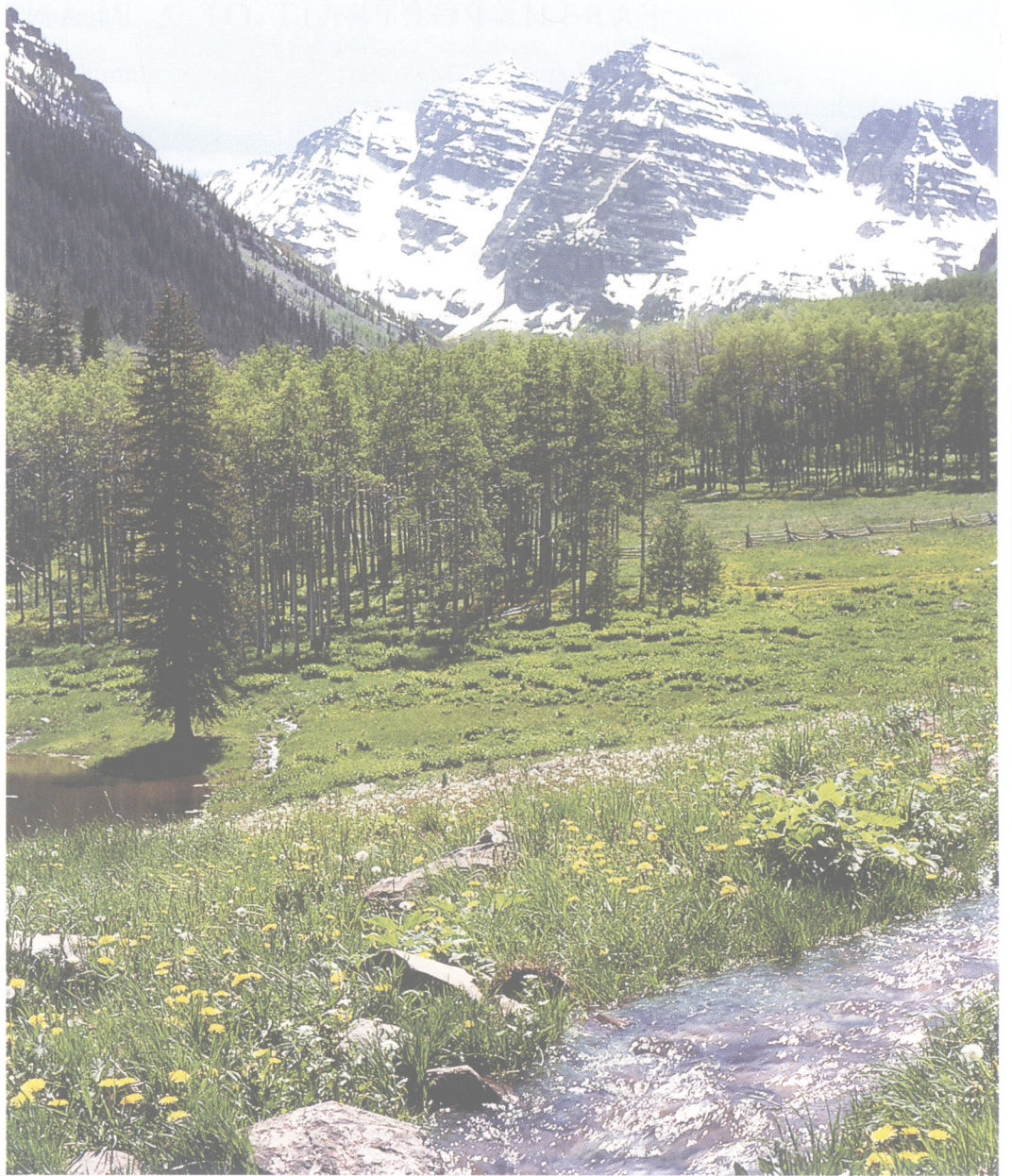
Appendix B Flow Charts for Identifying Minerals B-1

Glossary G-1

Credits C-1

Index I-1

EARTH: PORTRAIT OF A PLANET



And Just What Is Geology?

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

—WILL DURANT (1885–1981)

P.1 IN SEARCH OF IDEAS

In the glare of the midnight sun, our C-130 Hercules transport plane rose from a smooth ice runway on the frozen sea surface at McMurdo Station, Antarctica, and we were off to spend a month studying unusual rocks exposed on a cliff about 250 kilometers (km) away. As we climbed past the smoking summit of Mt. Erebus, Earth's southernmost volcano, we had one nagging thought: no aircraft had ever landed at our destination, so the ground conditions there were unknown; if deep snow covered the landing site, the massive plane might get stuck and not be able to return to McMurdo. Because of this concern, the flight crew had added a crate of rocket canisters to the pile of snowmobiles, sleds, tents, and food in the plane's cargo hold. "If the turboprops can't lift us, we can clip a few canisters to the tail, light them, and rocket out of the snow," they claimed.

For the next hour, we flew along the Transantarctic Mountains, a ridge of rock that divides the continent into two parts, East Antarctica and West Antarctica (►Fig. P.1). A vast ice sheet, in places over 3 km thick, covers East Antarctica—the surface of this ice sheet forms a high plain known as the Polar Plateau. Rivers of ice from the Polar Plateau slowly flow down valleys cut through the Transantarctic Mountains. (Ice sheets and ice rivers are called **glaciers**.) From the plane's windows, we admired long stripes of rock debris that had been shed from mountains onto the glaciers in these valleys. Suddenly, we heard the engines slow.

As the plane descended, it lowered its landing gear, which was equipped with skis. The loadmaster shouted a reminder of the emergency alarm code: "If you hear three short blasts of the siren, hold on for dear life!" Roaring toward the ground, the plane touched the surface of our first choice for a landing spot, the ice at the base of the rock cliff we wanted to study. *Wham, wham, wham, wham!!!!*

We can see the Earth system at a glance near the Maroon Bells, a row of mountains in Colorado. Here, sunlight, air, water, rock, and life all interact.