

"We hope that [students] take away from this text an enhanced understanding of how our planet operates, of how to protect themselves and their societies from natural disasters, and of how to minimize their impacts on Earth systems through wise use of resources. We also hope they take away a sense of awe and reverence for the amazing world we live in." —from the Preface

The 21st century has been a time of increasingly more complex environmental events—earthquakes, tsunamis, hurricanes, tornados, floods, wildfires, droughts, polar vortexes. It is more apparent than ever that understanding these events requires studying how all of Earth's different systems—atmosphere, hydrosphere, pedosphere, biosphere, and lithosphere—interact with each other.

Now in a thoroughly updated new edition, *Environmental Geology* remains the only textbook for its course to follow this Earth systems approach, weaving together basic concepts of Earth system science and environmental geoscience to explore how Earth works, how human behavior affects the environment, how natural hazards develop, and how an understanding of environmental geology can improve our lives.

In the New Edition

More emphasis on human impact and sustainability, including a new final chapter, "Humans and the Whole Earth System"

New coverage of public policies resulting from environmental geology studies, including:

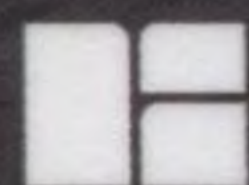
- California's Alquist-Priolo Earthquake Fault Zoning Act, which aims to minimize earthquake damage through stringent development requirements
- Bans by most state legislatures of detergent phosphates to protect aquatic ecosystems
- Ordinances enacted by southwestern U.S. cities to conserve dwindling water supplies

Detailed case studies and chapter-opening stories relating recent major events to the overall study of Earth systems and environmental issues, including:

- Superstorm Sandy, the Tōhoku earthquake and tsunami, and Hurricane Katrina

The latest on ongoing research projects addressing unresolved issues in environmental geology, including:

- The San Andreas Fault Observatory at Depth—an instrumented borehole drilled into the Parkfield section of the fault that will reveal, for the first time, the physical and chemical processes that control earthquake generation within a seismically active fault
- Studies of the amount of methane released from melting permafrost as a result of global warming of the Arctic
- Our evolving understanding of the Hawaiian hotspot, which apparently migrates over time, rather than staying fixed (as was assumed in the first edition of this book)



W. H. Freeman and Company
41 Madison Avenue, New York, NY 10010
Houndmills, Basingstoke RG21 6XS, England

Cover photo of Stromness, South Georgia, by Andrew de Wet

ISBN-13: 978-1-4292-3743-7

ISBN-10: 1-4292-3743-0



9 781429 237437

PART I Introduction 1**CHAPTER 1 Dynamic Earth Systems 3**

Earth System Science 4

The Concept of Systems 6

Types of Systems 6

System Behavior 7

Feedbacks in Earth Systems 8

Earth's Environmental Systems 9

The Geosphere: Earth's Metallic

Interior and Rocky Outer Shell 9

The Pedosphere: Where Soils Form 13

The Hydrosphere: Earth's Distinguishing

Characteristic 14

The Atmosphere: Earth's Envelope

of Gases 16

The Biosphere: Where Life Exists 17

Earth's Energy System 18

States of Energy 18

Sources of Energy 20

Energy Budget of Earth 21

Human Consumption of Energy 22

Human Population and Earth System

Boundaries 22

Human Population Growth 23

Resources and Sustainable Development 24

Pollution, Wastes, and Environmental

Impact 26

Natural Disasters, Hazards, and Risks 28

The Anthropocene and Planetary

Boundaries 28

Closing Thoughts 30

Summary and Key Terms 30

Questions and Exercises 31

Suggested Readings 32

**PART II Solid Earth Systems
and Geologic Time****33****CHAPTER 2 Plate Tectonics: Solid
Earth in Motion 35**

Introduction 36

BOX 2-1 Global and Environmental
Change: Plate Tectonics and the Evolution
of Species 37**An Early Conundrum and the Scientific
Method 38**Science, Pseudoscience, and the Scientific
Method 40**Plate Properties and Motions 40**Divergent Plate Boundaries, Spreading
Ridges, and Normal Faults 41Convergent Plate Boundaries, Subduction
Zones, and Reverse Faults 44Transform Plate Boundaries and
Strike-Slip Faults 47**Piecing the Theory Together 48**Paleomagnetism and Proof of
Continental Drift 49Magnetic Reversals and the Magnetic
Polarity Timescale 51

Paleomagnetism and Seafloor Spreading 52

More Evidence in Support of the Theory 52

BOX 2-2 Emerging Research: Drilling into
a Subduction Zone: The NanTroSEIZE Project 54**The Driver of Plate Tectonics 55****BOX 2-3** Emerging Research: Our Evolving
Understanding of the Hawaiian Hot Spot 56

Closing Thoughts 58

Summary and Key Terms 58

Questions and Exercises 58

Suggested Readings 59

CHAPTER 3 Earthquakes: Their Causes, Hazards, and Risks	61
Introduction	62
The Buildup and Release of Seismic Energy	64
Fault Behavior	65
Seismic Sources and Waves	67
Locating Earthquake Epicenters	68
BOX 3–1 Geologist’s Toolbox: Imaging Earth’s Interior	70
Tectonic Loading and the Earthquake Cycle	72
Assessing Earthquake Hazards	75
Earthquake Moment Magnitude	75
Earthquake Intensity	76
Looking for Earthquakes in the Geologic Record	78
BOX 3–2 Case Study: Magnitude Versus Intensity: The 2010 Haiti and Chile Events	79
The Potential for Future Earthquakes	82
BOX 3–3 Emerging Research: The Parkfield Earthquake and the Difficulties of Prediction	84
Minimizing the Risks from Earthquakes	86
BOX 3–4 Earth Science and Public Policy: Earthquakes and Legislation	87
Closing Thoughts	89
Summary and Key Terms	89
Questions and Exercises	90
Suggested Readings	91
CHAPTER 4 Earth Materials: Elements, Minerals, and Rocks	93
Introduction	94
Minerals: Building Blocks of the Lithosphere	96
Crystallization and Mineral Structure	97
Major Mineral Groups	98
BOX 4–1 Geologist’s Toolbox: Soft Crystals and Hard Science in the Cave of Crystals, Mexico	100
Mineral Properties: Hardness and Cleavage	102
Rocks and the Rock Cycle	103

Igneous Rocks	103
Sediments and Sedimentary Rocks	107
Metamorphic Rocks	111
The Rock Cycle	113
Rock and Mineral Resources	114
Industrialization and Mineral Resources	115
Critical Minerals	116
Ore Deposits and Ore Minerals	116
Types of Ore Deposits	117
BOX 4–2 Case Study: Rare Earth Elements: Not Rare, But Hard to Get	118
Depletion and Recycling of Mineral Resources	124
Environmental Impacts of Mining	125
Environmental Regulation of Mining	126
Metal Cycling Through Earth Systems: Copper Case Study	127
BOX 4–3 Case Study: Butte, Montana— From Boom Town to Superfund Site	128
Closing Thoughts	133
Summary and Key Terms	133
Questions and Exercises	134
Suggested Readings	137
CHAPTER 5 Volcanoes	139
Introduction	140
Volcanic Eruptions	142
How Volcanoes Erupt	142
Magma Types and Eruptive Styles	143
Shield Volcanoes, Stratovolcanoes, and Cinder Cones	145
Craters, Calderas, and Climate	148
Volcanic Hazards	149
Volcanic Ash	149
BOX 5–1 Earth Science and Public Policy: Creating Artificial Volcanic Eruptions to Counter Global Warming: Geoengineering or Geo–Fantasy?	151
Volcanic Gases	152
Tsunamis from Volcanic Eruptions	153
Active, Dormant, and Extinct Volcanoes	153
The Volcanic Explosivity Index	153
Determining Volcanic Threat Levels	154
BOX 5–2 Earth Science and Public Policy: The Prediction Challenge	157

Minimizing the Risks from Volcanic Eruptions	159
The Lahars of Mount Rainier	159
BOX 5–3 Earth Science and Public Policy: Volcano Databases and Volcanic Ash Advisory Centers	161
Stopping the Lava on Mount Etna	162
Closing Thoughts	163
Summary and Key Terms	163
Questions and Exercises	164
Suggested Readings	165

CHAPTER 6 Geologic Time, Environmental Change, and Earth System Cycles 167

Introduction	168
Scales of Time and Earth System Cycles	169
Time and Earth System Cycles	169
Measuring Time: Relative and Absolute Age Dating	169
BOX 6–1 Global and Environmental Change: One Billion Years of Rock Cycling Revealed in the Grand Canyon	170
Fossils, Evolution, and Relative Geologic Time	172
Radioactivity and Absolute Geologic Time	175
Radiometric Dating	178
BOX 6–2 Geologist's Toolbox: How Is the Rate of Radioactive Decay Used to Date Earth Materials?	180
BOX 6–3 Geologist's Toolbox: Family History: Radiometric Dating and the Tempo of Human Evolution	182

Global Change over Different Scales of Time 184

Global Change over Historic Time Scales	184
Global Change over Short Geologic Time Scales	185
BOX 6–4 Geologist's Toolbox: How Do Scientists Date Ice Cores?	186
Global Change over Long Geologic Time Scales	186

Closing Thoughts	187
Summary and Key Terms	187
Questions and Exercises	188
Suggested Readings	189

PART III Earth's Surface System 191

CHAPTER 7 The Biosphere 193

Introduction	194
Biosphere Structure and Functioning	194
Energy for Life: Photosynthesis and Respiration	195
Nutrients and Biogeochemical Cycles	195
Trophic Levels and Food Chains	199
Competition and Cooperation	200
Population Growth and Carrying Capacity	200
BOX 7–1 Case Study: The Guano Era in Peruvian History	201
Biomes, Habitats, and Ecological Niches	203
Biodiversity	205
BOX 7–2 Emerging Research: Anthropogenic Biomes: Humanity's Imprint on the Biosphere	206
BOX 7–3 Case Study: Consequences of Wolf Reintroduction into Yellowstone National Park	208
Ecosystem Services	210
Environmental Goods	210
Pollination of Crops and Native Vegetation	211
Water Purification	211
Human Impacts on the Biosphere	212
Human Population Growth	213
Human Impacts on Biogeochemical Cycles	216
Habitat Fragmentation	216
Exotic Species	216
Extinctions and Loss of Biodiversity	218
BOX 7–4 Earth Science and Public Policy: Detergent Phosphates: From Good Housekeeping Necessity to Environmental Nuisance	219
Restoration Ecology	221
Closing Thoughts	222
Summary and Key Terms	222
Questions and Exercises	223
Suggested Readings	225

CHAPTER 8 Soil and Weathering Systems 227

Introduction	228
The Pedosphere: A Geomembrane to Other Earth Systems	230
Physical Weathering	231
Chemical Weathering	233
BOX 8-1 Global and Environmental Change: Tectonic Uplift, Rock Weathering, and Long-Term Climate Change	236
BOX 8-2 Geologist's Toolbox: The Unusual Properties of Clay Minerals	240
Biological Processes and Their Role in Weathering	240
Soil Profiles and Soil-Forming Factors	242
The Interaction of Earth Systems to Form Soil	243
Cycling of Nitrogen Among the Atmosphere, Biosphere, and Pedosphere	245
Pedosphere Resources: Soils, Clays, and Mineral Ores	245
The Fertile Soil	245
BOX 8-3 Earth Science and Public Policy: Population-Supporting Capacities and Soil Clay, Laterite, and Mineral Ores	248
Clay, Laterite, and Mineral Ores	249
Soil Erosion Hazards, Land Degradation, and Soil Conservation	250
Soil Erosion: A Quiet Crisis	250
BOX 8-4 Case Study: Droughts, Land Degradation, and the American "Dust Bowl"	252
Soil Erosion by Water	253
Land Degradation and Desertification	254
Assessing Soil Erosion	255
Soil Conservation Practices	256
Mass Movement Hazards and Their Mitigation	257
The Roles of Gravity and Water in Mass Movement	258
Types of Mass Movement	259
Causes and Prevention of Mass Movement	261
Closing Thoughts	263
Summary and Key Terms	263
Questions and Exercises	264
Suggested Readings	266

PART IV Fluid Earth Systems 267

CHAPTER 9 Earth's Surface Water	269
Introduction	270
The Hydrologic Cycle	271
Surface Water Distribution	272
Hydrologic Budgets	273
BOX 9-1 Earth Science and Public Policy: Surface Water Use in the Colorado River Basin and Long-Term Records of Runoff from Tree Rings	275
Drainage Basins and Streams	277
Drainage Networks and Base-Level Controls	277
What Happens When It Rains?	278
Stream Stage, Discharge, and Hydrographs	280
Stream Channel Patterns and Processes	281
Floods	284
Flood Hazards	284
Flood Frequency Analysis	286
The U.S. National Flood Insurance Program	287
BOX 9-2 Case Study: The Geologic Record of Flooding in South Dakota's Black Hills	288
Altered Streams	290
Dams	290
Dam Removal	293
Artificial Levees and Floodwalls	294
Channelization	294
Wetlands	295
Characteristics and Benefits of Wetlands	295
Protecting Wetlands	296
Managing and Restoring Streams and Wetlands	297
River Corridor and Wetland Restoration	297
BOX 9-3 Emerging Research: Stream and Wetland Restoration: What Is Natural?	298
Unchannelizing the Kissimmee River	301
Water Resources and Protection	302
Freshwater Use and Virtual Water	302
Surface Water Systems and Waste Disposal	304

The Clean Water Act and Watershed Management	304
Regulations to Protect Drinking Water	307
The National Wild and Scenic Rivers Act	308
Droughts	309
Types of Droughts	309
Impacts of Droughts on Socioeconomic and Environmental Systems	310
Drought History and Global Warming	311
BOX 9–4 Case Study: Water Battles in Wet Places: Drought and the Tri-State Water Dispute	312
Closing Thoughts	315
Summary and Key Terms	315
Questions and Exercises	316
Suggested Readings	318
CHAPTER 10 The Groundwater System	321
Introduction	322
Water in the Ground	323
The Water Table	323
Porosity and Groundwater Storage	324
Permeability and Groundwater Flow	326
Aquifers	326
BOX 10–1 Geologist’s Toolbox: Darcy’s Law and the Flow of Water and Contaminants in Rocks and Sediments	330
Natural Groundwater Chemistry	332
BOX 10–2 Earth Science and Public Policy: Saving Water in the Desert	335
Groundwater as a Resource	335
Global Distribution and Use	336
Groundwater Resource Management	336
BOX 10–3 Case Study: Water Resource Management in Los Angeles	340
Groundwater Hazards	342
Solution Caverns and Sinkholes	342
Land Subsidence from Groundwater Mining	342
BOX 10–4 Case Study: Dead Sea Sinkholes	344
Intrusion of Salt Water	346
Groundwater Pollution and Its Cleanup	347
Types and Sources of Groundwater Pollution	347

Migration of Groundwater Pollutants	349
BOX 10–5 Case Study: Contaminant Plume at Cape Cod, Massachusetts	350
U.S. Laws Governing the Quality of Water Resources	352
Groundwater and Aquifer Restoration	353
Closing Thoughts	355
Summary and Key Terms	355
Questions and Exercises	356
Suggested Readings	357

CHAPTER 11 The Atmospheric System	359
Introduction	360
The Atmosphere: An Envelope of Gases	362
Present Atmospheric Composition	362
BOX 11–1 Global and Environmental Change: The Intertwined Histories of Atmospheric Oxygen and Life	364
Atmospheric Structure	366
Atmospheric Circulation and Climate	369
The Greenhouse Effect	369
Differential Heating of Earth	370
BOX 11–2 Geologist’s Toolbox: Electromagnetic Radiation	372
Tropospheric Circulation	374
Climate Zones	378
Storms	381
Development of Air Masses and Frontal Weather Systems	381
Severe Weather	383
Tropical Storms and Hurricanes	386
BOX 11–3 Geologist’s Toolbox: Clouds: Thor’s Anvil and Castles in the Air	387
Human Influence on Atmospheric Chemistry	390
Acid Rain	391
BOX 11–4 Case Study: The Destructive Power of Tomados	392
Smog	394
Ozone Depletion	396
Air Pollution and Environmental Management	398

Legislation	398
Cleanup Technologies	399
Closing Thoughts	400
Summary and Key Terms	401
Questions and Exercises	402
Suggested Readings	403

CHAPTER 12 The Ocean and Coastal System 405

Introduction 406

The Ocean Basins 408

Features of the Seafloor	409
The Changing Ocean Basins	409
Coastlines	410
Sea Level Changes	411

Seawater Chemistry 412

The Salinity of Seawater	413
Nutrients in Seawater	414
Dissolved Gases and pH in Seawater	414

Ocean Structure and Circulation 416

Vertical Structure of the Oceans	416
Circulation in the Surface Mixed Layer	417

BOX 12-1 Global and Environmental Change: El Niño Climatic Events 420

Circulation in the Deep Ocean	420
-------------------------------	-----

Coastal Processes and the Hazards of Living by the Sea 424

Beaches and Waves	424
Tides	426
Coastal Erosion and Attempts to Control It	428
Controlling Cliff Erosion	430
Tsunamis	431

Human Impacts on the Seas 436

Waste Disposal and Polluted Runoff Along Continental Shelves	436
--	-----

BOX 12-2 Earth Science and Public Policy: Who Owns the Seas? 438

Plastics in the Sea	443
---------------------	-----

BOX 12-3 Case Study: Chesapeake Bay and Population Growth 444

Ocean Acidification	447
Protecting the Oceans	447

Closing Thoughts	449
Summary and Key Terms	451
Questions and Exercises	452
Suggested Readings	454

PART V Energy, Changing Earth, and Human–Earth Interactions 455

CHAPTER 13 Energy 457

Energy and Humans 458

Earth's Energy System 460

States of Energy	460
Energy, Work, and Power	460
Sources of Energy	462
Earth's Energy Cycle and Budget	463
Energy Transfers and Photosynthesis	463
Resources, Energy Currency, and End-Use Services	464

Petroleum: Crude Oil and Natural Gas 465

Origin of Petroleum	465
Finding, Extracting, and Refining Petroleum	468
Peak Oil and Gas: How Long Will Crude Oil and Natural Gas Last?	470

BOX 13-1 Earth Science and Public Policy: The Essential Trade-off between Fossil Fuels and the Environment 472

Unconventional Fluid Hydrocarbons: Oil Sands, Shale Oil, and Gas	474
Environmental Impacts Associated with Petroleum Use	478

BOX 13-2 Earth Science and Public Policy: Deepwater Drilling and Well Blowouts 482

Coal 484

Origin of Coal	485
Global Distribution of Coal Deposits	486
Coal Production and Reserves	487
Coal Mining	487
Environmental Impacts of Mining and Burning Coal	488

BOX 13-3 Geologist's Toolbox: Visualizing Mountaintop Removal in 3-D with Remote Sensing and Lidar 490

Carbon Capture and Storage	493
----------------------------	-----

Geothermal Energy	495	Global Climate Models	554
Nuclear Energy	497	Closing Thoughts	556
The Nuclear Fuel Cycle	497	Summary and Key Terms	557
Fission and Fusion	501	Questions and Exercises	558
Nuclear Power Plant Safety	502	Suggested Readings	559
Nuclear Waste	502		
Renewable Energy	504	CHAPTER 15 Humans and the	
Solar Energy	504	Whole Earth System: Living in the	
Wind Energy	507	Anthropocene	561
Hydropower	510	Introduction	562
Biomass	510	Planetary Boundaries	564
Energy Efficiency and Conservation	511	Atmospheric Aerosol Loading	565
BOX 13–4 Case Study: The “New		Biodiversity Loss	565
EnergyEra”: Green Buildings and The Road		BOX 15–1 Global and Environmental	
Taken	512	Change: Tipping Points	566
Closing Thoughts	516	Changes in Biogeochemical Cycles	566
Summary and Key Terms	517	Changes in Land Use	567
Questions and Exercises	518	Chemical Pollution	568
Suggested Readings	519	Global Freshwater Use	568
		Stratospheric Ozone Depletion	569
CHAPTER 14 Understanding		Anthropogenic Climate Change	570
Climatic and Environmental Change	521	Evidence for a Warming Earth	571
Introduction	522	Causes of Climatic Change	571
Climate on Terrestrial Planets	523	BOX 15–2 Earth Science and Public Policy:	
Earth’s Temperature and the Faint		Manufacturing a Controversy	573
Young Sun Problem	524	The Case for Human Sources	574
Mars: A Frozen Planet	526	BOX 15–3 Emerging Research: Atmospheric	
Venus: A Runaway Greenhouse Effect	526	CO₂ and Temperature: Resolving a Chicken	
Causes of Climatic Change	527	and Egg Problem	578
Climate and the Evolution of Life	528	Impacts of Rising Greenhouse Gas	
Influence of Plate Tectonics on Climate	530	Concentrations	580
Influence of the Oceans on Climate	532	Greenhouse Gas Scenarios	581
BOX 14–1 Case Study: Snowball Earth	534	Temperature	581
Influence of Earth’s Orbital Parameters		Sea Level Rise	583
on Climate	536	Changes to the Hydrologic Cycle	587
Influence of Humans on Climate	538	Impacts on Human Health	587
Climatic Feedbacks	539	Ecosystem Impacts of a Warming Planet	588
Indicators of Environmental Change	541	Lessons from Former Worlds	589
Geologic Records of Climate and		BOX 15–4 Emerging Research:	
Environment	541	Frozen Methane: A Climatic Bomb Waiting	
BOX 14–2 Emerging Research: Earth’s		to Go Off?	590
Flickering Temperature and Climatic Seesaw	546	Climate Change Benefits	592
Biological Records of Climate and		Coming to Grips with the Anthropocene	592
Environment	551		

Greenhouse Gas Reduction Strategies	592
Geoengineering	594
Adaptations to a Warmer World	595
International Agreements	598
Closing Thoughts	600
Summary and Key Terms	601
Questions and Exercises	602
Suggested Readings	603

Appendix 1: Classification of Biological Organisms	A-1
Appendix 2: Periodic Table of Elements	A-2
Appendix 3: Units and Conversions	A-3
Appendix 4: Properties of Common Minerals	A-8
Glossary	G-1
References	R-1
Index	I-1