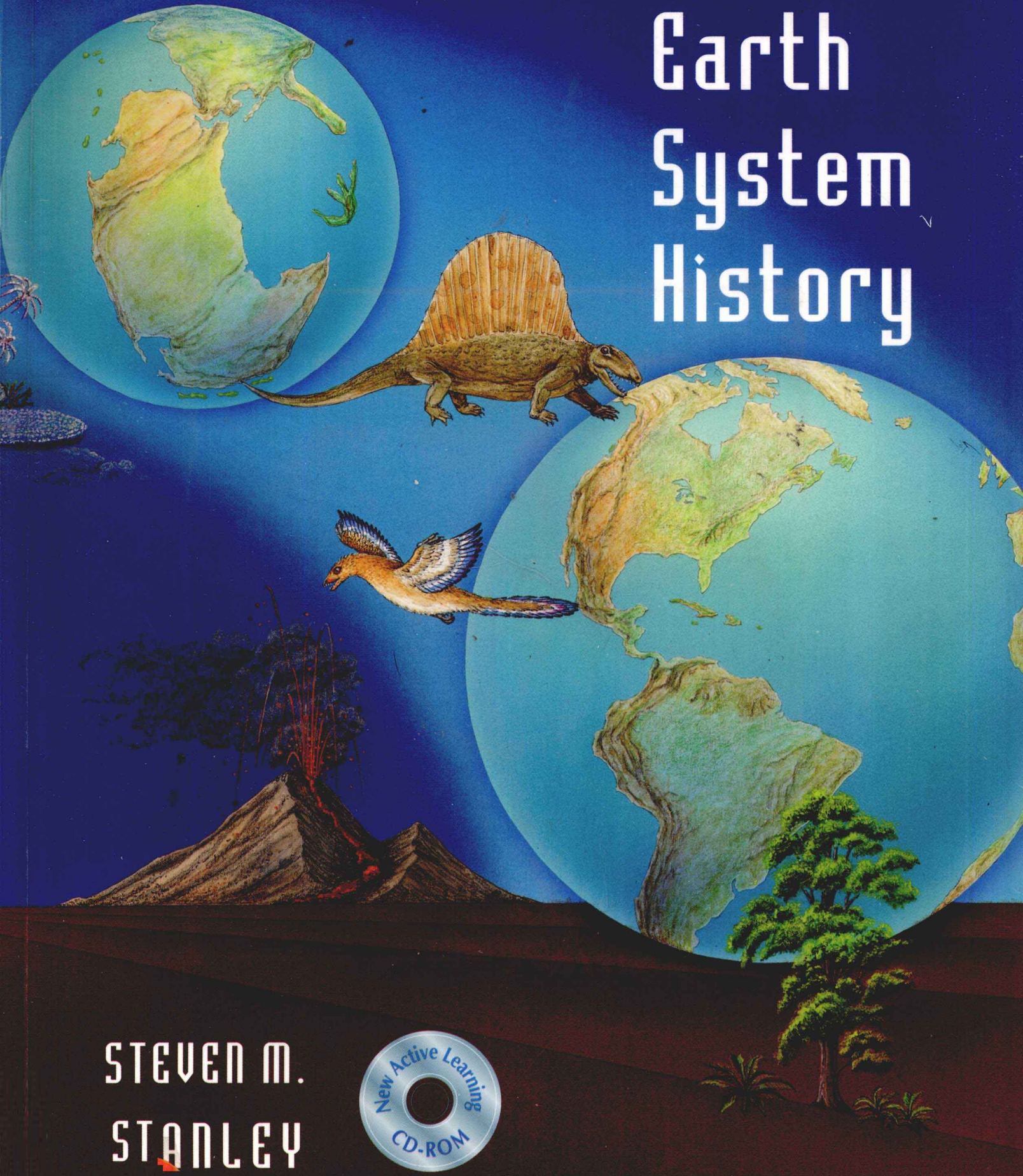


Earth System History



STEVEN M.
STANLEY



Earth System History

STEVEN M. STANLEY

Johns Hopkins University



W. H. Freeman and Company • *New York*

To Nell and Sveta

About the Cover: Early Earth was a glowing, liquid planet. After it cooled, the ocean, atmosphere, and continental crust formed, and as continents coalesced and fragmented, life appeared. Throughout its subsequent evolution, life has interacted with Earth's dynamic crust and enveloping fluids. The cover for this first edition of *Earth System History* depicts these geologic and biological events, showing four stages of Earth's development as a planet.

Sponsoring Editors: Holly Hodder, Melissa Levine Wallerstein
Development Editors: Kay Ueno, Diana Gill
Project Editor: Georgia Lee Hadler
Cover Illustrator: Tomo Nagashima
Text Designer: Blake Logan
Illustration Coordinator: Susan Wein
Illustrations: Roberto Osti; Fine Line Studios
Photo Researcher: Kathy Bendo
Production Coordinators: Maura Studley, Susan Wein
Composition: Sheridan Sellers and Bonnie Stuart, W. H. Freeman
Electronic Publishing Center; Progressive Information Technologies
Manufacturing: RR Donnelley & Sons Company
Supplements Coordinators: Patrick Shriner, Robert Christie
Marketing Manager: John Britch

Library of Congress Cataloging-in-Publication Data

Stanley, Steven M.

Earth system history / Steven M. Stanley.

p. cm.

Includes bibliographical references and index.

ISBN 0-7167-2882-6

1. Historical geology. 2. Physical geology. I. Title.

QE28.3.S735 1998

551.7—dc21

18-21861

CIP

© 1999 by W. H. Freeman and Company. All rights reserved.

No part of this book may be reproduced by any mechanical, photographic, or electronic process, or in the form of a phonographic recording, nor may it be stored in a retrieval system, transmitted, or otherwise copied for public or private use, without written permission from the publisher.

Printed in the United States of America

Third Printing, 2002

Preface

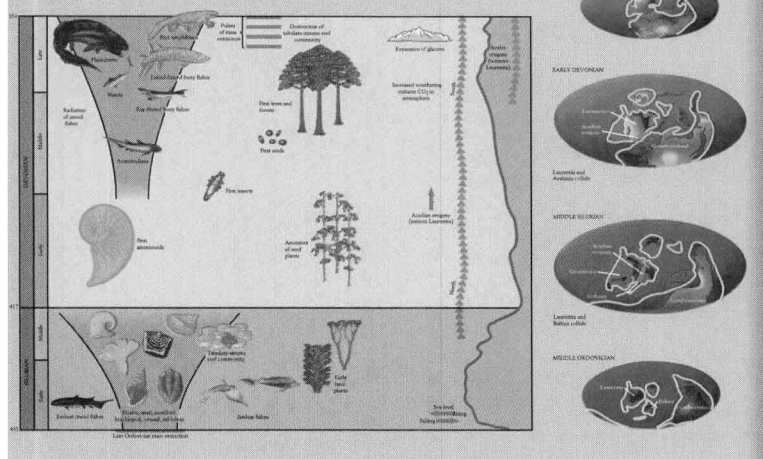
The curriculum in the Earth sciences has been evolving rapidly in the last few years, after many decades of relative stability. Appropriately, the new approach to teaching reflects a shift in research toward integrative study of the entire Earth system and its many subsystems. This Earth system approach demands a rethinking of the field traditionally called historical geology: the only way to reconstruct and interpret Earth's history effectively is by treating the lithosphere, biosphere, hydrosphere, and atmosphere as parts of a single system. *Earth System History* reforges its successful predecessor, *Exploring Earth and Life Through Time*, to reflect this powerful new way of studying Earth's history. The traditional topics of historical geology still remain at the core of *Earth System History* but are enriched by placement in the broader framework of the planet as a whole.

Now more than ever, Earth's history deserves a central place in a balanced undergraduate curriculum. The rock record of Earth's deep history is what sets geology apart from all other sciences, and in an era of heightened concern about the environment it is imprudent to ignore this unique archive and to focus strictly on present-day geologic processes. The full geologic record of life and environments is more broadly relevant: it documents the myriad unique natural experiments that show how the Earth system functions. We will never duplicate these experiments in the laboratory or in the field. We must study them in rocks. Understanding changes of the past will help us—and our students—confront future environmental changes.

The history of life and the history of the physico-chemical environment are inextricably intertwined. This is not a unidirectional relationship: environmental changes affect life, but biologic changes in turn alter the environment. For example, my colleague Lawrie Hardie and I have found that simple changes in ocean chemistry, governed by global spreading rates along mid-ocean ridges, have determined what kinds of organisms have been the dominant reef formers and sediment producers during particular intervals of the Phanerozoic Eon. Thus, "For The Record 10-1: Seawater Chemistry and Chalk" presents strong evidence that the massive chalk deposits that gave the Cretaceous System its name accumulated because of the presence of "calcite seas," which resulted from unusually high rates of seafloor spreading. As another example, Chapters 10 and 14 describe how the advent of forests in Devonian time must have reduced carbon dioxide levels in the

Visual Overview

Major Events of the Middle Paleozoic



atmosphere and set the stage for the late Paleozoic ice age.

A survey of instructors revealed a strong consensus that courses covering Earth's history should explain how studies of stable isotopes shed light on events of the geologic past. Accordingly, Chapter 10 introduces the use of stable isotopes to study the history of key chemical cycles and other aspects of the Earth system including the greenhouse effect and the effects of plate tectonic activity on seawater. This new chapter is central to the Earth system approach, introducing concepts and techniques that later emerge in discussions of particular events in Earth's history. The Earth system approach culminates in the new final chapter on the Holocene, which ushers students into the modern ice age and raises issues about future global change.

How This Book Is Organized

This edition has been substantially revised to provide teachers and students with a comprehensive guide to Earth system history. It has been updated in accordance with the latest scientific knowledge.

Chapter 1 introduces the Earth system approach, emphasizing the rock cycle and the hydrological cycle as well as plate tectonic cycling of materials. It also contrasts the gradual and catastrophic processes that shape Earth.

New to this book, Chapter 2 introduces important groups of rocks and rock-forming minerals and explains how they relate to one another within the rock cycle. This chapter includes information on how chemical bonds and structures affect the properties of minerals. It can serve as a review for students who have completed a course in physical geology or as a primer for those with no background in physical geology.

Also new to this edition, Chapter 3 reviews the biology and classification of the six kingdoms of organisms and introduces methods of phylogenetic reconstruction. This chapter assumes no background in biology on the student's part, but provides a context for subsequent discussions of the history of life.

Chapter 4 includes an expanded discussion of the influence of topography on climate and a new treatment of thermal regimes of shallow seas.

Chapter 5 includes a new discussion of the use of fossils to delineate sedimentary environments.

Chapter 6 now introduces the field of stratigraphy by showing how it arose as a branch of geology. This chapter also integrates the definition of formal stratigraphic units with discussions of stratigraphic concepts.

Chapter 7 invokes the origin of whales to exemplify the origins of higher taxa. It also contains a new introduction to major mass extinctions.

Chapter 8 integrates an introduction to the basic kinds of faults with a discussion of plate tectonics, and Chapter 9 integrates folding with mountain building in a similar way.

Chapter 10 is an entirely new chapter that uses an approach never before seen in an introductory textbook. This chapter examines the oxygen and carbon cycles and describes the factors that govern levels of atmospheric oxygen and carbon dioxide. To comprehend Earth system history it is necessary to understand the impact of major chemical cycles on Earth, and Chapter 10 uses simple diagrams and real-world examples to clearly explain the effects of chemical cycles in the past and their possible consequences for the future.

Chapter 11 presents the widely favored explanation of the origin of the moon as the result of an asteroid impact and the likely origin of life in the heated zone along a mid-ocean ridge.

Chapter 12 presents new evidence about major events near the end of the Proterozoic Eon, including the assembly of a supercontinent, profound glaciation, the possible buildup of atmospheric oxygen, and the explosive diversification of multicellular organisms.

In response to instructors' comments, I have rewritten Chapters 13, 14, and 15 to place mountain-building episodes in the Appalachian region in the context of Earth's Paleozoic history. These chapters also provide up-to-date reviews of the great Paleozoic mass extinctions and show how the origin of forests and coal swamps probably led to late Paleozoic glaciation by reducing greenhouse warming.

Chapters 16 and 17 are highlighted by new discoveries that change our view of dinosaurs and Mesozoic land plants. Chapter 16 also focuses on new evidence that the arrival of a meteorite brought the Mesozoic Era to an end.

Chapters 18 and 19 present new evidence of climatic, biotic, and oceanographic changes during the Cenozoic, new chronologies of mountain building in the American West, and recent discoveries that place human origins in a new light.

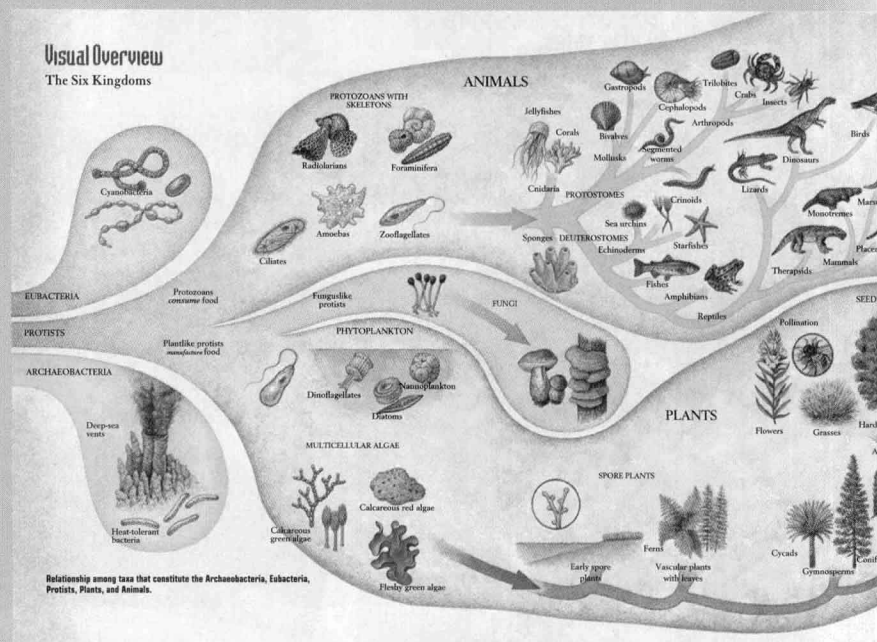
Chapter 20, an entirely new review of the Holocene, describes Earth's complicated emergence from the most recent glacial maximum. This chapter emphasizes changes in climate and sea level in recent history, and their consequences for the environment. The present world emerges in this chapter: having gained a broad knowledge of Earth's past, the student becomes oriented toward its future.


A New Vision, a New Book

Several features highlight the new approach of *Earth System History*.

Visual Overviews

Visual Overviews provide students with vivid illustrations of the key themes and concepts of Chapters 2 through 20. Expanded from the Major Events diagrams in the previous edition, *Visual Overviews* concisely portray major geologic events and cycles.



Furthermore, a *Review Question* at the end of each chapter challenges the student to use the chapter's *Visual Overview* to synthesize key points. Each special *Review Question* is identified by a System Icon: .

Review Questions

- 11 Suppose that you were to encounter a well-trained geologist who was unfairly imprisoned in 1955 and was deprived of reading materials until he was released last week. He entered prison firmly opposed to the idea that continents have moved large distances across Earth's surface. Given an hour of time, how would you convince this unfortunate geologist that continents have actually moved thousands of kilometers? Use the *Visual Overview* on p. 208 as a guide to develop your argument.

For the Record

Chapters 2 through 20 feature *For the Record*, an in-depth look at an environmental, evolutionary, or resource-oriented example in Earth system history. Ranging from the extinction of the dinosaurs to drilling for oil off the shore of New Jersey, *For the Record* boxes offer real-world examples of Earth system history in action.

Seawater Chemistry and Chalk

Chalk is a soft, white, fine-grained limestone that we use to write on blackboards, but it is also the formal name for a large Upper Cretaceous body in western Europe. Along the coast of France the Chalk forms cliffs that Allied troops scaled during the invasion of Normandy in 1944, and it rises up as the famous White Cliffs of Dover on the British side of the English Channel. The Cretaceous contains a vastly larger volume of chalk than any other geologic system. As it turns out, this unusual abundance probably reflects the chemical composition of Cretaceous seas.

The most massive deposits of Cretaceous chalk are those of western Europe, which are typically about 200 meters (660 feet) thick, but substantial bodies of chalk also accumulated in an epicontinental sea in North America. Between Alabama and Kansas, Upper Cretaceous chalks have yielded spectacularly well-preserved fossils, including skeletons of huge marine reptiles that might be described as sea monsters. Fossils are exceptionally well-preserved in chalk for the same reason that the chalk is soft: it is formed of minute grains of calcite. The small size of these grains makes

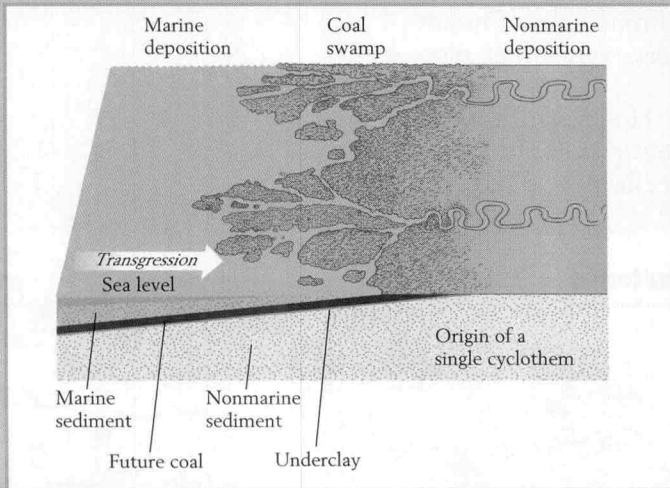
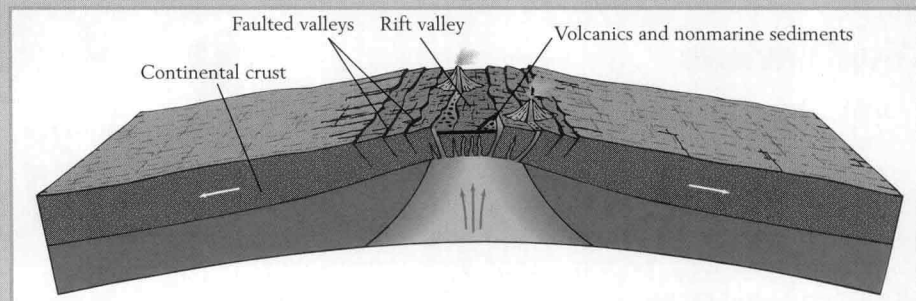


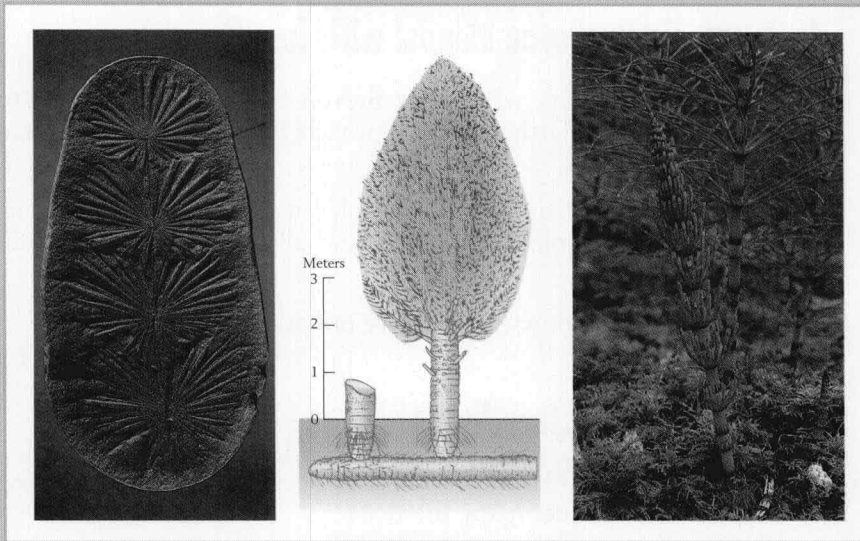
Illustration Program

A full-color illustration program enhances *Earth System History's* new approach. Line illustrations have been clarified and recreated in full-color, and many black-and-white photographs have been replaced by striking new color photographs.

New three-dimensional block diagrams illustrate processes, cycles, and events in Earth system history.

For effective presentation of key subjects, line art and photographs have been paired frequently: line diagrams illustrate important patterns and accompanying photographs provide actual examples.





Chapter Summaries, Review Questions, and Additional Readings

End-of-chapter material aids students in identifying and retaining key themes of each chapter. *Chapter Summaries* reiterate integral concepts and facts, *Review Questions* help students understand and remember important ideas, and *Additional Readings* offer interested students resources for learning more about Earth system history.

Appendix and Glossary

The *Appendix* covers the major stratigraphic stages of Earth's history in one compact, comprehensive source. The *Glossary* includes concise definitions of important scientific and geologic terms that may be unfamiliar to the student. Scientific and geologic terms are printed in **boldface** when they first appear in the text and then are gathered with their definitions in the comprehensive *Glossary*.

Supplements

Earth System History provides a complete historical geology program for instructors and students.

Student CD-ROM

- Selected exercise modules and activities on key areas such as the evolution of the continents and sedimentary environments.
- Student study features include multiple-choice quizzes with built-in feedback and mnemonic exercises for learning the intervals of the geologic time scale.
- Original geological animations convey challenging but essential concepts of atmospheric chemistry, mountain building, stratigraphy, sedimentology, and paleoclimatology.

Instructor's Resource Manual with Test Questions

- Recommendations, written by Steven Stanley, explain how to emphasize the Earth system approach in covering the material in each chapter.
- Many of the test questions for each chapter, in a variety of formats, contain geologic diagrams, and all test questions provide page references.
- Original transparency masters are provided.

Slide Set with Lecture Notes

- A selection of 60 top-quality historical geology slides picked specifically to accompany the text.
- An accompanying booklet of lecture notes puts each slide in the context of the course material. The slide set was curated by renowned geology photographer Peter Kresan of the University of Arizona.

Overhead Transparency Set

- 50 full-color overheads, including key diagrams from the text as well as original illustrations.

Computerized Test Banks

- Amenable to editing and the addition of questions.
- Available for both Windows and Macintosh operating systems.

Freeman Geology Web Site

<http://www.whfreeman.com/geology/>

- Provides links to hundreds of Web sites related to geology.
- Includes expansion modules with additional information on historical and physical geology.
- Presents a complete list of geology newsgroups.

Acknowledgments

A large group of colleagues offered advice and reviewed the text as this edition was created. I thank them for their hard work and valuable suggestions, but accept full responsibility for any errors that remain. These colleagues are

Beth Nichols Boyd, <i>Yavapai College</i>	Karl J. Koenig, <i>Texas A&M University</i>
Fred Clark, <i>University of Alberta</i>	Michael T. May, <i>Western Kentucky University</i>
William C. Cornell, <i>University of Texas at El Paso</i>	Cathryn R. Newton, <i>Syracuse University</i>
John W. Creasy, <i>Bates College</i>	Geoffrey Norris, <i>University of Toronto</i>
R. A. Davis, <i>College of Mount St. Joseph</i>	Mark E. Patzkowsky, <i>Pennsylvania State University</i>
Steven R. Dent, <i>Northern Kentucky University</i>	Gregory J. Retallack, <i>University of Oregon</i>
Stanley C. Finney, <i>California State University, Long Beach</i>	Charles A. Ross, <i>Western Washington University</i>
John P. Grotzinger, <i>Massachusetts Institute of Technology</i>	Frederic J. Schwab, <i>Washington and Lee University</i>
Bryce M. Hand, <i>Syracuse University</i>	Peter Sheehan, <i>Milwaukee Public Museum</i>
Leo J. Hickey, <i>Yale University</i>	John F. Taylor, <i>Indiana University of Pennsylvania</i>
Calvin James	David K. Watkins, <i>University of Nebraska, Lincoln</i>
Markes E. Johnson, <i>Williams College</i>	Neil A. Wells, <i>Kent State University</i>
James O. Jones, <i>University of Texas at San Antonio</i>	
Andrew H. Knoll, <i>Harvard University</i>	

I am also grateful to colleagues who contributed their efforts to the previous edition: Barbara Brande, University of Montevallo; William Cornell, University of Texas, El Paso; Louis Dellwig, University of Kansas; Jay M. Gregg, University of Missouri, Rolla; Bryce Hand, Syracuse University; James Jones, University of Texas, San Antonio; Karl Koenig, Texas A&M University; David Liddell, Utah State University; Robert Merrill, California State University, Fresno; Anne Noland, University of Louisville; Lisa Pratt, University of Indiana, Bloomington; Randall Spencer; Old Dominion University.

I owe special thanks to many people at W. H. Freeman and Company who aided me in launching this book. Holly Hodder and her successor, Melissa Levine Wallerstein, provided invaluable guidance along the way, and Moira Lerner, Kay Ueno, and Diana Gill were a great help at various stages of the molding process. As always, Mary Shuford and Philip McCaffrey managed things beautifully, and Georgia Lee Hadler was her usual pillar of strength and reliability while assembling the book. Barbara Salazar copyedited deftly once again, offering improvements without offence. Chris Scotese kindly made available his splendid reconstructions of ancient worlds. Blake Logan created a splendid design, and I feel privileged to have had the brilliant watercolorist Roberto Osti render the magnificent Visual Overviews in the first part of the book. Kathy Bendo gathered many excellent photographs under great time pressure. Finally, Patrick Shriner and Robert Christie opened the door to wonderful new supplemental resources.



Contents in Brief

CHAPTER	1	Earth as a System	1
CHAPTER	2	Rock-Forming Minerals and Rocks	29
CHAPTER	3	The Diversity of Life	57
CHAPTER	4	Environments and Life	91
CHAPTER	5	Sedimentary Environments	121
CHAPTER	6	Correlation and Dating of the Rock Record	151
CHAPTER	7	Evolution and the Fossil Record	181
CHAPTER	8	The Theory of Plate Tectonics	207
CHAPTER	9	Continental Tectonics and Mountain Chains	231
CHAPTER	10	Major Chemical Cycles	257
CHAPTER	11	The Archean Eon of Precambrian Time	285
CHAPTER	12	The Proterozoic Eon of Precambrian Time	315
CHAPTER	13	The Early Paleozoic World	341
CHAPTER	14	The Middle Paleozoic World	369
CHAPTER	15	The Late Paleozoic World	399
CHAPTER	16	The Early Mesozoic Era	435
CHAPTER	17	The Cretaceous World	465
CHAPTER	18	The Paleogene World	495
CHAPTER	19	The Neogene World	519
CHAPTER	20	The Holocene	559

Contents

Preface	xvii	Plate Tectonics	17
CHAPTER 1		Plate Movements	17
Earth as a System	1	The Engine of Plate Tectonics	19
Exploring the Earth System	2	Plate Tectonics and the Rock Cycle	19
The Components of the System	2	The Water Cycle	20
The Fragility of the System	2	The Reservoirs	21
The Principle of Uniformitarianism	3	Interactions with the Rock Cycle	22
Actualism: The Present as the Key to the Past	3	Directional Change in Earth's History	22
The End of Catastrophism	4	The Evolution of Life	22
The Nature and Origin of Rocks	5	Physical and Chemical Trends	23
Basic Kinds of Rocks	5	The History of Ecosystems	24
Classification of Bodies of Rock	8	Episodic Change in Earth's History	24
Steno's Three Laws for Sedimentary Rocks	9	Gaps in the Stratigraphic Record	24
The Rock Cycle	9	Catastrophic Deposition	25
Global Dating of the Rock Record	11	Episodic Events in the History of Life	25
Fossils, Markers, and the Relative Ages of Rocks	11	Chapter Summary/Review Questions/ Additional Reading	26
Radioactivity and the Actual Ages of Rocks	12	CHAPTER 2	
The Geologic Time Scale	13	Rock-Forming Minerals and Rocks	29
Development of the Time Scale	14	The Structure of Minerals	29
Imaging the Earth Below	14	Atoms, Elements, and Isotopes	29
The Density Gradient	15	<i>Visual Overview: Rocks and Their Origins</i>	30
Lithosphere and Asthenosphere	16	Chemical Reactions	33

Crystal Lattices	35		
Ion Substitution	36		
The Properties of Minerals		37	
Hardness	37		
Density	38		
Fracture Patterns	38		
The Origins of Minerals	38		
Tracing the Origins of Rocks	38		
Families of Rock-Forming Minerals	38		
Types of Rock		40	
Igneous Rocks	40		
Sediments and Sedimentary Rocks	42		
<i>For the Record 2-1: Why Our Buildings Are Made from Fossils</i>	48		
Metamorphic Rocks	51		
Chapter Summary/Review Questions/ Additional Readings	54		
CHAPTER 3			
The Diversity of Life		57	
<i>Visual Overview: The Six Kingdoms</i>	58		
Fossils		60	
Hard Parts: Commonly Preserved Skeletal Features of Animals	60		
Preservation of Soft Parts of Animals	60		
Permineralization	61		
Molds and Impressions	61		
Trace Fossils	62		
Fossil Fuels	62		
The Quality of the Fossil Record	63		
Kingdoms of Organisms		63	
Taxonomic Groups	64		
Reconstructing the Tree of Life	64		
Identifying Clades and Their Relationships		66	
A General Cladogram for Vertebrates	66		
A General Phylogeny for Vertebrates	67		
Analyses at Lower Taxonomic Levels for Horses	69		
The Quality of Phylogenetic Reconstructions	70		
Prokaryotes: The Two Kingdoms of Bacteria		70	
Archaeobacteria	70		
Eubacteria	70		
The Protist and Fungus Kingdoms		71	
Protists	71		
Fungi	74		
The Plant Kingdom		74	
Seedless Vascular Plants	75		
Seed Plants	75		
The Animal Kingdom		76	
Sponges: Simple Invertebrates	76		
Cnidarians	77		
Chordates	82		
<i>For the Record 3-1: Bringing Some Very Old Vertebrates to Light</i>	86		
Chapter Summary/Review Questions/ Additional Reading	88		
CHAPTER 4			
Environments and Life		91	
<i>Visual Overview: The Distribution of Environments and Life on Earth</i>	92		
The Principles of Ecology		94	
A Species' Position in Its Environment	94		
Communities of Organisms	95		
Biogeography	97		
The Atmosphere		98	
The Chemical Composition of the Atmosphere	98		

Temperatures and Circulation
in the Atmosphere 99

The Terrestrial Realm 101

 Latitudinal Zones and Vegetation 101

 The Effects of Altitude on Climate 105

 Land, Water, and Seasonal Temperature
 Change 106

 Fossil Plants as Indicators
 of Climate 108

The Marine Realm 109

 Water Movements 109

 The Depth of the Sea 111

 Marine Life Habits and Food Webs 112

 Marine Temperature and
 Biogeography 114

 Salinity as a Limiting Factor 115

For the Record 4-1: The Fragile Reef 116

 Freshwater Environments 117

Chapter Summary/Review Questions/
Additional Reading 118

CHAPTER 5

Sedimentary Environments 121

*Visual Overview: Depositional
Environments and Accumulation
of Sediments* 122

Soil Environments 124

 How Soils Form 124

 Ancient Soils 125

The Depositional Environments
of Freshwater Lakes and Glaciers 126

 Freshwater Lake Environments 126

 Glacial Environments 126

Deserts and Arid Basins 128

 Death Valley: A Modern Example 129

 Sand Dunes 130

River Systems as Depositional
Environments 131

 Alluvial Fans and Braided-Stream
 Deposits in Moist Climates 131

 Meandering Rivers 132

 Deltas 134

*For the Record 5-1: The Shrinking
Mississippi Delta* 137

Marine Depositional Environments 138

 The Barrier Island–Lagoon
 Complex 138

 Open Shelf Deposits 139

 Fossils as Marine Environmental
 Indicators 140

 Reefs 140

 Carbonate Platforms 143

 Deep-Sea Sediments 145

 Submarine Slopes and Turbidites 145

 Pelagic Sediments 147

Chapter Summary/Review Questions/
Additional Reading 148

CHAPTER 6

**Correlation and Dating
of the Rock Record 151**

The Geologic Time Scale 151

*Visual Overview: Methods
of Stratigraphic Correlation* 152

 The Fossil Succession 154

 Geologic Systems 155

Stratigraphic Units 156

 Time-Rock Units and Time Units 156

 Biostratigraphic Units 157

 Magnetic Stratigraphy and Polarity
 Time-Rock Units 158

 Rock Units, Stratigraphic Sections,
 and Facies 161

Early Estimates of Earth's Absolute Age 163

- Salts in the Ocean 163
- Rates of Accumulation of Sediment 163
- Earth's Temperature 164

Radioactivity and Absolute Ages 164

- Radiometric Dating 164
- Useful Isotopes 165
- Radioactivity vs. Fossils: The Accuracy of Correlation 167

Dating by Other Stratigraphic Features 169

- Isotope Stratigraphy 169
- Event Stratigraphy 169
- Unconformities, Bedding Surfaces, and Seismic Stratigraphy 172
- Sequences 173

For the Record 6-1: Searching for Oil Off Southern New Jersey 176

Chapter Summary/Review Questions/
Additional Reading 177

CHAPTER 7

Evolution and the Fossil Record 181

Visual Overview: The Evolution of Life 182

Charles Darwin's Contribution 185

- The Voyage of the *Beagle* 185
- Anatomical Evidence 188
- Natural Selection 188

Genes, DNA, and Chromosomes 189

Populations, Species, and Speciation 190

Extinction 190

Rates of Origination and Extinction of Taxa 191

Evolutionary Radiation 191

Rates of Extinction 194

For the Record 7-1: The Coming Mass Extinction 194

Evolutionary Convergence 198

Evolutionary Trends 198

- Change of Body Size 198
- The Structure of Evolutionary Trends 200
- The Irreversibility of Evolution 204

Chapter Summary/Review Questions/
Additional Reading 204

CHAPTER 8

The Theory of Plate Tectonics 207

The History of Opinion about Continental Drift 207

Visual Overview: Elements of Plate Tectonics 208

A Twentieth-Century Pioneer: Alfred Wegener 211

Alexander Du Toit and the Gondwanaland Sequence 212

- The Rejection of Continental Drift 214
- The Puzzle of Paleomagnetism 215

The Rise of Plate Tectonics 216

- Seafloor Spreading 217
- The Triumph of Paleomagnetism 219

Faulting and Volcanism along Plate Boundaries 220

- Kinds of Faults 220
- What Happens at Ridges 221
- Transform Faults 222
- Subduction at Deep-Sea Trenches 223

For the Record 8-1: The Ring of Fire 224

Why Plates Move 226

Where Slabs Go 226

- Relative Plate Movements 226
- Absolute Plate Movements 227

Chapter Summary/Review Questions/
Additional Reading 228

CHAPTER 9

Continental Tectonics and Mountain Chains 231

Visual Overview: Formation and Deformation of Continental Margins 232

The Rifting of Continents 234

- Three-Armed Rifts and Hot Spots 234
- Geologic Features of Continental Rift Valleys 235
- Passive Margins of Continents 236

Bending and Flowing of Rocks 237

- Folding 237
- The Terminology of Folds 238

Mountain Building 240

- Orogenesis by Continental Collision 240
- Orogenesis without Continental Collision 241
- Mechanisms of Deformation 242
- Foreland Basin Deposition 243

The Andes: Mountain Building without Continental Collision 244

For the Record 9-1: Where Earth Shakes 246

The Himalayas 248

- Plate Movements 248
- The Pattern of Orogenesis 249

Suturing of Small Landmasses to Continents 251

Tectonics of Continental Interiors 252

Chapter Summary/Review Questions/
Additional Reading 254

CHAPTER 10

Major Chemical Cycles 257

Reservoirs 257

Visual Overview: Key Chemical Cycles in Earth System History 258

- Fluxes 259
- Feedback 259

Carbon Dioxide, Oxygen, and Biological Processes 261

- The Photosynthesis-Respiration Cycle in Plants 261
- Photosynthesis for Tissue Growth 262
- Animal Respiration 262
- Respiration by Decomposers 262
- Burial of Plant Debris and Atmospheric Chemistry 263
- Aquatic Ecosystems 265

The Use of Isotopes to Study Global Cycles 266

- Carbon Isotopes 266
- Atmospheric Oxygen 268
- Atmospheric Carbon Dioxide 269
- The Importance of Weathering 270

Phanerozoic Trends in Atmospheric CO₂ 272

- Negative Feedbacks: How CO₂ Levels Are Held in Check 273
- Temperature and Rates of Weathering 273
- Precipitation and Rates of Weathering 274

Oxygen Isotopes, Climate, and the Water Cycle 274

- Temperatures and Isotope Ratios in Skeletons 275
- Salinity and Isotope Ratios 277