

Earth Science

Tarbuck • Lutgens • Illustrated by Tasa

FOURTEENTH EDITION



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Edward J. Tarbuck
Frederick K. Lutgens

Illustrated by
Dennis Tasa

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BRIEF CONTENTS

| | | |
|-------------------|--|------------|
| 1 | Introduction to Earth Science | 3 |
| <hr/> | | |
| UNIT ONE | EARTH MATERIALS | 32 |
| 2 | Matter and Minerals | 33 |
| 3 | Rocks: Materials of the Solid Earth | 59 |
| <hr/> | | |
| UNIT TWO | SCULPTING EARTH'S SURFACE | 94 |
| 4 | Weathering, Soil, and Mass Wasting | 95 |
| 5 | Running Water and Groundwater | 131 |
| 6 | Glaciers, Deserts, and Wind | 171 |
| <hr/> | | |
| UNIT THREE | FORCES WITHIN | 208 |
| 7 | Plate Tectonics: A Scientific Revolution Unfolds | 209 |
| 8 | Earthquakes and Earth's Interior | 245 |
| 9 | Volcanoes and Other Igneous Activity | 277 |
| 10 | Crustal Deformation and Mountain Building | 317 |
| <hr/> | | |
| UNIT FOUR | DECIPHERING EARTH'S HISTORY | 346 |
| 11 | Geologic Time | 347 |
| 12 | Earth's Evolution Through Geologic Time | 373 |

| | | |
|-------------------|---|------------|
| UNIT FIVE | THE GLOBAL OCEAN | 408 |
| 13 | The Ocean Floor | 409 |
| 14 | Ocean Water and Ocean Life | 433 |
| 15 | The Dynamic Ocean | 453 |
| <hr/> | | |
| UNIT SIX | EARTH'S DYNAMIC ATMOSPHERE | 484 |
| 16 | The Atmosphere: Composition, Structure, and Temperature | 485 |
| 17 | Moisture, Clouds, and Precipitation | 517 |
| 18 | Air Pressure and Wind | 551 |
| 19 | Weather Patterns and Severe Storms | 577 |
| 20 | World Climates and Global Climate Change | 607 |
| <hr/> | | |
| UNIT SEVEN | EARTH'S PLACE IN THE UNIVERSE | 638 |
| 21 | Origins of Modern Astronomy | 639 |
| 22 | Touring Our Solar System | 663 |
| 23 | Light, Astronomical Observations, and the Sun | 695 |
| 24 | Beyond Our Solar System | 719 |

FIND SMART FIGURES AND MOBILE FIELD TRIP FIGURES

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Chapter 1

- 1.1 Internal and External Processes (p. 4)
- 1.6 Magnitude of Geologic Time (p. 8)
- 1.8 Nebular Theory (p. 13)
- 1.15 Earth's Layers (p. 19)
- 1.21 The Continents (p. 24)

Chapter 2

- 2.3 Most Rocks Are Aggregates of Minerals (p. 35)
- 2.12 Color Variations in Minerals (p. 43)
- 2.15 Common Crystal Habits (p. 44)
- 2.16 Hardness Scales (p. 44)
- 2.18 Cleavage Directions Exhibited by Minerals (p. 45)

Chapter 3

- 3.1 The Rock Cycle (p. 61)
- 3.4 Composition of Common Igneous Rocks (p. 64)
- 3.5 Igneous Rock Textures (p. 65)
- 3.7 Classifications of Igneous Rocks, Based on Their Mineral Composition and Texture (p. 67)
- 3.14 Sedimentary Rocks Exposed in Capitol Reef National Park, Utah (p. 71)
- 3.20 Bonneville Salt Flats (p. 75)
- 3.21 From Plants to Coal (p. 76)
- 3.25 Metamorphic Rocks in the Adirondacks, New York. (p. 78)
- 3.27 Confining Pressure and Differential Stress (p. 80)
- 3.35 Common Oil Traps (p. 88)

Chapter 4

- 4.1 Excavating the Grand Canyon (p. 96)
- 4.3 Mechanical Weathering Increases Surface Area (p. 99)
- 4.5 Ice Breaks Rock (p. 99)
- 4.6 Unloading Leads to Sheetting (p. 100)
- 4.8 The Formation of Rounded Boulders (p. 103)
- 4.9 Rock Types Influences Weathering (p. 104)
- 4.11 Monuments to Weathering (p. 105)
- 4.32 Gros Vestre Rockslide (p. 121)
- 4.34 Creep (p. 123)

Chapter 5

- 5.2 The Hydrologic Cycle (p. 133)
- 5.4 Mississippi River Drainage Basin (p. 134)

- 5.9 Channel Changes from Head to Mouth (p. 137)
- 5.13 Formation of Cut Banks and Point Bars (p. 142)
- 5.20 Incised Meanders (p. 146)
- 5.25 Broken Levee (p. 151)
- 5.32 Cone of Depression (p. 157)
- 5.33 Artesian Systems (p. 157)

Chapter 6

- 6.4 Movement of a Glacier (p. 175)
- 6.7 Zones of a Glacier (p. 178)
- 6.11 Glacial Abrasion (p. 180)
- 6.12 Erosional Landforms Created by Alpine Glaciers (p. 181)
- 6.20 Common Depositional Landforms (p. 186)
- 6.27 Orbital Variations (p. 191)
- 6.30 Dry Climates (p. 193)
- 6.32 Landscape Evolution in the Basin and Range Region (p. 195)
- 6.38 White Sands National Monument (p. 199)
- 6.39 Cross Bedding (p. 200)
- 6.40 Types of Sand Dunes (p. 201)

Chapter 7

- 7.2 Reconstructions of Pangaea (p. 211)
- 7.10 Rigid Lithosphere Overlies the Weak Asthenosphere (p. 216)
- 7.15 Continental Rifting (p. 220)
- 7.17 Three Types of Convergent Plate Boundaries (p. 222)
- 7.21 Transform Plate Boundaries (p. 225)
- 7.23 Movement along the San Andreas Fault (p. 226)
- 7.31 Time Scale of Magnetic Reversals (p. 233)

Chapter 8

- 8.5 Elastic Rebound (p. 248)
- 8.10 Body Waves (P and S waves) versus Surface Waves (p. 251)
- 8.23 Turnagain Heights Slide (p. 258)
- 8.31 Seismic Gaps: Tools for Forecasting Earthquakes (p. 265)

Chapter 9

- 9.10 Anatomy of a Volcano (p. 286)
- 9.12 Cinder Cone (p. 290)
- 9.20 Super-Eruptions at Yellowstone (p. 298)
- 9.25 Sill Exposed in Utah's Sinbad Country (p. 302)
- 9.33 Earth's Zones of Volcanism (p. 308)
- 9.34 Subduction of the Juan Fuca Plate Produced the Cascade Volcanoes (p. 310)

Chapter 10

- 10.1 Deformed Sedimentary Strata (p. 318)
- 10.6 Common Types of Folds (p. 322)
- 10.7 Sheep Mountain Wyoming (p. 323)
- 10.8 Domes Versus Basins (p. 323)
- 10.15 Normal Dip-Slip Fault (p. 326)
- 10.16 Normal Faulting in the Basin and Range Province (p. 326)
- 10.26 Collision and Accretion of Small Crustal Fragments to a Continental Margin (p. 333)

- 10.29** India's Continued Northward Migration Severely Deformed Much of China and Southeast Asia (p. 335)
- 10.30** Formation of the Appalachian Mountains (p. 336)
- 10.31** The Valley and Ridge Province (p. 337)
- 10.33** The Effects of Isostatic Adjustment and Erosion on Mountainous Topography (p. 340)

Chapter 11

- 11.7** Inclusions (p. 352)
- 11.8** Formation of an Angular Unconformity (p. 352)
- 11.13** Applying Principles (p. 355)
- 11.18** Fossil Assemblage (p. 360)
- 11.21** Radioactive Decay Curve (p. 362)

Chapter 12

- 12.4** Major Events That Led to the Formation of Early Earth (p. 378)
- 12.10** Growth of Large Continental Masses Through the Collision and Accretion of Smaller Crustal Fragments (p. 383)
- 12.12** The Major Geologic Provinces of North America and Their Ages in Billions of Years (Ga) (p. 384)
- 12.16** Connection Between Oceans Circulation and the Climate in Antarctica (p. 386)
- 12.28** Relationships of Vertebrate Groups and Their Divergence from Lobe-finned Fish (p. 395)

Chapter 13

- 13.2** Distribution of Land and Water (p. 411)
- 13.6** Satellite Altimeter (p. 413)
- 13.12** Active Continental Margins (p. 418)
- 13.19** Examples of Hydrogenous Sediment (p. 425)

Chapter 14

- 14.2** Variations in Surface Temperature and Salinity with Latitude (p. 435)
- 14.8** Variations in Ocean-Water Density with Depth for Low- and High-Latitude Regions (p. 438)
- 14.12** Benthos (p. 441)
- 14.16** Productivity in Temperate Oceans (Northern Hemisphere) (p. 446)
- 14.19** Ecosystem Energy Flow and Efficiency (p. 448)

Chapter 15

- 15.2** Major Surface-Ocean Currents (p. 455)
- 15.5** Coastal Upwelling (p. 457)
- 15.12** Passage of a Wave (p. 462)
- 15.16** Wave Refraction (p. 464)
- 15.17** The Longshore Transport System (p. 465)
- 15.21** Some Depositional Features (p. 467)
- 15.31** East Coast Estuaries (p. 476)
- 15.35** Tidal Patterns (p. 478)

Chapter 16

- 16.5** Monthly CO₂ Concentrations (p. 489)
- 16.7** Antarctic Ozone Hole (p. 490)
- 16.12** The Changing Sun Angle (p. 495)
- 16.16** Characteristics of the Solstices and Equinoxes (p. 497)
- 16.19** The Three Mechanisms of Heat Transfer (p. 500)
- 16.21** Paths Taken by Solar Radiation (p. 503)
- 16.24** The Greenhouse Effect (p. 504)
- 16.26** Isotherms (p. 506)
- 16.28** Monthly Mean Temperatures for Vancouver, British Columbia, and Winnipeg Manitoba (p. 507)
- 16.32** The Daily Cycle of Temperature at Peoria, Illinois, for Two July Days (p. 509)
- 16.34** World Mean Sea-Level Temperatures in July, in Celsius (°C) and Fahrenheit (°F) (p. 511)

Chapter 17

- 17.2** Changes of State Involve an Exchange of Heat (p. 519)
- 17.8** Map Showing Dew-Point Temperatures on a Typical September Day (p. 523)
- 17.13** Surface Convergence Enhances Cloud Development (p. 527)
- 17.17** Atmospheric Conditions That Result in Absolute Stability (p. 529)
- 17.20** Classification of Clouds, Based on Height and Form (p. 532)
- 17.25** Map Showing the Average Number of Days per Year with Heavy Fog (p. 537)
- 17.30** Formation of Hailstones (p. 541)

Chapter 18

- 18.2** Inches and Millibars (p. 553)
- 18.7** Isobars on a Weather Map (p. 555)
- 18.8** Coriolis Effect (p. 556)
- 18.17** Idealized Global Circulation Proposed for the Three-Cell Circulation Model of a Rotating Earth (p. 561)
- 18.19** Sea and Land Breezes (p. 563)

Chapter 19

- 19.4** Snowfall Map (p. 580)
- 19.8** Cold Front (p. 582)
- 19.11** Idealized Structure of a Large, Mature Midlatitude Cyclone (p. 584)
- 19.19** Thunderstorm Development (p. 589)
- 19.23** The Formation of a Mesocyclone Often Precedes Tornado Formation (p. 591)

Chapter 20

- 20.7** Tropical Rain Forest (p. 614)
- 20.16** Examples of E Climates (p. 621)
- 20.17** Highland Climate (p. 622)
- 20.21** Global Temperatures (p. 625)
- 20.28** Slope of the Shoreline (p. 632)

Chapter 21

- 21.3** Orientation of the Sun's Rays at Syene (Aswan) and Alexandria, Egypt on June 21 (p. 641)
- 21.6** Ptolemy's Explanation of Retrograde Motion (p. 643)
- 21.15** Using a Telescope, Galileo Discovered That Venus Has Phases Like Earth's Moon (p. 647)
- 21.17** Orbital Motion of Earth and Other Planets (p. 649)
- 21.20** Locating the North Star (Polaris) from the Pointer Stars in the Big Dipper (p. 653)
- 21.23** Precession of Earth's Axis (p. 655)
- 21.25** Phases of the Moon (p. 656)
- 21.27** Lunar Eclipse (p. 658)

Chapter 22

- 22.1** Orbits of the Planets (p. 664)
- 22.3** Bodies with Atmospheres Versus Airless Bodies (p. 667)
- 22.7** Formation and Filling of Large Impact Basins (p. 670)
- 22.14** Olympus Mons (p. 675)
- 22.33** Meteor Crater, Near Winslow, Arizona (p. 688)

Chapter 23

- 23.3** Formation of the Three Types of Spectra (p. 697)
- 23.6** The Doppler Effect (p. 700)
- 23.11** Reflecting Telescope (p. 702)
- 23.20** Diagram of the Sun's Structure (p. 708)

Chapter 24

- 24.8** Hertzsprung–Russell Diagram (p. 725)
- 24.10** Evolutionary Stages of Stars Having Various Masses (p. 728)
- 24.16** Spiral Galaxies (p. 734)
- 24.22** Raisin Bread Analogy for an Expanding Universe (p. 737)

CONTENTS

1 Introduction to Earth Science 3

FOCUS ON CONCEPTS 3

What Is Earth Science? 4

- Geology 4
- Oceanography 5
- Meteorology 5
- Astronomy 5
- Earth Science Is Environmental Science 5
- Scales of Space and Time in Earth Science 7

The Nature of Scientific Inquiry 9

- Hypothesis 9

GEO GRAPHICS | World Population Passes 7 Billion 10

- Theory 10
- Scientific Methods 10

EYE ON EARTH 11

Early Evolution of Earth 12

- Origin of Planet Earth 12
- The Inner Planets Form 13
- The Outer Planets Develop 14

Earth's Spheres 14

GEO GRAPHICS | Solar System: Size and Scale 15

- Hydrosphere 16
- Atmosphere 16
- Biosphere 17

EYE ON EARTH 17

- Geosphere 18

A Closer Look at the Geosphere 18

- Earth's Internal Structure 18
- The Mobile Geosphere 20

The Face of Earth 22

- Major Features of the Continents 23
- Major Features of the Ocean Basins 25

EYE ON EARTH 25

Earth as a System 26

- Earth System Science 26
- The Earth System 27

Concepts in Review 28 | Give It Some Thought 29 |

MasteringGeology 31

UNIT ONE | EARTH MATERIALS 32

2 Matter and Minerals 33

FOCUS ON CONCEPTS 33

Minerals: Building Blocks of Rock 34

- Defining a Mineral 34
- What Is a Rock? 35

Atoms: Building Blocks of Minerals 36

- Properties of Protons, Neutrons, and Electrons 36
- Elements: Defined by Their Number of Protons 36

GEO GRAPHICS | Gold 38

Why Atoms Bond 40

- The Octet Rule and Chemical Bonds 40
- Ionic Bonds: Electrons Transferred 40
- Covalent Bonds: Electron Sharing 40
- Metallic Bonds: Electrons Free to Move 41

EYE ON EARTH 42

Properties of a Mineral 42

- Optical Properties 42
- Crystal Shape, or Habit 43
- Mineral Strength 44
- Density and Specific Gravity 46
- Other Properties of Minerals 46

Mineral Groups 46

- Silicate Minerals 47

EYE ON EARTH 47

- Important Nonsilicate Minerals 50

Natural Resources 52

- Renewable Versus Nonrenewable Resources 52
- Mineral Resources 52

GEO GRAPHICS | Gemstones 54

Concepts in Review 55 | Give It Some Thought 56 |

MasteringGeology 57

3 Rocks: Materials of the Solid Earth 59

FOCUS ON CONCEPTS 59

Earth as a System: The Rock Cycle 60

- The Basic Cycle 60
- Alternative Paths 60

Igneous Rocks: "Formed by Fire" 62

- From Magma to Crystalline Rock 62
- Igneous Compositions 63
- What Can Igneous Textures Tell Us? 64
- Common Igneous Rocks 66
- How Different Igneous Rocks Form 69

EYE ON EARTH 69

Sedimentary Rocks: Compacted and Cemented Sediment 71

- Classifying Sedimentary Rocks 72
- Lithification of Sediment 75
- Features of Sedimentary Rocks 76

Metamorphic Rocks: New Rock from Old 78

- What Drives Metamorphism? 78



EYE ON EARTH 79

- Metamorphic Textures 81
- Common Metamorphic Rocks 81

Resources from Rocks and Minerals 83

- Metallic Mineral Resources 83

GEO GRAPHICS | Marble 84

- Nonmetallic Mineral Resources 87
- Energy Resources: Fossil Fuels 87

EYE ON EARTH 89

Concepts in Review 90 | **Give It Some Thought** 92 |

MasteringGeology 93

UNIT TWO | SCULPTING EARTH'S SURFACE 94

4 Weathering, Soil, and Mass Wasting 95

FOCUS ON CONCEPTS 95

Earth's External Processes 96

Weathering 97

GEO GRAPHICS | Some Everyday Examples of Weathering 98

- Mechanical Weathering 99
- Chemical Weathering 101

EYE ON EARTH 101**GEO GRAPHICS | The Old Man of the Mountain 102****Rates of Weathering 104**

- Rock Characteristics 104
- Climate 104
- Differential Weathering 104

Soil 105

- An Interface in the Earth System 105
- What Is Soil? 106
- Soil Texture and Structure 106

Controls of Soil Formation 107

- Parent Material 107
- Time 107
- Climate 108
- Plants and Animals 108
- Topography 108

The Soil Profile 109**Classifying Soils 110****EYE ON EARTH 111****Soil Erosion: Losing a Vital Resource 112****Mass Wasting: The Work of Gravity 114**

- Landslides as Geologic Hazards 114
- The Role of Mass Wasting in Landform Development 114
- Slopes Change Through Time 114

GEO GRAPHICS | Landslides as Natural Disasters 115**Controls and Triggers of Mass Wasting 116**

- The Role of Water 116
- Oversteepened Slopes 117
- Removal of Vegetation 117
- Earthquakes as Triggers 118

Classifying Mass-Wasting Processes 118

- Type of Motion 118
- Rate of Movement 119

EYE ON EARTH 119**Rapid Forms of Mass Wasting 120**

- Slump 120
- Rockslide 121
- Debris Flow 121
- Earthflow 122

Slow Forms of Mass Wasting 122

- Creep 122
- Solifluction 123

Concepts in Review 124 | **Give It Some Thought** 127 |

MasteringGeology 129

5 Running Water and Groundwater 131

FOCUS ON CONCEPTS 131**Earth as a System: The Hydrologic Cycle 132**

- Earth's Water 132
- Water's Paths 132
- Storage in Glaciers 133
- Water Balance 133

Running Water 133

- Drainage Basins 134
- River Systems 134
- Drainage Patterns 135

Streamflow 136

- Factors Affecting Flow Velocity 136
- Changes from Upstream to Downstream 137

The Work of Running Water 138

- Stream Erosion 138

EYE ON EARTH 138**GEO GRAPHICS | What Are the Largest Rivers? 139**

- Transportation of Sediment 140
- Deposition of Sediment 141

Stream Channels 141

- Bedrock Channels 142
- Alluvial Channels 142

Shaping Stream Valleys 144

- Base Level and Stream Erosion 144
- Valley Deepening 144
- Valley Widening 145
- Changing Base Level and Incised Meanders 145

Depositional Landforms 147

- Deltas 147

EYE ON EARTH 147

Natural Levees 148

Alluvial Fans 149

Floods and Flood Control 149

- Causes of Floods 149
- Flood Control 149

GEO GRAPHICS | Flash Floods 150

Groundwater: Water Beneath the Surface 152

- The Importance of Groundwater 152
- Groundwater's Geologic Roles 152
- Distribution of Groundwater 152

EYE ON EARTH 153

- Factors Influencing the Storage and Movement of Groundwater 154
- Groundwater Movement 155

Springs, Wells, and Artesian Systems 155

- Springs 155
- Artesian Systems 157

EYE ON EARTH 158**Environmental Problems of Groundwater 159**

- Treating Groundwater as a Nonrenewable Resource 159
- Land Subsidence Caused by Groundwater Withdrawal 159
- Groundwater Contamination 160

The Geologic Work of Groundwater 162

- Caverns 162
- Karst Topography 163

Concepts in Review 165 | **Give It Some Thought** 167 |

MasteringGeology 169

6 Glaciers, Deserts, and Wind 171

FOCUS ON CONCEPTS 171**Glaciers and the Earth System 172**

- Glaciers: A Part of Two Basic Cycles 172
- Valley (Alpine) Glaciers 172
- Ice Sheets 172
- Other Types of Glaciers 174

How Glaciers Move 175

- Observing and Measuring Movement 175

GEO GRAPHICS | Antarctica Fact File 176

- Budget of a Glacier: Accumulation Versus Wastage 178

Glacial Erosion 179

- How Glaciers Erode 180
- Landforms Created by Glacial Erosion 180

Glacial Deposits 183

- Types of Glacial Drift 183

EYE ON EARTH 183

- Moraines, Outwash Plains, and Kettles 184
- Drumlins, Eskers, and Kames 186

Other Effects of Ice Age Glaciers 187

- Changing Rivers 187
- Crustal Subsidence and Rebound 187
- Proglacial Lakes Created by Ice Dams 188
- Sea-Level Changes 188
- Pluvial Lakes 189

Extent of Ice Age Glaciation 189**Causes of Ice Ages 190**

- Plate Tectonics 190
- Variations in Earth's Orbit 191
- Other Factors 191

Deserts 192

- Distribution and Causes of Dry Lands 193
- Geologic Processes in Arid Climates 194

Basin and Range: The Evolution of a Mountainous Desert Landscape 195**EYE ON EARTH 196****Wind Erosion 197**

- Deflation, Blowouts, and Desert Pavement 197
- Wind Abrasion 198

Wind Deposits 198

- Loess 199
- Sand Dunes 199
- Types of Sand Dunes 200

EYE ON EARTH 201

Concepts in Review 202 | **Give It Some Thought** 205 |

MasteringGeology 207

UNIT THREE | FORCES WITHIN 208

7 Plate Tectonics: A Scientific Revolution Unfolds 209

FOCUS ON CONCEPTS 209**From Continental Drift to Plate Tectonics 210****Continental Drift: An Idea Before Its Time 211**

- Evidence: The Continental Jigsaw Puzzle 211
- Evidence: Fossils Matching Across the Seas 212
- Evidence: Rock Types and Geologic Features 213
- Evidence: Ancient Climates 214

The Great Debate 215

- Rejection of the Drift Hypothesis 215

The Theory of Plate Tectonics 216

- Rigid Lithosphere Overlies Weak Asthenosphere 216
- Earth's Major Plates 217
- Plate Boundaries 217

Divergent Plate Boundaries and Seafloor Spreading 218

- Oceanic Ridges and Seafloor Spreading 219
- Continental Rifting 220

Convergent Plate Boundaries and Subduction 221

- Oceanic–Continental Convergence 222
- Oceanic–Oceanic Convergence 223
- Continental–Continental Convergence 224

Transform Plate Boundaries 225**How Do Plates and Plate Boundaries Change? 227**

- The Breakup of Pangaea 227

EYE ON EARTH 227

- Plate Tectonics in the Future 228

Testing the Plate Tectonics Model 229

- Evidence: Ocean Drilling 229
- Evidence: Mantle Plumes and Hot Spots 230
- Evidence: Paleomagnetism 231

How Is Plate Motion Measured 234

- Geologic Evidence for Plate Motion 234
- Measuring Plate Motion from Space 236

What Drives Plate Motions? 236

- Forces That Drive Plate Motion 236
- Models of Plate–Mantle Convection 237

EYE ON EARTH 238

Concepts in Review 239 | **Give It Some Thought** 242 |

MasteringGeology 243



8 Earthquakes and Earth's Interior 245

FOCUS ON CONCEPTS 245

What Is an Earthquake? 246

- Discovering the Causes of Earthquakes 247
- Aftershocks and Foreshocks 248
- Faults and Large Earthquakes 249

EYE ON EARTH 249

Seismology: The Study of Earthquake Waves 250

- Instruments That Record Earthquakes 250
- Seismic Waves 251

Determining the Size of Earthquakes 252

- Intensity Scales 252
- Magnitude Scales 253

GEO GRAPHICS | Finding the Epicenter of an Earthquake 255

Earthquake Destruction 256

- Destruction from Seismic Vibrations 256
- Landslides and Ground Subsidence 258
- Fire 258

EYE ON EARTH 258

- What Is a Tsunami? 259

Earthquake Belts and Plate Boundaries 261

GEO GRAPHICS | Historic Earthquakes East of the Rockies 262

Can Earthquakes Be Predicted? 264

- Short-Range Predictions 264
- Long-Range Forecasts 264

GEO GRAPHICS | Seismic Risks on the San Andreas Fault System 266

Earth's Interior 269

- Formation of Earth's Layered Structure 269
- Probing Earth's Interior: "Seeing" Seismic Waves 269

Earth's Layers 270

- Crust 270
- Mantle 271
- Core 271

Concepts in Review 272 | Give It Some Thought 274 |

MasteringGeology 275

9 Volcanoes and Other Igneous Activity 277

FOCUS ON CONCEPTS 277

Mount St. Helens Versus Kilauea 278

The Nature of Volcanic Eruptions 279

- Factors Affecting Viscosity 279
- Quiescent Versus Explosive Eruptions 280

Materials Extruded During an Eruption 281

- Lava Flows 281
- Gases 283
- Pyroclastic Materials 283

Anatomy of a Volcano 284

GEO GRAPHICS | Comparison of Three Types of Volcanic Cones 285

Shield Volcanoes 286

- Mauna Loa: Earth's Largest Shield Volcano 286
- Kilauea, Hawaii: Eruption of a Shield Volcano 287

GEO GRAPHICS | Kilauea's East Rift Zone Eruption 288

Cinder Cones 290

Parícutin: Life of a Garden-Variety Cinder Cone 290

Composite Volcanoes 291

GEO GRAPHICS | Eruption of Mount Vesuvius, AD 79 292

Volcanic Hazards 293

- Pyroclastic Flow: A Deadly Force of Nature 294
- Lahars: Mudflows on Active and Inactive Cones 295
- Other Volcanic Hazards 295

Other Volcanic Landforms 297

- Calderas 297
- Fissure Eruptions and Basalt Plateaus 299

EYE ON EARTH 299

- Volcanic Necks and Pipes 300

Intrusive Igneous Activity 301

- Nature of Intrusive Bodies 301

NATURE ON EARTH 301

- Tabular Intrusive Bodies: Dikes and Sills 302
- Massive Intrusive Bodies: Batholiths, Stocks, and Laccoliths 303

Partial Melting and the Origin of Magma 304

- Partial Melting 304
- Generating Magma from Solid Rock 304
- Decrease in Pressure: Decompression Melting 305

Plate Tectonics and Volcanic Activity 306

- Volcanism at Convergent Plate Boundaries 306
- Volcanism at Divergent Plate Boundaries 307
- Intraplate Volcanism 307

Concepts in Review 311 | Give It Some Thought 313 |

MasteringGeology 315

10 Crustal Deformation and Mountain Building 317

FOCUS ON CONCEPTS 317

Crustal Deformation 318

- What Causes Rocks to Deform? 318
- Types of Deformation 319
- Factors That Affect Rock Strength 320

Folds: Rock Structures Formed by Ductile Deformation 321

- Anticlines and Synclines 321

EYE ON EARTH 321

- Domes and Basins 322
- Monoclines 323

Faults and Joints: Rock Structures Formed by Brittle Deformation 325

- Dip-Slip Faults 325
- Strike-Slip Faults 326
- Joints 327

Mountain Building 329

Subduction and Mountain Building 330

- Island Arc-Type Mountain Building 330
- Andean-Type Mountain Building 330

EYE ON EARTH 331

- Sierra Nevada, Coast Ranges, and Great Valley 332

Collisional Mountain Belts 332

- Cordilleran-Type Mountain Building 332
- Alpine-Type Mountain Building: Continental Collisions 334
- The Himalayas 334
- The Appalachians 335

What Causes Earth's Varied Topography? 337

GEO GRAPHICS | The Laramide Rockies 338

- The Principle of Isostasy 340
- How High Is Too High? 340

Concepts in Review 341 | Give It Some Thought 343 |

MasteringGeology 345

UNIT FOUR | DECIPHERING EARTH'S HISTORY 346

11 Geologic Time 347

FOCUS ON CONCEPTS 347

A Brief History of Geology 348

- Catastrophism 348
- The Birth of Modern Geology 348
- Geology Today 349

Creating a Time Scale: Relative Dating Principles 349

- The Importance of a Time Scale 349
- Numerical and Relative Dates 349
- Principle of Superposition 350
- Principle of Original Horizontality 350
- Principle of Lateral Continuity 351
- Principle of Cross-Cutting Relationships 351

EYE ON EARTH 351

- Principle of Inclusions 352
- Unconformities 352
- Applying Relative Dating Principles 354

EYE ON EARTH 354

Fossils: Evidence of Past Life 355

- Types of Fossils 356

GEO GRAPHICS | How is Paleontology Different from Archaeology? 357

- Conditions Favoring Preservation 358

Correlation of Rock Layers 358

- Correlation Within Limited Areas 358
- Fossils and Correlation 358

Dating with Radioactivity 360

- Reviewing Basic Atomic Structure 361
- Radioactivity 361
- Half-Life 362
- Using Various Isotopes 362
- Dating with Carbon-14 363

The Geologic Time Scale 364

- Structure of the Time Scale 365
- Precambrian Time 365

EYE ON EARTH 365

- Terminology and the Geologic Time Scale 366

Determining Numerical Dates for Sedimentary Strata 366

EYE ON EARTH 367

GEO GRAPHICS | Did Humans and Dinosaurs Ever Coexist? 368

Concepts in Review 369 | Give It Some Thought 370

12 Earth's Evolution Through Geologic Time 373

FOCUS ON CONCEPTS 373

Is Earth Unique? 374

- The Right Planet 374
- The Right Location 375
- The Right Time 375
- Viewing Earth's History 375

Birth of a Planet 377

- From the Big Bang to Heavy Elements 377
- From Planetesimals to Protoplanets 377
- Earth's Early Evolution 377

Origin and Evolution of the Atmosphere and Oceans 379

- Earth's Primitive Atmosphere 379
- Oxygen in the Atmosphere 379
- Evolution of the Oceans 380

Precambrian History: The Formation of Earth's Continents 381

- Earth's First Continents 381

EYE ON EARTH 381

- The Making of North America 384
- Supercontinents of the Precambrian 384

Geologic History of the Phanerozoic: The Formation of Earth's Modern Continents 386

- Paleozoic History 386
- Mesozoic History 387
- Cenozoic History 389

Earth's First Life 390

- Origin of Life 390
- Earth's First Life: Prokaryotes 390

Paleozoic Era: Life Explodes 391

- Early Paleozoic Life-Forms 391

GEO GRAPHICS | Evolution of Life Through Geologic Time 392

EYE ON EARTH 393

- Vertebrates Move to Land 394
- Reptiles: The First True Terrestrial Vertebrates 394
- The Great Permian Extinction 395

GEO GRAPHICS | Demise of the Dinosaurs 396

Mesozoic Era: Age of the Dinosaurs 398

- Gymnosperms: The Dominant Mesozoic Trees 398
- Reptiles: Dominating the Land, Sea, and Sky 398

Cenozoic Era: Age of Mammals 400

- From Reptiles to Mammals 400
- Marsupial and Placental Mammals 400
- Humans: Mammals with Large Brains and Bipedal Locomotion 401
- Large Mammals and Extinction 401

Concepts in Review 403 | Give It Some Thought 405 |

MasteringGeology 407

UNIT FIVE | THE GLOBAL OCEAN 408

13 The Ocean Floor 409

FOCUS ON CONCEPTS 409

The Vast World Ocean 410

- Geography of the Oceans 410
- Comparing the Oceans to the Continents 411

An Emerging Picture of the Ocean Floor 411

- Mapping the Seafloor 411
- Provinces of the Ocean Floor 414

Continental Margins 416

- Passive Continental Margins 416



EYE ON EARTH 417

Active Continental Margins 419

Features of Deep-Ocean Basins 419

Deep-Ocean Trenches 419

GEO GRAPHICS | Explaining Coral Atolls: Darwin's Hypothesis 420

Abyssal Plains 422

Volcanic Structures on the Ocean Floor 422

The Oceanic Ridge 423

Anatomy of the Oceanic Ridge 423

Why Is the Oceanic Ridge Elevated? 423

Seafloor Sediments 424

Types of Seafloor Sediments 424

Seafloor Sediment—A Storehouse of Climate Data 425

Resources from the Seafloor 426

Energy Resources 426

Other Resources 427

EYE ON EARTH 427**Concepts in Review** 428 | **Give It Some Thought** 430 |**MasteringGeology** 431

14 Ocean Water and Ocean Life 433

FOCUS ON CONCEPTS 433**Composition of Seawater 434**

Salinity 434

Sources of Sea Salts 434

Processes Affecting Seawater Salinity 435

Recent Increase in Ocean Acidity 436

Variations in Temperature and Density with Depth 436

Temperature Variations 437

Density Variations 437

EYE ON EARTH 437

Ocean Layering 438

The Diversity of Ocean Life 439

Classification of Marine Organisms 439

Marine Life Zones 441

GEO GRAPHICS | Deep-Sea Hydrothermal Vents 442**EYE ON EARTH 444****Ocean Productivity 445**

Productivity in Polar Oceans 445

Productivity in Tropical Oceans 445

Productivity in Midlatitude Oceans 446

Oceanic Feeding Relationships 447

Trophic Levels 447

Transfer Efficiency 447

Food Chains and Food Webs 447

Concepts in Review 449 | **Give It Some Thought** 450 |**MasteringGeology** 451

15 The Dynamic Ocean 453

FOCUS ON CONCEPTS 453**The Ocean's Surface Circulation 454**

The Pattern of Ocean Currents 454

Upwelling and Deep-Ocean Circulation 457

Coastal Upwelling 457

Deep-Ocean Circulation 457

The Shoreline: A Dynamic Interface 458

The Coastal Zone 459

Basic Features 459

Beaches 460

Ocean Waves 461

Wave Characteristics 461

EYE ON EARTH 461

Circular Orbital Motion 462

Waves in the Surf Zone 462

The Work of Waves 463

Wave Erosion 463

Sand Movement on the Beach 463

Shoreline Features 466

Erosional Features 466

Depositional Features 466

The Evolving Shore 467

Stabilizing the Shore 468

Hard Stabilization 469

Alternatives to Hard Stabilization 470

EYE ON EARTH 471**Contrasting America's Coasts 472**

Atlantic and Gulf Coasts 472

Pacific Coast 472

Coastal Classification 473

EYE ON EARTH 473**GEO GRAPHICS** | A Brief Tour of America's Coasts 474**Tides 476**

Causes of Tides 476

Monthly Tidal Cycle 477

Tidal Patterns 478

Tidal Currents 478

Concepts in Review 479 | **Give It Some Thought** 482 |**MasteringGeology** 483

UNIT SIX | EARTH'S DYNAMIC ATMOSPHERE 484

16 The Atmosphere: Composition, Structure, and Temperature 485

FOCUS ON CONCEPTS 485**Focus on the Atmosphere 486**

Weather in the United States 486

Weather and Climate 486

EYE ON EARTH 487**Composition of the Atmosphere 488**

Major Components 488

Carbon Dioxide (CO₂) 488

Variable Components 489

Ozone Depletion: A Global Issue 490

GEO GRAPHICS | Acid Precipitation 491

Vertical Structure of the Atmosphere 492

- Pressure Changes 492
- Temperature Changes 493

Earth–Sun Relationships 494

- Earth's Motions 495
- What Causes the Seasons? 495
- Earth's Orientation 496
- Solstices and Equinoxes 496

EYE ON EARTH 499**Energy, Heat, and Temperature 500**

- Mechanism of Heat Transfer: Conduction 500

EYE ON EARTH 500

- Mechanism of Heat Transfer: Convection 501
- Mechanism of Heat Transfer: Radiation 501

Heating the Atmosphere 502

- What Happens to Incoming Solar Radiation? 502
- Reflection and Scattering 502
- Absorption 503
- Heating the Atmosphere: The Greenhouse Effect 504

For the Record: Air Temperature Data 505**Why Temperatures Vary: The Controls of Temperature 506**

- Land and Water 506
- Altitude 508
- Geographic Position 508
- Cloud Cover and Albedo 508

EYE ON EARTH 509**World Distribution of Temperature 510**

- Concepts in Review** 511 | **Give It Some Thought** 514 | **MasteringGeology** 515

17 Moisture, Clouds, and Precipitation 517

FOCUS ON CONCEPTS 517**Water's Changes of State 518**

- Ice, Liquid Water, and Water Vapor 518
- Latent Heat 518

EYE ON EARTH 519**Humidity: Water Vapor in the Air 520**

- Saturation 520
- Mixing Ratio 521
- Relative Humidity 521
- Dew-Point Temperature 522
- Measuring Humidity 523

The Basis of Cloud Formation: Adiabatic Cooling 524

- Fog and Dew Versus Cloud Formation 524
- Adiabatic Temperature Changes 525
- Adiabatic Cooling and Condensation 525

Processes That Lift Air 526

- Orographic Lifting 526
- Frontal Wedging 526
- Convergence 527
- Localized Convective Lifting 527

The Weathermaker: Atmospheric Stability 528

- Types of Stability 528
- Stability and Daily Weather 530

Condensation and Cloud Formation 531

- Types of Clouds 532

EYE ON EARTH 533**Fog 535**

- Fogs Caused by Cooling 536
- Evaporation Fogs 537

How Precipitation Forms 538

- Precipitation from Cold Clouds: The Bergeron Process 538
- Precipitation from Warm Clouds: The Collision–Coalescence Process 539

Forms of Precipitation 539

- Rain 540
- Snow 540
- Sleet and Glaze 540
- Hail 541

GEO GRAPHICS | Our Water Supply 542

- Rime 544

Measuring Precipitation 544

- Measuring Snowfall 544
- Precipitation Measurement by Weather Radar 544

Concepts in Review 545 | Give It Some Thought 548 |**MasteringGeology 549**

18 Air Pressure and Wind 551

FOCUS ON CONCEPTS 551**Understanding Air Pressure 552**

- Visualizing Air Pressure 552
- Measuring Air Pressure 553

Factors Affecting Wind 554

- Pressure Gradient Force 554
- Coriolis Effect 555
- Friction with Earth's Surface 556

Highs and Lows 558

- Cyclonic and Anticyclonic Winds 558
- Weather Generalizations About Highs and Lows 558

General Circulation of the Atmosphere 560

- Circulation on a Nonrotating Earth 560
- Idealized Global Circulation 560
- Influence of Continents 560

EYE ON EARTH 560

- The Westerlies 562

Local Winds 563

- Land and Sea Breezes 563
- Mountain and Valley Breezes 563
- Chinook and Santa Ana Winds 564

Measuring Wind 565**EYE ON EARTH 565****El Niño and La Niña and the Southern Oscillation 566**

- Impact of El Niño 566
- Impact of La Niña 567

GEO GRAPHICS | The 1930s Dust Bowl 569

- Southern Oscillation 570

Global Distribution of Precipitation 570

- The Influence of Pressure and Wind Belts 570
- Other Factors 571

EYE ON EARTH 571**Concepts in Review 572 | Give It Some Thought 574 |****MasteringGeology 575**



19 Weather Patterns and Severe Storms 577

FOCUS ON CONCEPTS 577

Air Masses 578

- What Is an Air Mass? 578
- Source Regions 579
- Weather Associated with Air Masses 579

EYE ON EARTH 580

Fronts 581

- Warm Fronts 582
- Cold Fronts 582
- Stationary Fronts and Occluded Fronts 583

Midlatitude Cyclones 584

- Idealized Weather of a Midlatitude Cyclone 584
- The Role of Airflow Aloft 586

EYE ON EARTH 586

Thunderstorms 587

- What's in a Name? 587
- Thunderstorm Occurrence 588
- Stages of Thunderstorm Development 588

Tornadoes 590

- Tornado Occurrence and Development 590
- Tornado Destruction and Loss of Life 592

EYE ON EARTH 592

- Tornado Forecasting 593

Hurricanes 595

- Profile of a Hurricane 595

GEO GRAPHICS | Hurricane Katrina from Space 597

- Hurricane Formation and Decay 598
- Hurricane Destruction 598
- Tracking Hurricanes 600

[Concepts in Review](#) 601 | [Give It Some Thought](#) 603 | [MasteringGeology](#) 605

20 World Climates and Global Climate Change 607

FOCUS ON CONCEPTS 607

The Climate System 608

World Climates 609

EYE ON EARTH 609

- Climate Classification 610
- The Köppen Classification 610

Humid Tropical (A) Climates 612

- The Wet Tropics 612
- Tropical Wet and Dry 614

Dry (B) Climates 615

- Low-Latitude Deserts and Steppes 615
- Middle-Latitude Deserts and Steppes 616

EYE ON EARTH 616

Humid Middle-Latitude Climates (C and D Climates) 617

- Humid Middle-Latitude Climates with Mild Winters (C Climates) 617
- Humid Middle-Latitude Climates with Severe Winters (D Climates) 618

Polar (E) Climates 620

Highland Climates 621

Human Impact on Global Climate 623

- Rising CO₂ Levels 623

EYE ON EARTH 623

- The Atmosphere's Response 624
- The Role of Trace Gases 625

GEO GRAPHICS | Greenhouse Gas (GHG) Emissions 626

Climate-Feedback Mechanisms 628

- Types of Feedback Mechanisms 628
- Computer Models of Climate: Important yet Imperfect Tools 629

How Aerosols Influence Climate 629

Some Possible Consequences of Global Warming 630

- Sea-Level Rise 631
- The Changing Arctic 632
- The Potential for "Surprises" 633

[Concepts in Review](#) 633 | [Give It Some Thought](#) 636 |

[MasteringGeology](#) 637

UNIT SEVEN | EARTH'S PLACE IN THE UNIVERSE 638

21 Origins of Modern Astronomy 639

FOCUS ON CONCEPTS 639

Ancient Astronomy 640

- The Golden Age of Astronomy 640
- Ptolemy's Model 642

The Birth of Modern Astronomy 643

- Nicolaus Copernicus 643
- Tycho Brahe 644
- Johannes Kepler 645
- Galileo Galilei 646
- Sir Isaac Newton 648

Positions in the Sky 649

- Constellations 649

GEO GRAPHICS | Orion the Hunter 650

- The Equatorial System 652

The Motions of Earth 653

- Rotation 653
- Revolution 654

EYE ON THE UNIVERSE 654

- Precession 655

Motions of the Earth–Moon System 655

- Lunar Motions 655
- Phases of the Moon 657

Eclipses of the Sun and Moon 657

[Concepts in Review](#) 659 | [Give It Some Thought](#) 660 | [MasteringGeology](#) 661

22 Touring Our Solar System 663

FOCUS ON CONCEPTS 663

Our Solar System: An Overview 664

- Nebular Theory: Formation of the Solar System 665
- The Planets: Internal Structures and Atmospheres 666
- Planetary Impacts 667

Earth's Moon: A Chip Off the Old Block 669

- How Did the Moon Form? 669

EYE ON THE UNIVERSE 669

Terrestrial Planets 672

- Mercury: The Innermost Planet 672

EYE ON THE UNIVERSE 672

- Venus: The Veiled Planet 673
- Mars: The Red Planet 674

GEO GRAPHICS | Mars Exploration 676

Jovian Planets 679

- Jupiter: Lord of the Heavens 679
- Saturn: The Elegant Planet 681
- Uranus and Neptune: Twins 683

Small Solar System Bodies 685

- Asteroids: Leftover Planetesimals 685
- Comets: Dirty Snowballs 686
- Meteoroids: Visitors to Earth 687
- Dwarf Planets 689

Concepts in Review 690 | Give It Some Thought 692 |

MasteringGeology 693

23 Light, Astronomical Observations, and the Sun 695

FOCUS ON CONCEPTS 695

Signals from Space 696

- Nature of Light 696
- Light as Evidence of Events and Processes 698

Spectroscopy 698

- Continuous Spectrum 698
- Dark-Line Spectrum 699
- Bright-Line Spectrum 699
- The Doppler Effect 699

Collecting Light Using Optical Telescopes 700

- Refracting Telescopes 700
- Reflecting Telescopes 700
- Light Collection 702

Radio- and Space-Based Astronomy 704

- Radio Telescopes 704
- Orbiting Observatories 705

The Sun 706

- Photosphere 707
- Chromosphere 708
- Corona 708

The Active Sun 709

- Sunspots 709
- Prominences 711
- Solar Flares 711

EYE ON THE UNIVERSE 711

GEO GRAPHICS | Hubble Space Telescope 712

The Source of Solar Energy 714

Concepts in Review 715 | Give It Some Thought 717 |

MasteringGeology 717

24 Beyond Our Solar System 719

FOCUS ON CONCEPTS 719

The Universe 720

- How Large Is It? 720
- A Brief History of the Universe 721

Interstellar Matter: Nursery of the Stars 722

- Bright Nebulae 722
- Dark Nebulae 724

Classifying Stars: Hertzsprung–Russell Diagrams (H-R Diagrams) 724

Stellar Evolution 726

- Stellar Birth 726
- Protostar Stage 727
- Main-Sequence Stage 727
- Red Giant Stage 727

EYE ON THE UNIVERSE 727

- Burnout and Death 728

Stellar Remnants 729

- White Dwarfs 729
- Neutron Stars 730
- Black Holes 730

Galaxies and Galactic Clusters 731

GEO GRAPHICS | The Milky Way 732

- Types of Galaxies 734
- Galactic Clusters 735
- Galactic Collisions 736

The Big Bang Theory 736

- Evidence for an Expanding Universe 736
- Predictions of the Big Bang Theory 737
- What Is the Fate of the Universe? 737

Concepts in Review 739 | Give It Some Thought 741 |

MasteringGeology 742

APPENDIX A Metric and English Units Compared 743

APPENDIX B Relative Humidity and Dew-Point Tables 744

APPENDIX C Stellar Properties 745

GLOSSARY 748

INDEX 761



PREFACE

Earth Science, 14th edition, is a college-level text designed for an introductory course in Earth science. It consists of seven units that emphasize broad and up-to-date coverage of basic topics and principles in geology, oceanography, meteorology, and astronomy. The textbook is intended to be a meaningful, nontechnical survey for undergraduate students who have little background in science. Usually these students are taking an Earth science class to meet a portion of their college's or university's general requirements.

In addition to being informative and up-to-date, *Earth Science*, 14th edition, strives to meet the need of beginning students for a readable and user-friendly text and a highly usable tool for learning basic Earth science principles and concepts.

NEW TO THIS EDITION

- **SmartFigures—art that teaches.** Inside every chapter are several *SmartFigures*. *Earth Science*, 14th edition, has more than 100 of these figures. Just use your mobile device to scan the Quick Response (QR) code next to a SmartFigure, and the art comes alive. Each 3- to 5-minute feature, prepared and narrated by Professor Callan Bentley, is a mini-lesson that examines and explains the concepts illustrated by the figure. It is truly *art that teaches*.
- **Mobile Field Trips.** Scattered through this new edition of *Earth Science* are thirteen Mobile Field Trips. On each trip, you will accompany geologist–pilot–photographer Michael Collier in the air and on the ground to see and learn about landscapes that relate to discussions in the chapter. These extraordinary field trips are accessed in the same way as SmartFigures. You will scan a QR code that accompanies a figure in the chapter—usually one of Michael's outstanding photos.
- **New and expanded active learning path.** *Earth Science*, 14th edition, is designed for learning. Every chapter begins with *Focus on Concepts*. Each numbered learning objective corresponds to a major section in the chapter. The statements identify the knowledge and skills students should master by the end of the chapter, helping students prioritize key concepts. Within the chapter, each major section concludes with *Concept Checks* that allow students to check their understanding and comprehension of important ideas and terms before moving on to the next section. Chapters conclude with sections called *Give It Some Thought* and *Examining the Earth System*. The questions and problems in these sections challenge learners by involving them in activities that require higher-order thinking skills such as application, analysis, and synthesis of material in the chapter. The questions and problems in *Examining the Earth System* are intended to develop an awareness of and appreciation for some of the Earth system's many interrelationships.
- **Concepts in Review.** This all-new end-of-chapter feature is an important part of the text's revised active learning path. Each review is coordinated with the *Focus on Concepts* at the beginning of the chapter and with the numbered sections within the chapter. It is a readable and concise overview of key ideas, which makes it a valuable review tool for students. Photos, diagrams, and questions also help students focus on important ideas and test their understanding.
- **Eye on Earth.** Within every chapter are two or three images, often aerial or satellite views, that challenge students to apply their understanding of basic facts and principles. A brief explanation of each image is followed by questions that help focus students on visual analysis and critical thinking.
- **GEOgraphics.** As you turn the pages of each chapter, you will encounter striking visual features that we call GEOgraphics. They are engaging magazine-style “geo-essays” that explore topics that promote greater understanding and add interest to the story each chapter is telling.
- **An unparalleled visual program.** In addition to more than 200 new, high-quality photos and satellite images, dozens of figures are new or have been redrawn by renowned geoscience illustrator Dennis Tasa. Maps and diagrams are frequently paired with photographs for greater effectiveness. Further, many new and revised figures have additional labels that narrate the process being illustrated and guide students as they examine the figures. The result is a visual program that is clear and easy to understand.
- **MasteringGeology™.** MasteringGeology delivers engaging, dynamic learning opportunities—focused on course objectives and responsive to each student's progress—that are proven to help students absorb course material and understand difficult concepts. Assignable activities in MasteringGeology include Encounter Earth activities using Google Earth™, SmartFigure activities, Mobile Field Trips, GeoTutor activities, GigaPan® activities, Geoscience Animation activities, GEODE tutorial activities, and more. MasteringGeology also includes all instructor resources and a robust Study Area with resources for students.
- **Significant updating and revision of content.** A basic function of a college science text book is to provide clear, understandable presentations that are accurate, engaging, and up-to-date. Our number-one goal is to keep *Earth Science* current, relevant, and highly readable for beginning students. Every part of this text has been examined carefully with this goal in mind. Many discussions, case studies, and examples have been revised. This 14th edition represents perhaps the *most extensive and thorough revision* in the long history of this textbook.
- **Learning Catalytics™.** Learning Catalytics is a “bring your own device” student engagement, assessment, and classroom intelligence system. Learning Catalytics is a technology that has grown out of twenty years of cutting edge research, innovation, and implementation of interactive teaching and peer instruction. Available integrated with MasteringGeology.

DISTINGUISHING FEATURES

Readability

The language of this textbook is straightforward and *written to be understood*. Clear, readable discussions with a minimum of technical language are the rule. The frequent headings and subheadings help students follow discussions and identify the important ideas presented in each chapter. In this 14th edition, we have continued to improve readability by examining

chapter organization and flow and by writing in a more personal style. Significant portions of several chapters have been substantially rewritten in an effort to make the material easier to understand.

Focus on Basic Principles

Although many topical issues are treated in this 14th edition of *Earth Science*, it should be emphasized that the main focus of this new edition remains the same as the focus of each of its predecessors: to promote student understanding of basic Earth science principles. As much as possible, we have attempted to provide the reader with a sense of the observational techniques and reasoning processes that constitute the Earth sciences.

A Strong Visual Component

Earth science is highly visual, and art and photographs play a critical role in an introductory textbook. As in all previous editions, Dennis Tasa, a gifted artist and respected geoscience illustrator, has worked closely with the authors to plan and produce the diagrams, maps, graphs, and sketches that are so basic to student understanding. The result is art that is clearer and easier to understand than ever before.

Our aim is to get *maximum effectiveness* from the visual component of the text. Michael Collier, an award-winning geologist–photographer aided greatly in this quest. As you read through this text, you will see dozens of his extraordinary aerial photographs. His contribution truly helps bring geology alive for the reader.

FOR THE INSTRUCTOR

Pearson continues to improve the instructor resources for this text, with the goal of saving you time in preparing for your classes.

MasteringGeology from Pearson is an online homework, tutorial, and assessment system designed to improve results by helping students quickly master concepts. Students using MasteringGeology benefit from self-paced tutorials that feature specific wrong-answer feedback and hints to keep them engaged and on track. MasteringGeology™ offers:

- Assignable activities, including Encounter Earth activities using Google Earth™, SmartFigure activities, GeoTutor activities, GigaPan® activities, Geoscience Animation activities, GEODE tutorial activities, and more
- Additional Give It Some Thought questions, Test Bank questions, and Reading Quizzes
- A student Study Area with Geoscience Animations, GEODE: Earth Science activities, SmartFigures, Video Field Trips *In the News* RSS feeds, Self Study Quizzes, Web Links, Glossary, and Flashcards
- Pearson eText for *Earth Science*, 14th edition, which gives students access to the text whenever and wherever they can access the Internet and includes powerful interactive and customization functions
See www.masteringgeology.com

Learning Catalytics

Learning Catalytics™ is a “bring your own device” student engagement, assessment, and classroom intelligence system. With Learning Catalytics you can:

- Assess students in real time, using open-ended tasks to probe student understanding.
- Understand immediately where students are and adjust your lecture accordingly.
- Improve your students’ critical-thinking skills.
- Access rich analytics to understand student performance.

- Add your own questions to make Learning Catalytics fit your course exactly.
- Manage student interactions with intelligent grouping and timing.

Learning Catalytics is a technology that has grown out of twenty years of cutting edge research, innovation, and implementation of interactive teaching and peer instruction. Available integrated with MasteringGeology. www.learningcatalytics.com

Instructor’s Resource DVD

The Instructor’s Resource DVD puts all your lecture resources in one easy-to-reach place:

- Three PowerPoint® presentations for each chapter
- The Geoscience Animation Library
- All the line art, tables, and photos from the text, in .jpg files
- “Images of Earth” photo gallery
- Instructor’s Manual in Microsoft Word
- Test Bank in Microsoft Word
- TestGen test-generation and management software

PowerPoints®

The Instructor’s Resource DVD provides three PowerPoint files for each chapter to cut down on your preparation time, no matter what your lecture needs:

- **Art.** All the line art, tables, and photos from the text have been preloaded into PowerPoint slides for easy integration into your presentations.
- **Lecture outline.** This set averages 35 slides per chapter and includes customizable lecture outlines with supporting art.
- **Classroom Response System (CRS) questions.** These questions have been authored for use in conjunction with any classroom response system. You can electronically poll your class for responses to questions, pop quizzes, attendance, and more.

Animations and “Images of Earth”

The Pearson Prentice Hall Geoscience Animation Library includes more than 100 animations illustrating many difficult-to-visualize topics in Earth science. Created through a unique collaboration among five of Pearson Prentice Hall’s leading geoscience authors, these animations represent a significant step forward in lecture presentation aids. They are provided both as Flash files and, for your convenience, preloaded into PowerPoint slides.

“Images of Earth” allows you to supplement your personal and text-specific slides with an amazing collection of more than 300 geologic photos contributed by Marli Miller (University of Oregon) and other professionals in the field. The photos are available on the Instructor’s Resource DVD.

Instructor’s Manual with Test Bank

The *Instructor’s Manual* contains learning objectives, chapter outlines, answers to end-of-chapter questions, and suggested short demonstrations to spice up your lecture. The Test Bank incorporates art and averages 75 multiple-choice, true/false, short-answer, and critical thinking questions per chapter.

TestGen

Use this electronic version of the Test Bank to customize and manage your tests. Create multiple versions, add or edit questions, add illustrations, and so on. This powerful software easily addresses your customization needs.

Course Management

Pearson Prentice Hall offers instructor and student media for the 14th edition of *Earth Science* in formats compatible with Blackboard and other course management platforms. Contact your local Pearson representative for more information.

FOR THE STUDENT

The student resources to accompany *Earth Science*, 14th edition, have been further refined, with the goal of focusing the students' efforts and improving their understanding of Earth science concepts.

MasteringGeology from Pearson is an online homework, tutorial, and assessment system designed to improve results by helping students quickly master concepts. Students using MasteringGeology benefit from self-paced tutorials that feature specific wrong-answer feedback and hints to keep them engaged and on track. MasteringGeology™ also offers students the Study Area, which contains:

- **Geoscience Animation Library.** More than 100 animations illustrating many difficult to understand Earth science concepts.
- **GEODE: Earth Science.** An interactive visual walkthrough of each chapter's content.
- **In the News RSS Feeds.** Current Earth science events and news articles are pulled into the site, with assessment.
- **SmartFigures and Mobile Field Trips**
- **Pearson eText**
- **Optional Self Study Quizzes**
- **Web Links**
- **Glossary**
- **Flashcards**

FOR THE LABORATORY

Applications and Investigations in Earth Science, 8th edition, was written by Ed Tarbuck, Fred Lutgens, and Ken Pinzke. This full-color laboratory manual contains 23 exercises that provide students with hands-on experience in geology, oceanography, meteorology, astronomy, and Earth science skills. The lab manual is available at a discount when purchased with the text; please contact your local Pearson representative for more details.

ACKNOWLEDGMENTS

Writing a college textbook requires the talents and cooperation of many people. It is truly a team effort, and the authors are fortunate to be part of an extraordinary team at Pearson Education. In addition to being great people to work with, all are committed to producing the best textbooks possible. Special thanks to our geology editor, Andy Dunaway, who invested a great deal of time, energy, and effort in this project. We appreciate his enthusiasm, hard work, and quest for excellence. We also appreciate our conscientious project manager, Crissy Dudonis, whose job it was to keep track of all that was going on—and a lot was going on. The text's new design and striking cover resulted from the creative talents of Derek Bacchus and his team. We think it is a job well done. As always, our marketing manager, Maureen McLaughlin, provided helpful advice and many good ideas. *Earth Science*, 14th edition, was truly improved with the help of our developmental editor, Jonathan Cheney. Many thanks. The production team was led by Gina Cheselka at Pearson Education and by Heidi Allgair at Cenveo® Publisher Services. It was their job to make this text into a finished product. The talents of copy editor Kitty Wilson, compositor Annamarie Boley, and photo researcher Kristin Piljay were an important part of the production process. We think they all did a great job. They are true professionals, with whom we are very fortunate to be associated.

The authors owe a special thanks to three people who were a very important part of this project:

- Working with Dennis Tasa, who is responsible for all of the text's outstanding illustrations, is always special for us. He has been a part of our team for more than 30 years. We not only value his artistic talents, hard work, patience, and imagination but his friendship as well.
- As you read this text, you will see dozens of extraordinary photographs by Michael Collier, an award-winning geologist, author, and photographer. Most are aerial shots taken from his nearly 60-year-old Cessna 180. Michael was also responsible for preparing the remarkable Mobile Field Trips that are scattered through the text. Among his many awards is the American Geological Institute Award for Outstanding Contribution to the Public Understanding of the Geosciences. We think that Michael's photographs and field trips are the next best thing to being there. We were very fortunate to have had Michael's assistance on *Earth Science*, 14th edition. Thanks, Michael.
- Callan Bentley has been an important addition to the *Earth Science* team. Callan is an assistant professor of geology at Northern Virginia Community College in Annandale, where he has been honored many times as an outstanding teacher. He is a frequent contributor to *Earth* magazine and is author of the popular geology blog Mountain Beltway. Callan was responsible for preparing the *SmartFigures* that appear throughout *Earth Science*'s 24 chapters. As you take advantage of these outstanding learning aids, you will hear his voice explaining the ideas. Callan also helped with the preparation of the Concepts in Review feature found at the end of each chapter. We appreciate Callan's contributions to this new edition of *Earth Science*.

Great thanks also go to our colleagues who prepared in-depth reviews. Their critical comments and thoughtful input helped guide our work and clearly strengthened the text. Special thanks to:

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 Haluk Cetin, *Murray State University*
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 Adam Davis, *Vincennes University*
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 Xiaoming Zhai, *College of Lake County*

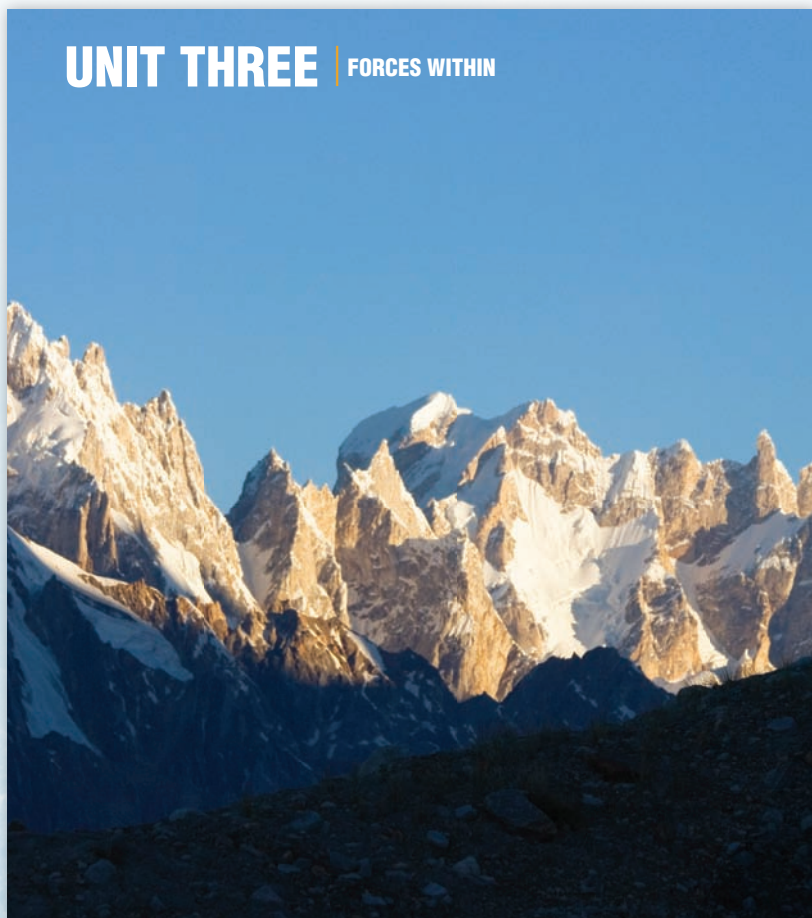
Last, but certainly not least, we gratefully acknowledge the support and encouragement of our wives, Joanne Bannon and Nancy Lutgens. Preparation of *Earth Science*, 14th edition, would have been far more difficult without their patience and understanding.

Ed Tarbuck
 Fred Lutgens

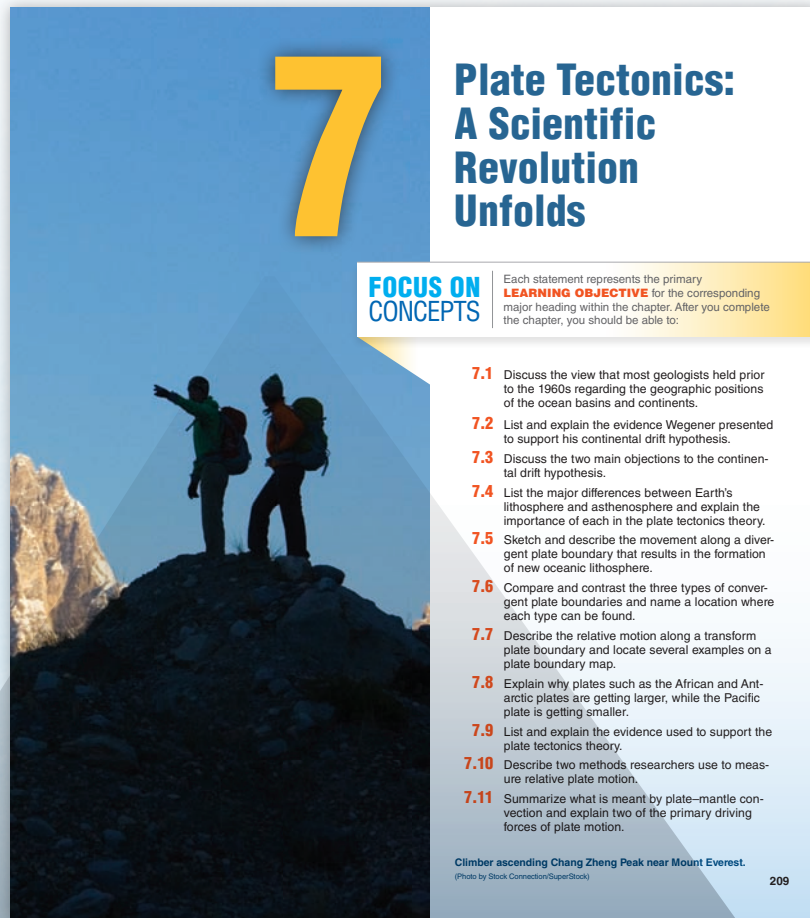
New learning path helps students master the concepts

The new edition is designed to support a new **four-part learning path**, an innovative structure which facilitates active learning and easily allows students to focus on important ideas as they pause to assess their progress at frequent intervals.

The chapter-opening **Focus on Concepts** lists the learning objectives for each chapter. Each section of the chapter is tied to a specific learning objective, providing students with a clear learning path to the chapter content.



UNIT THREE | FORCES WITHIN



7

Plate Tectonics: A Scientific Revolution Unfolds

FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

- 7.1** Discuss the view that most geologists held prior to the 1960s regarding the geographic positions of the ocean basins and continents.
- 7.2** List and explain the evidence Wegener presented to support his continental drift hypothesis.
- 7.3** Discuss the two main objections to the continental drift hypothesis.
- 7.4** List the major differences between Earth's lithosphere and asthenosphere and explain the importance of each in the plate tectonics theory.
- 7.5** Sketch and describe the movement along a divergent plate boundary that results in the formation of new oceanic lithosphere.
- 7.6** Compare and contrast the three types of convergent plate boundaries and name a location where each type can be found.
- 7.7** Describe the relative motion along a transform plate boundary and locate several examples on a plate boundary map.
- 7.8** Explain why plates such as the African and Antarctic plates are getting larger, while the Pacific plate is getting smaller.
- 7.9** List and explain the evidence used to support the plate tectonics theory.
- 7.10** Describe two methods researchers use to measure relative plate motion.
- 7.11** Summarize what is meant by plate-mantle convection and explain two of the primary driving forces of plate motion.

Climber ascending Chang Zheng Peak near Mount Everest.
(Photo by Stock Connection/SuperStock)

209

Each chapter section concludes with **Concept Checks**, a feature that lists questions tied to the section's learning objective, allowing students to monitor their grasp of significant facts and ideas.

7.4 CONCEPT CHECKS

- 1** What major ocean floor feature did oceanographers discover after World War II?
- 2** Compare and contrast the lithosphere and the asthenosphere.
- 3** List the seven largest lithospheric plates.
- 4** List the three types of plate boundaries and describe the relative motion at each of them.

FOCUS ON CONCEPTS

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- 7.3** Discuss the two main objections to the continental drift hypothesis.
- 7.4** List the major differences between Earth's lithosphere and asthenosphere and explain the importance of each in the plate tectonics theory.
- 7.5** Sketch and describe the movement along a divergent plate boundary that results in the formation of new oceanic lithosphere.

Concepts in Review, a fresh approach to the typical end-of-chapter material, provides students with a structured and highly visual review of the chapter.

Key Terms **Section Title** **Learning Objective** **Review Statements**

7 CONCEPTS IN REVIEW

Plate Tectonics: A Scientific Revolution Unfolds

Consistent with the Focus on Concepts and Concept Checks, the **Concepts in Review** is structured around the section title and the corresponding learning objective for each section.

7.1 FROM CONTINENTAL DRIFT TO PLATE TECTONICS

Discuss the view that most geologists held prior to the 1960s regarding the geographic positions of the ocean basins and continents.

- Fifty years ago, most geologists thought that ocean basins were very old and that continents were fixed in place. Those ideas were discarded with a scientific revolution that revitalized geology: the theory of plate tectonics. Supported by multiple kinds of evidence, plate tectonics is the foundation of modern Earth science.

7.2 CONTINENTAL DRIFT: AN IDEA BEFORE ITS TIME

List and explain the evidence Wegener presented to support his continental drift hypothesis.

KEY TERMS continental drift, supercontinent, Pangaea

- German meteorologist Alfred Wegener formulated the idea of continental drift in 1917. He suggested that Earth's continents are not fixed in place but have moved slowly over geologic time.
- Wegener reconstructed a super-continent called Pangaea that existed about 200 million years ago, during the late Paleozoic and early Mesozoic.
- Wegener's evidence that Pangaea existed but later broke into pieces that drifted apart included (1) the shape of the continents, (2) continental fossil organisms that matched across oceans, (3) matching rock types and modern mountain belts, and (4) sedimentary rocks that recorded ancient climates, including glaciers on the southern portion of Pangaea.

Q Why did Wegener choose organisms such as *Glossopteris* and *Mesosaurus* as evidence for continental drift, as opposed to other fossil organisms such as sharks or jellyfish?



7.3 THE GREAT DEBATE

Discuss the two main objections to the continental drift hypothesis.

- Wegener's hypothesis suffered from two flaws: It proposed tidal forces as the mechanism for the motion of continents, and it implied that the continents would have plowed their way through weaker oceanic crust, like a boat cutting through a thin layer of sea ice. Geologists rejected the idea of continental drift when Wegener

Give It Some Thought (GIST) is found at the end of each chapter and consists of questions and problems asking students to analyze, synthesize, and think critically about Earth science. GIST questions relate back to the chapter's learning objectives, and can easily be assigned using MasteringGeology™.

7.4 THE THEORY OF PLATE TECTONICS

List the major differences between Earth's lithosphere and asthenosphere and explain the tectonics theory.

KEY TERMS ocean ridge system, theory of plate tectonics, lithosphere, asthenosphere, lithospheric plate (plate)

- Research conducted during World War II led to new insights that helped revive Wegener's hypothesis of continental drift. It revealed previously unknown features, including an extremely long mid-ocean ridge system. Sampling of the young relative to the continents.
- The lithosphere is Earth's outermost rocky layer that is broken into plates. It is relatively stiff and deforms little. The asthenosphere, a relatively weak layer that deforms by flowing. The lithosphere consists both of crust and upper mantle.
- There are seven large plates, another seven intermediate-size plates, and numerous relatively small plates that may either be divergent (moving apart from each other), convergent (moving toward each other), or transform (sliding past each other).

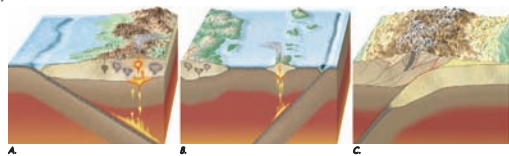
GIVE IT SOME THOUGHT

1. After referring to the section in the Introduction titled "The Nature of Scientific Inquiry," answer the following:

- What observation led Alfred Wegener to develop his continental drift hypothesis?
- Why did the majority of the scientific community reject the continental drift hypothesis?
- Do you think Wegener followed the basic principles of scientific inquiry? Support your answer.

2. Referring to the accompanying diagrams that illustrate the three types of convergent plate boundaries, complete the following:

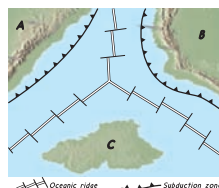
- Identify each type of convergent boundary.
- On what type of crust do volcanic island arcs develop?
- Why are volcanoes largely absent where two continental blocks collide?
- Describe two ways that oceanic-oceanic convergent boundaries are different from oceanic-continental boundaries. How are they similar?



3. Some predict that California will sink into the ocean. Is this idea consistent with the theory of plate tectonics? Explain.

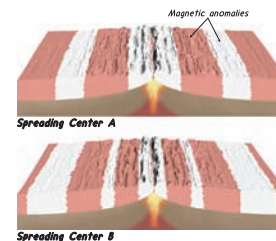
4. Refer to the accompanying hypothetical plate map to answer the following questions:

- How many portions of plates are shown?
- Are continents A, B, and C moving toward or away from each other? How did you determine your answer?
- Explain why active volcanoes are more likely to be found on continents A and B than on continent C.
- Provide at least one scenario in which volcanic activity might be triggered on continent C.



5. Volcanoes, such as the Hawaiian chain, that form over mantle plumes are some of the largest shield volcanoes on Earth. However, several shield volcanoes on Mars are gigantic compared to those on Earth. What does this difference tell us about the role of plate motion in shaping the Martian surface?

6. Imagine that you are studying seafloor spreading along two different oceanic ridges. Using data from a magnetometer, you produced the two accompanying maps. From these maps, what can you determine about the relative rates of seafloor spreading along these two ridges? Explain.



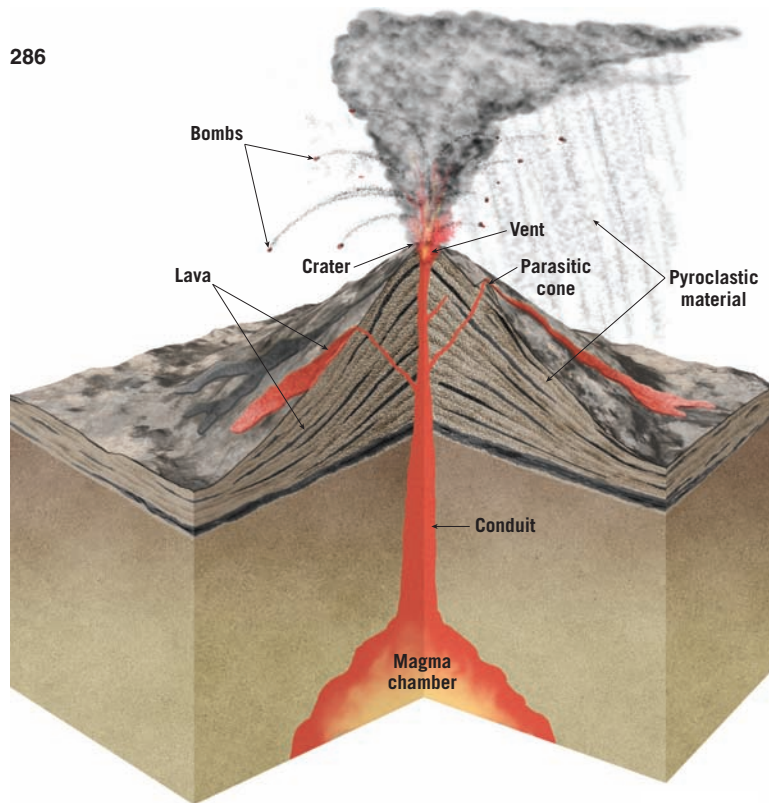
7. Australian marsupials (kangaroos, koala bears, etc.) have direct fossil links to marsupial opossums found in the Americas. Yet the modern marsupials in Australia are markedly different from their American relatives. How does the breakup of Pangaea help to explain these differences (see Figure 7.24)?

8. Density is a key component in the behavior of Earth materials and is especially important in understanding key aspects of plate tectonics. Describe three different ways that density and/or density differences play a role in plate tectonics.

Dynamic visual program integrates text and technology

Carefully selected art and photos aid understanding, add realism, and heighten student interest.

286



SmartFigure 9.10 Anatomy of a Volcano Compare the structure of a "typical" composite cone to that of a shield volcano (Figure 9.11) and a cinder cone (Figure 9.12).



NEW! SmartFigures bring key chapter illustrations to life! Found throughout the book, SmartFigures are sophisticated, annotated illustrations that are also narrated videos. The SmartFigure videos are accessible on mobile devices via scannable Quick Response (QR) codes printed in the text and through the Study Area in MasteringGeology. See the Preface for more detailed information on SmartFigures.



Callan Bentley, SmartFigure author, is an assistant professor of geology at Northern Virginia Community College (NOVA) in Annandale, Virginia. Trained as a structural geologist, Callan teaches introductory level geology at NOVA, including field-based and hybrid courses. Callan writes a popular geology blog called *Mountain Beltway*, contributes cartoons, travel articles, and book reviews to *EARTH Magazine*, and is a leader in the two-year college geoscience community.



Mobile Field Trips

Scattered through this new edition of Earth Science are thirteen video field trips. On each trip, you will accompany geologist-pilot-photographer Michael Collier in the air and on the ground to see and learn about landscapes that relate to discussions in the chapter. These extraordinary field trips are accessed in the same way as SmartFigures. You will scan a QR code that accompanies a figure in the chapter—usually one of Michael's outstanding photos.



Mobile Field Trip 9.25 Sill Exposed in Utah's Sinbad Country

The dark, essentially horizontal bands are sills of basaltic composition that intruded horizontal layers of sedimentary rock. (Photo by Michael Collier)



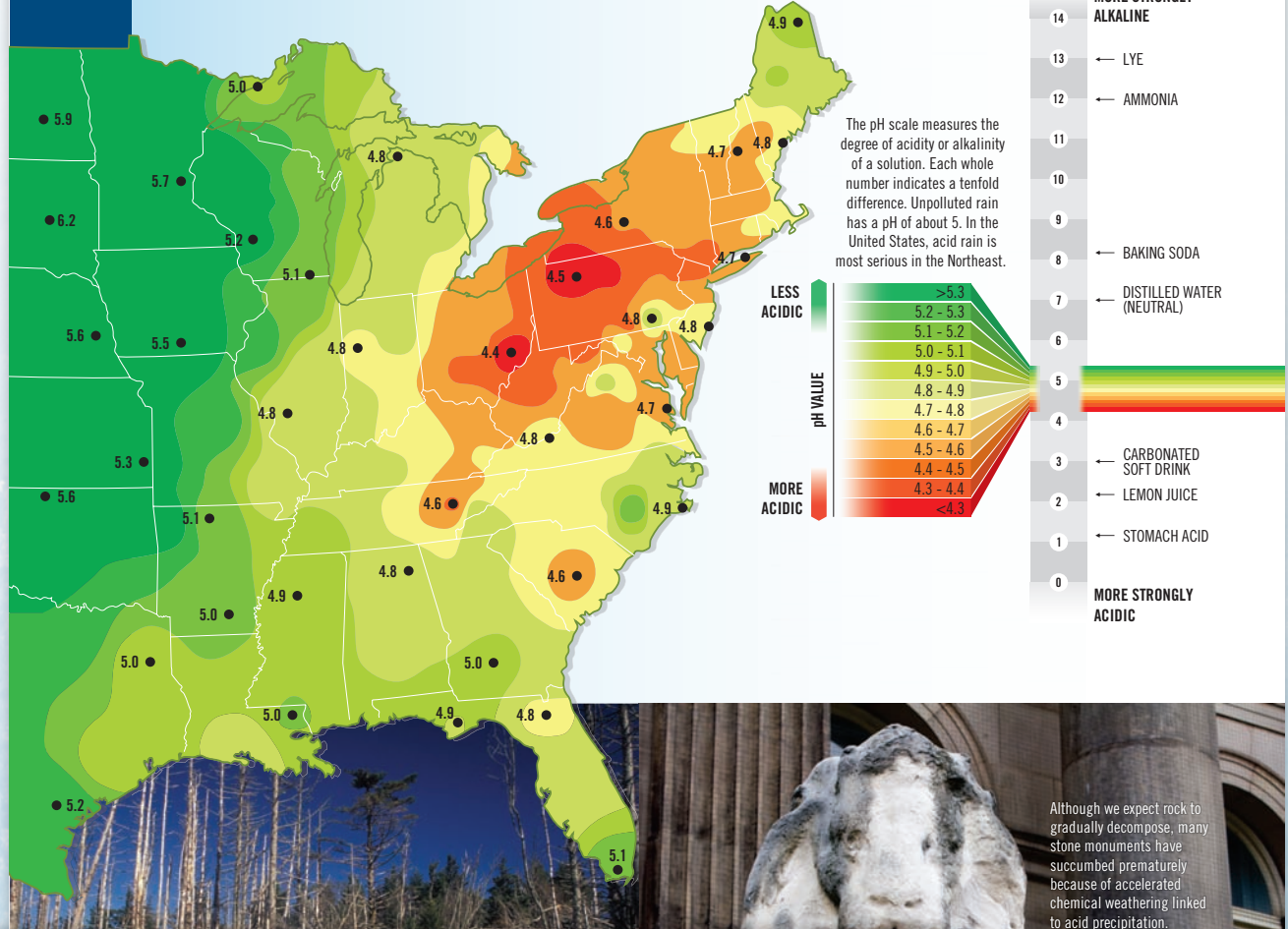
As you turn the pages of this book, you will see dozens of extraordinary photographs by Michael Collier. Most are aerial shots taken from his nearly 60-year-old Cessna 180. Michael is an award-winning geologist, author, and photographer. Michael's photographs are the next best thing to being there. We were fortunate to have had Michael's assistance on Earth Science, Fourteenth edition.

NEW! GEOgraphics use contemporary, compelling visual representations to illustrate complex concepts, enhancing students' ability to synthesize and recall information.

GEOGRAPHICS

Acid Precipitation A Human Impact on the Earth System

As a consequence of burning large quantities of coal and petroleum, tens of millions of tons of sulfur dioxide and nitrogen oxides enter the atmosphere each year. Through a series of complex chemical reactions, these pollutants are converted into acids that eventually fall to Earth's surface. The map shows precipitation pH values for 2008.



NEW! Eye on Earth features engage students in active learning, asking them to perform critical thinking and visual analysis tasks to evaluate data and make predictions.

Although we expect rock to gradually decompose, many stone monuments have succumbed prematurely because of accelerated chemical weathering linked to acid precipitation.

EYE ON EARTH



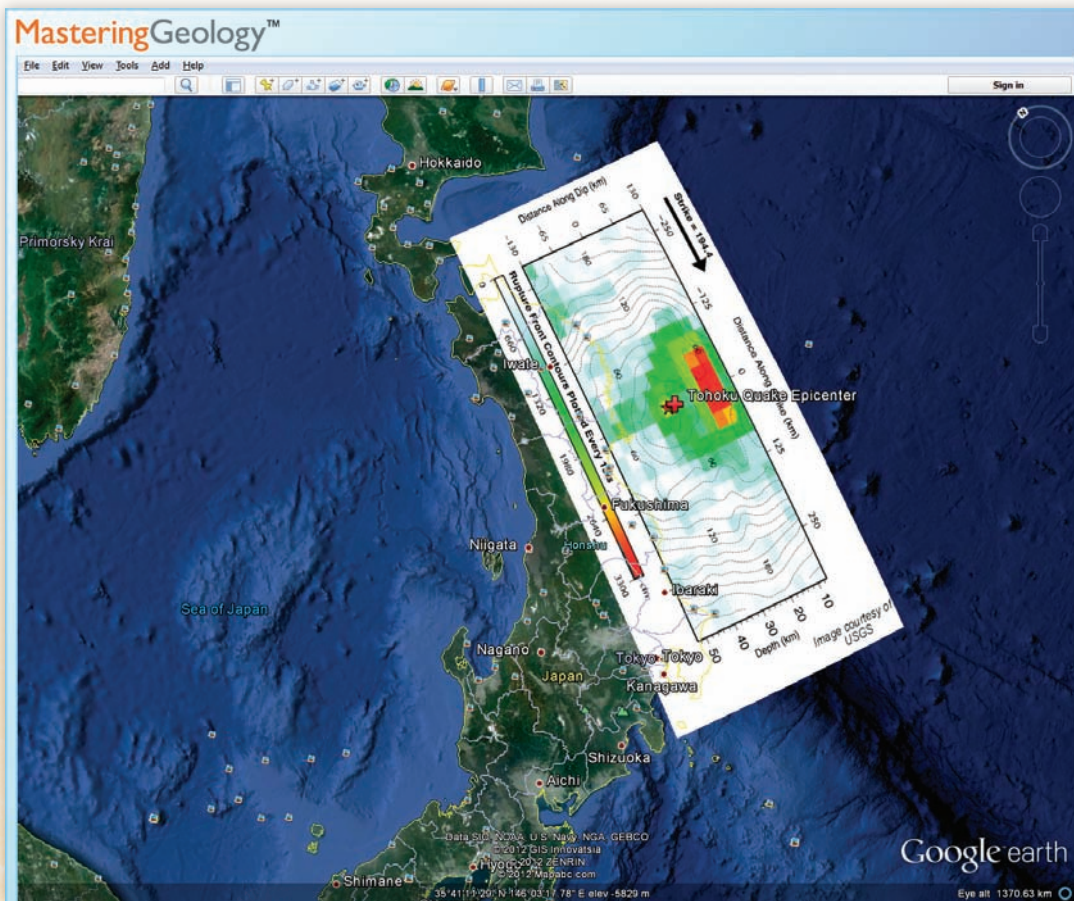
This image was obtained during the 1991 eruption of Mount Pinatubo in the Philippines. This was the largest eruption to affect a densely populated area in recent times. Timely forecasts of the event by scientists were credited with saving at least 5000 lives. (Alberto Garcia/CORBIS)

QUESTION 1 What name is given to the ash- and pumice-laden cloud that is racing toward the photographer?

QUESTION 2 At what speeds can these fiery clouds move down steep mountain slopes?



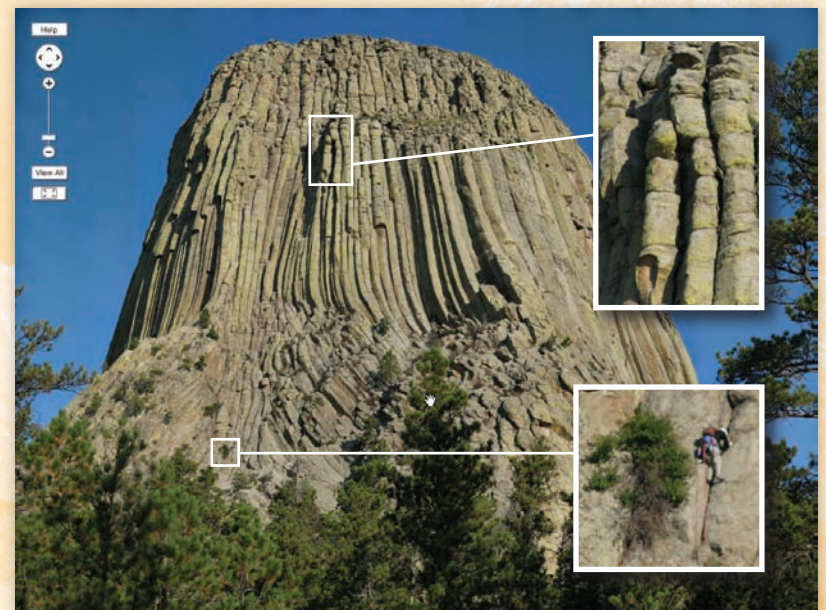
Available for the Earth science course, MasteringGeology delivers engaging, dynamic learning opportunities—focused on course objectives and responsive to each student’s progress—that are proven to help students absorb course material and understand difficult Earth science concepts.



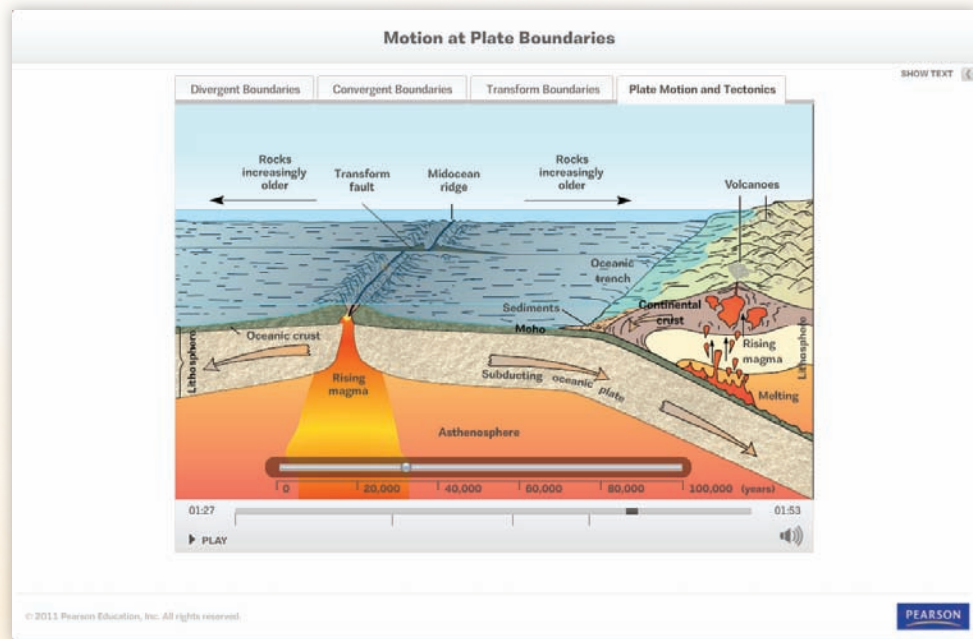
Encounter Activities provide rich, interactive explorations of Earth science concepts using the dynamic features of Google Earth™ to visualize and explore Earth’s varied physical landscapes. Dynamic assessment includes questions related to core Earth science concepts. All explorations include corresponding Google Earth KMZ media files, and questions include hints and specific wrong-answer feedback to help coach students toward mastery of the concepts.

NEW! Inquiry-based interactive simulations, developed to allow students to manipulate Earth processes, assist students in mastering the most difficult Earth science processes as identified by today’s instructors.

NEW! GigaPan® Activities take advantage of the GigaPan high-resolution panoramic picture technology developed by Carnegie Mellon University in conjunction with NASA. Photos and accompanying questions correlate with concepts in the student book.



Geoscience Animations and Activities illuminate difficult-to-visualize topics from across the physical geosciences. MasteringGeology allows instructors to easily assign the animations and corresponding assessment questions, all of which include hints and specific wrong-answer feedback.



GEODE Tutorials provide an interactive visual walkthrough of core content through animations, videos, illustrations, photographs, and narration. Activities include assessment questions to test those concepts with hints and specific wrong-answer feedback.

The "Running Water" interactive activity is titled "UNIT II SCULPTURING EARTH'S SURFACE Running Water". It features a 3D landscape diagram with a river system. Labels on the diagram include "Cut bank", "Floodplain", "Back swamp", "Natural levee", and "Oxbow lake". To the right, a list of terms includes "Cut bank", "Floodplain", "Back swamp", "Natural levee", and "Oxbow lake". Below the diagram are interactive buttons: "Is this right?", "I give up", a score of "51", and navigation arrows. The text "Move the correct term to the proper position on the diagram." is displayed at the bottom left.

Give It Some Thought questions and problems relate back to each chapter's learning objectives and challenge learners by involving them in activities that require higher-order thinking skills such as synthesis, analysis, and application.

The "Rock Cycle" interactive activity is titled "The Rock Cycle" and includes the question: "Can you correctly identify which processes lead to which rock types on the rock cycle diagram? Further, can you determine which processes occur at Earth's surface and which are subsurface processes? If they happen subsurface, do they happen deep within the Earth or fairly shallow?" Below the question is a circular diagram of the rock cycle with labels for "Igneous Rock", "Sedimentary Rock", "Metamorphic Rock", and "Magma". A list of processes to be placed includes "Compaction, cementation", "Sedimentation, weathering, erosion, deposition", "Melting", "Cooling, Crystallization", and "Heat, intense pressure". The interface includes a "PLAY" button and a "HELP" icon.

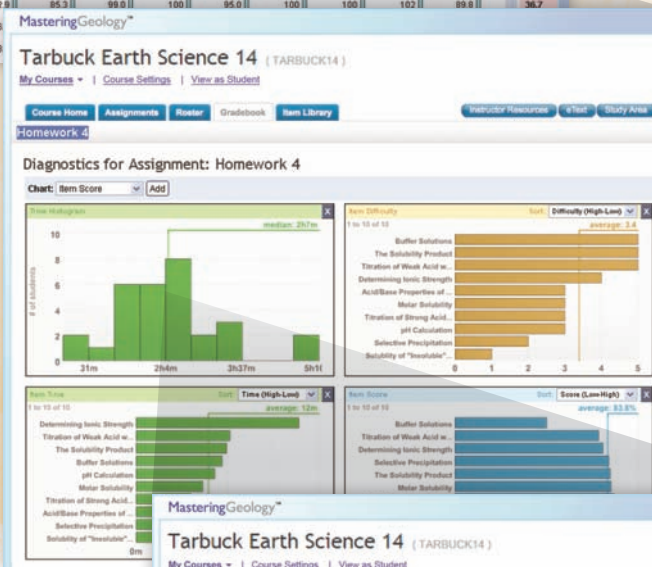
Quickly monitor and display student results

With the Mastering gradebook and diagnostics, instructors will be better informed about students' progress than ever before. Mastering captures the step-by-step work of every student—including wrong answers submitted, hints requested, and time taken at every step of every problem—all providing unique insight into the most common misconceptions of the class.

The **Gradebook** records all scores for automatically graded assignments. Shades of red highlight struggling students and challenging assignments.

| NAME | Intro-ry | Ch 2 | Ch 3 | Lab 2 | Ch 4 | Ch 5 | Ch 6 | Ch 7e | Chapter 7b | Lab 4 | Ch 8 | Ch 9 | Ch 12 | TOTAL |
|-------------------|----------|------|------|-------|------|------|------|-------|------------|-------|------|------|-------|-------|
| Class Average | -- | 76.4 | 86.0 | 82.6 | 89.1 | 89.5 | 86.7 | 91.6 | 83.7 | 90.0 | 88.4 | 77.7 | | 24.5 |
| Last01, First0... | -- | 84.4 | 73.3 | 83.3 | 102 | 99.9 | 0.0 | 95.9 | 101 | 100 | 0.0 | 87.4 | | 46.9 |
| Last02, First0... | -- | 70.3 | 64.9 | 92.9 | 88.0 | 49.5 | 86.2 | 72.9 | 47.5 | 80.0 | 86.9 | 66.3 | | 26.2 |
| Last03, First0... | -- | 73.6 | 46.0 | 61.9 | 104 | 102 | 94.9 | 85.0 | 100 | 95.0 | 99.7 | 67.3 | | 27.8 |
| Last04, First0... | -- | 72.5 | 53.8 | 0.0 | 34.3 | 86.3 | 85.3 | 80.0 | 83.4 | 90.0 | 99.2 | 67.0 | | 30.3 |
| Last05, First0... | -- | 78.8 | 69.3 | 78.6 | 99.0 | 87.8 | 85.2 | 82.5 | 34.8 | 85.0 | 88.3 | 87.7 | | 31.9 |
| Last07, First0... | -- | 77.9 | 66.7 | 51.8 | 101 | 96.1 | 95.9 | 90.0 | 76.7 | 95.0 | 84.8 | 70.6 | | 23.2 |
| Last08, First0... | -- | 84.4 | 70.7 | 92.8 | 85.3 | 99.0 | 100 | 95.0 | 100 | 100 | 102 | 89.8 | | 36.7 |
| Last09, First0... | -- | 66.2 | 70.0 | 76 | | | | | | | | | | |
| Last10, First0... | -- | 76.1 | 70.0 | 78 | | | | | | | | | | |

Diagnostics provide unique insight into class and student performance. With a single click, charts summarize the most difficult items, vulnerable students, grade distribution, and score improvement over the duration of the course.



With a single click, **Individual Student Performance Data** provides at-a-glance statistics into each individual student's performance, including time spent on the item, number of hints opened, and number of wrong and correct answers submitted.

Activity 1

Description: (a) In addition to viscosity, which of the following parameters has an influence on whether a volcanic eruption will be effusive or violent?

Part A

In addition to viscosity, which of the following parameters has an influence on whether a volcanic eruption will be effusive or violent?

ANSWER:

- amount of gas in the magma
- how fast the lava cools
- the slope of the volcanic cone
- the depth of the magma chamber
- temperature of the magma

| Answer State | Students | % Correct | % Unfinished | % Right Solution | Wrong Answers | Hints/Attempts |
|--------------|----------|-----------|--------------|------------------|---------------|----------------|
| Overall | 10138 | 92.5% | 6.8% | 0.7% | 0.6 | 0 |
| MID-GRADE 5 | 25 | 100% | 0% | 0% | 0.8 | 0 |

Wrong Answers for MID-GRADE 5

| % Wrong | Answer | Response |
|---------|--------------------------------|----------|
| 38.1% | amount of gas in the magma | |
| 23.8% | how fast the lava cools | |
| | the slope of the volcanic cone | |
| 23.8% | the depth of the magma chamber | |
| 14.3% | temperature of the magma | |

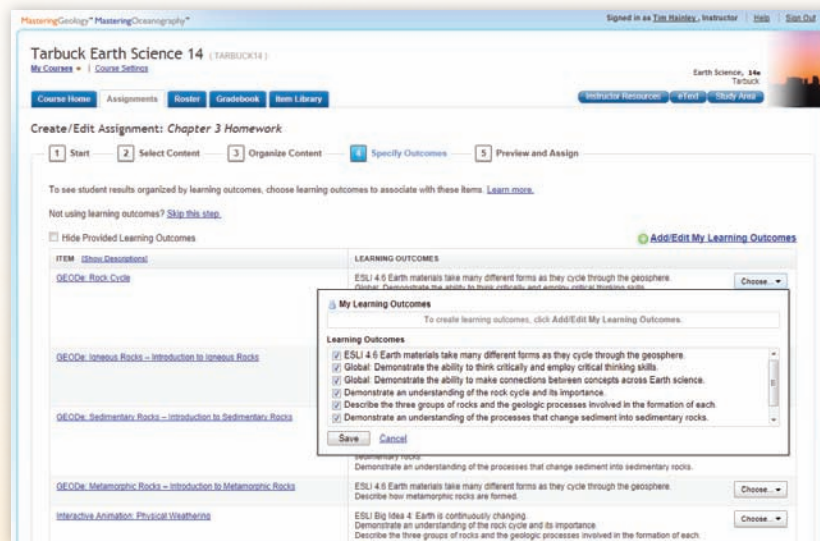
Easily measure student performance against learning outcomes

Learning Outcomes

MasteringGeology provides quick and easy access to information on student performance against learning outcomes and makes it easy for instructors to share those results.

Instructors can:

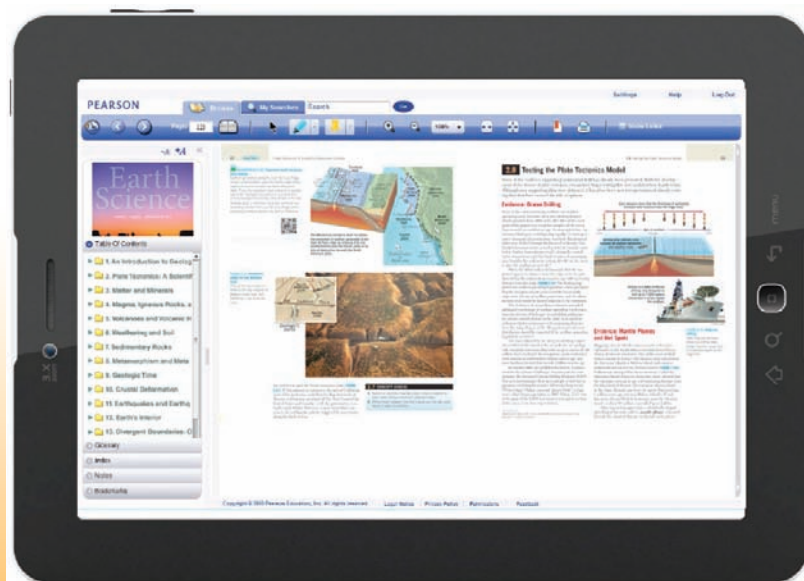
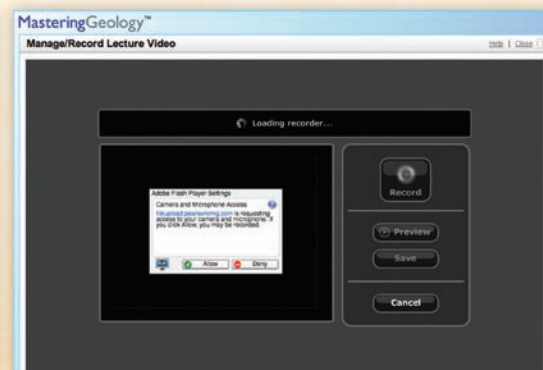
- Quickly add learning outcomes or use publisher-provided ones to track student performance and report it to administration.
- View class and individual student performance against specific learning outcomes.
- Effortlessly export results to a spreadsheet and further customize and/or share with chairs, deans, administrators, and/or accreditation boards.



Easy to Customize

Instructors can customize publisher-provided problems or quickly add their own. MasteringGeology makes it easy for instructors to edit any questions or answers, import their own questions, and quickly add images, links, and files to further enhance the student experience.

Instructors can upload their own video and audio files from their hard drives to share with students, as well as record video from their computer's webcam directly into MasteringGeology—no plug-ins required. Students can download video and audio files to their local computer or launch them in Mastering to view the content.



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1

Introduction to Earth Science

FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

- 1.1** List and describe the sciences that collectively make up Earth science. Discuss the scales of space and time in Earth science.
- 1.2** Discuss the nature of scientific inquiry and distinguish between a hypothesis and a theory.
- 1.3** Outline the stages in the formation of our solar system.
- 1.4** List and describe Earth's four major spheres.
- 1.5** Label a diagram that shows Earth's internal structure. Briefly explain why the geosphere can be described as being mobile.
- 1.6** List and describe the major features of the continents and ocean basins.
- 1.7** Define *system* and explain why Earth is considered to be a system.

An afternoon rainstorm near Muddy Creek in southern Utah.

(Photo by Michael Collier)

The spectacular eruption of a volcano, the magnificent scenery of a rocky coast, and the destruction created by a hurricane are all subjects for an Earth scientist. The study of Earth science deals with many fascinating and practical questions about our environment. What forces produce mountains? Why is our daily weather variable? Is climate really changing? How old is Earth, and how is our planet related to the

other planets in the solar system? What causes ocean tides? What was the Ice Age like? Will there be another? Can a successful well be located at a particular site?

The subject of this text is *Earth science*. To understand Earth is not an easy task because our planet is not a static and unchanging mass. Rather, it is a dynamic body with many interacting parts and a long and complex history.

1.1 WHAT IS EARTH SCIENCE? List and describe the sciences that collectively make up Earth science. Discuss the scales of space and time in Earth science.

Earth science is the name for all the sciences that collectively seek to understand Earth and its neighbors in space. It includes geology, oceanography, meteorology, and astronomy. Understanding Earth science is challenging because our planet is a dynamic body with many interacting parts and a complex history. Throughout its long existence, Earth has been changing. In fact, it is changing as you read this page and will continue to do so into the foreseeable future. Sometimes the changes are rapid and violent, as when severe storms, landslides, and volcanic eruptions occur. Conversely, many changes take place so gradually that they go unnoticed during a lifetime. Scales of size and space also vary greatly among the phenomena studied in Earth science.

Earth science is often perceived as science that is performed in the out of doors, and rightly so. A great deal of an Earth scientist's study is based on observations and experiments conducted in the field. But Earth science is also conducted in the laboratory, where, for example, the study of various Earth materials provides insights into many basic processes, and the creation of complex

computer models allows for the simulation of our planet's complicated climate system. Frequently, Earth scientists require an understanding and application of knowledge and principles from physics, chemistry, and biology. Geology, oceanography, meteorology, and astronomy are sciences that seek to expand our knowledge of the natural world and our place in it.

Geology

In this book, Units 1–4 focus on the science of **geology**, a word that literally means “study of Earth.” Geology is traditionally divided into two broad areas: physical and historical.

Physical geology examines the materials composing Earth and seeks to understand the many processes that operate beneath and upon its surface (**FIGURE 1.1**). Earth is a dynamic, ever-changing planet. Internal forces create earthquakes, build mountains, and produce volcanic structures. At the surface, external processes break rock apart and sculpt a broad array of landforms. The erosional



Mobile Field Trip 1.1 Internal and External

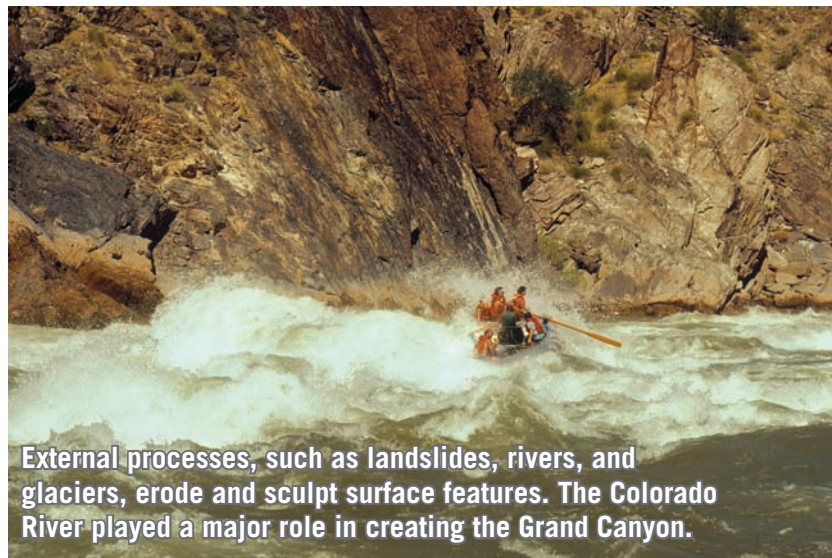
Processes The processes that operate beneath and upon Earth's surface are an important focus of physical geology.

(Volcano photo by Lucas

Jackson/
Reuters;
glacier
photo by
Michael
Collier)



Internal processes are those that occur beneath Earth's surface. Sometimes they lead to the formation of major features at the surface.



External processes, such as landslides, rivers, and glaciers, erode and sculpt surface features. The Colorado River played a major role in creating the Grand Canyon.

effects of water, wind, and ice result in a great diversity of landscapes. Because rocks and minerals form in response to Earth's internal and external processes, their interpretation is basic to an understanding of our planet.

In contrast to physical geology, the aim of *historical geology* is to understand the origin of Earth and the development of the planet through its 4.6-billion-year history. It strives to establish an orderly chronological arrangement of the multitude of physical and biological changes that have occurred in the geologic past. The study of physical geology logically precedes the study of Earth history because we must first understand how Earth works before we attempt to unravel its past.

Oceanography

Earth is often called the “water planet” or the “blue planet.” Such terms relate to the fact that more than 70 percent of Earth's surface is covered by the global ocean. If we are to understand Earth, we must learn about its oceans. Unit 5, *The Global Ocean*, is devoted to **oceanography**. Oceanography is actually not a separate and distinct science. Rather, it involves the application of all sciences in a comprehensive and interrelated study of the oceans in all their aspects and relationships. Oceanography integrates chemistry, physics, geology, and biology. It includes the study of the composition and movements of seawater, as well as coastal processes, seafloor topography, and marine life.

Meteorology

The continents and oceans are surrounded by an atmosphere. Unit 6, *Earth's Dynamic Atmosphere*, examines the mixture of gases that is held to the planet by gravity and thins rapidly with altitude. Acted on by the combined effects of Earth's motions and energy from the Sun, and influenced by Earth's land and sea surface, the formless and invisible atmosphere reacts by producing an infinite variety of weather, which in turn creates the basic pattern of global climates. **Meteorology** is the study of the atmosphere and the processes that produce weather and climate. Like oceanography, meteorology involves the application of other sciences in an integrated study of the thin layer of air that surrounds Earth.

Astronomy

Unit 7, *Earth's Place in the Universe*, demonstrates that an understanding of Earth requires that we relate our planet to the larger universe. Because Earth is related to all the other objects in space, the science of **astronomy**—the study of the universe—is very useful in

probing the origins of our own environment. Because we are so closely acquainted with the planet on which we live, it is easy to forget that Earth is just a tiny object in a vast universe. Indeed, Earth is subject to the same physical laws that govern the many other objects populating the great expanses of space. Thus, to understand explanations of our planet's origin, it is useful to learn something about the other members of our solar system. Moreover, it is helpful to view the solar system as a part of the great assemblage of stars that comprise our galaxy, which is but one of many galaxies.

Earth Science Is Environmental Science

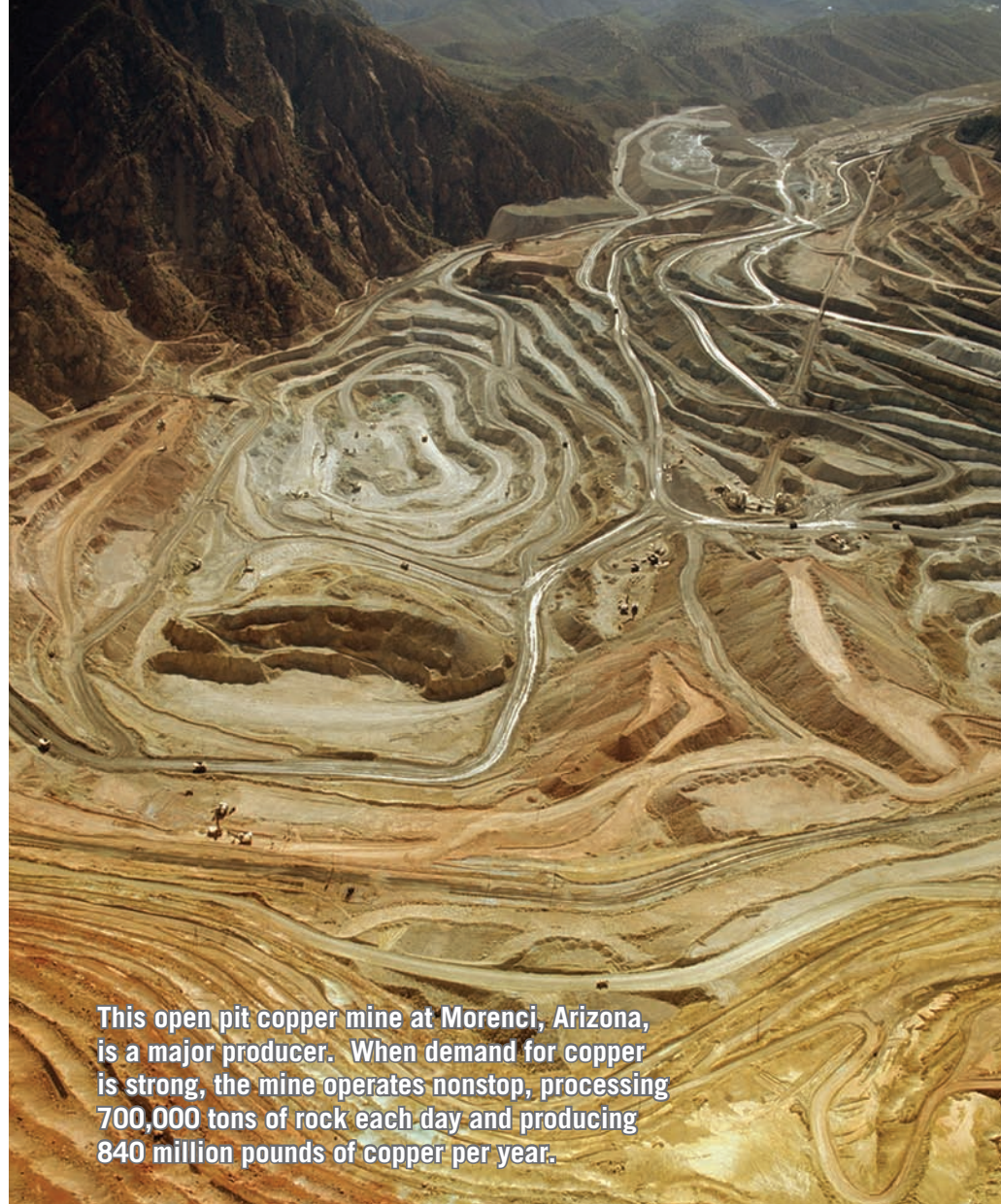
Earth science is an environmental science that explores many important relationships between people and the natural environment. Many of the problems and issues addressed by Earth science are of practical value to people.

Natural Hazards Natural hazards are a part of living on Earth. Every day they adversely affect literally millions of people worldwide and are responsible for staggering damages. Among the hazardous Earth processes studied by Earth scientists are volcanoes, floods, tsunamis, earthquakes, landslides, and hurricanes. Of course, these hazards are *natural* processes. They become hazards only when people try to live where these processes occur.

For most of history, most people lived in rural areas. According to the United Nations, that changed in 2008, and today more people live in cities than in rural areas. This global trend toward urbanization concentrates millions of people into megacities, many of which are vulnerable to natural hazards (**FIGURE 1.2**). Coastal sites are becoming more vulnerable because development often destroys

FIGURE 1.2 Hurricane Sandy A portion of the New Jersey shoreline shortly after this huge storm struck in late October 2012. The storm was especially destructive because it struck a region with a high population density and extensive development. Shifting shoreline sands and the desire of people to occupy these areas are often in conflict. (Photo by AP Photo/Mike Groll)





This open pit copper mine at Morenci, Arizona, is a major producer. When demand for copper is strong, the mine operates nonstop, processing 700,000 tons of rock each day and producing 840 million pounds of copper per year.

FIGURE 1.3 Copper Mine Resources represent an important link between people and Earth science. (Photo by Michael Collier)

FIGURE 1.4 Urban Air Pollution

A severe air pollution episode at Beijing, China, on March 18, 2008. Fuel combustion by factories, power plants, and motor vehicles provided a high proportion of the pollutants. Meteorological factors determine whether pollutants remain trapped in the city or are dispersed. (Photo by AP Photo/Ng Han)



natural defenses such as wetlands and sand dunes. In addition, there is a growing threat associated with human influences on the Earth system such as sea level rise that is linked to global climate change.¹ Other megacities are exposed to seismic (earthquake) and volcanic hazards where inappropriate land use and poor construction practices, coupled with rapid population growth, are increasing vulnerability.

Resources Resources represent another important focus that is of great practical value to people. They include water and soil, a great variety of metallic and nonmetallic minerals, and energy (FIGURE 1.3). Together they form the very foundation of modern civilization. Earth science deals with the formation and occurrence of these vital resources and also with maintaining supplies and with the environmental impact of their extraction and use.

People Influence Earth Processes Not only do Earth processes have an impact on people, but we humans can dramatically influence Earth processes as well. Human activities alter the composition of the atmosphere that trigger air pollution episodes and cause global climate change (FIGURE 1.4). River flooding is natural, but the magnitude and frequency of flooding can be changed significantly by human activities such as clearing forests, building cities, and constructing dams. Unfortunately, natural systems do not always adjust to artificial changes in ways that we can anticipate. Thus, an alteration to the environment that was intended to benefit society often has the opposite effect.

At various places throughout this book, you will have opportunities to examine different aspects of our relationship with the physical environment. It will be rare to find

¹The idea of the Earth system is explored later in the chapter. Global climate change and its effects are a focus of Chapter 20.

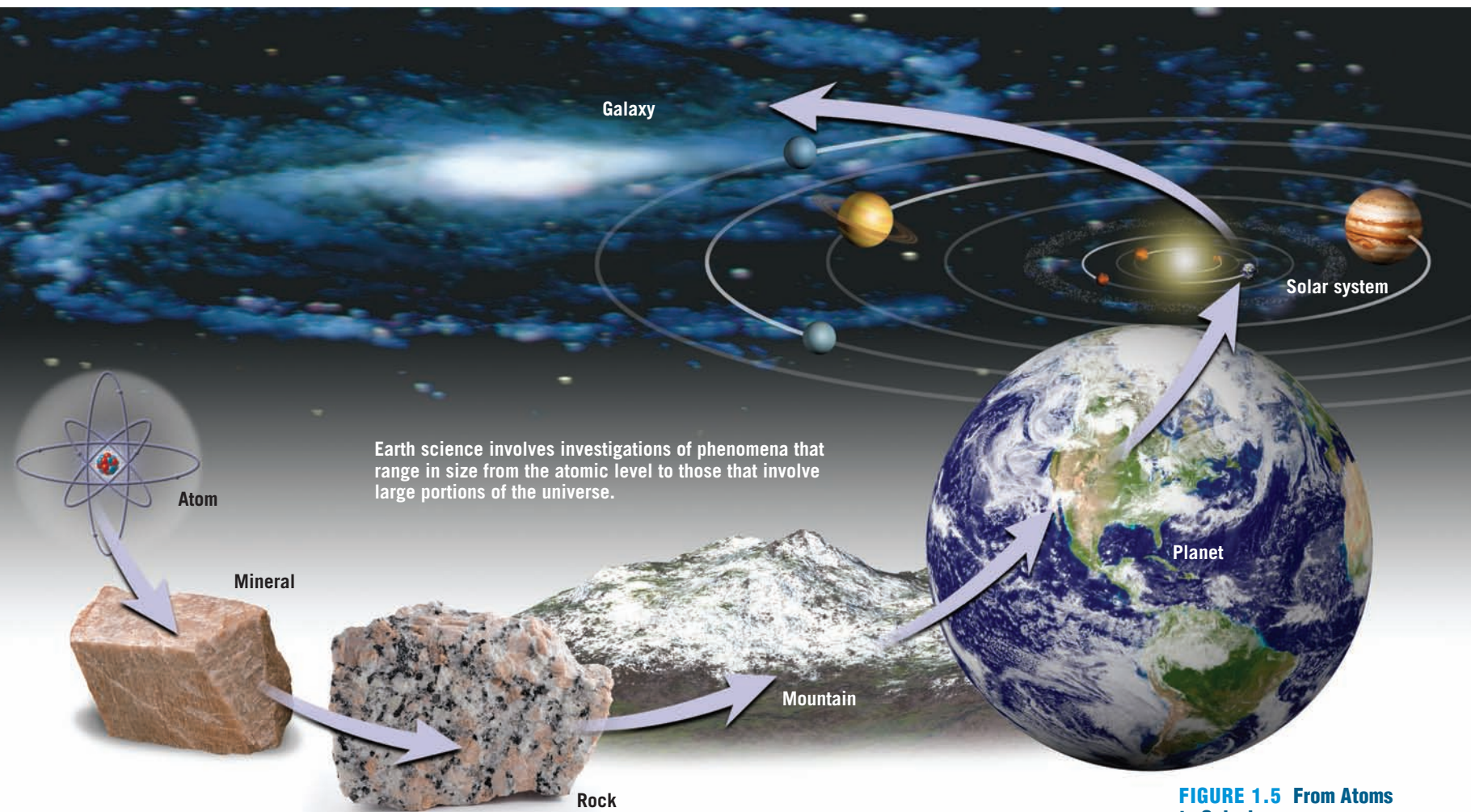


FIGURE 1.5 From Atoms to Galaxies Earth science studies phenomena on many different scales.

a chapter that does not address some aspect of natural hazards, environmental issues, or resources. Significant parts of some chapters provide the basic knowledge and principles needed to understand environmental problems.

Scales of Space and Time in Earth Science

When we study Earth, we must contend with a broad array of space and time scales (**FIGURE 1.5**). Some phenomena are relatively easy for us to imagine, such as the size and duration of an afternoon thunderstorm or the dimensions of a sand dune. Other phenomena are so vast or so small that they are difficult to imagine. The number of stars and distances in our galaxy (and beyond!) or the internal arrangement of atoms in a mineral crystal are examples of such phenomena.

Some of the events we study occur in fractions of a second. Lightning is an example. Other processes extend over spans of tens or hundreds of millions of years. For example, the lofty Himalaya Mountains began forming nearly 50 million years ago, and they continue to develop today.

The concept of **geologic time**, the span of time since the formation of Earth, is new to many nonscientists. People are accustomed to dealing with increments of time that are measured in hours, days, weeks, and years. Our history books often examine events over spans of centuries, but even a century is difficult to appreciate fully. For most of us, someone or something that is 90 years old is *very old*, and a 1000-year-old artifact is *ancient*.

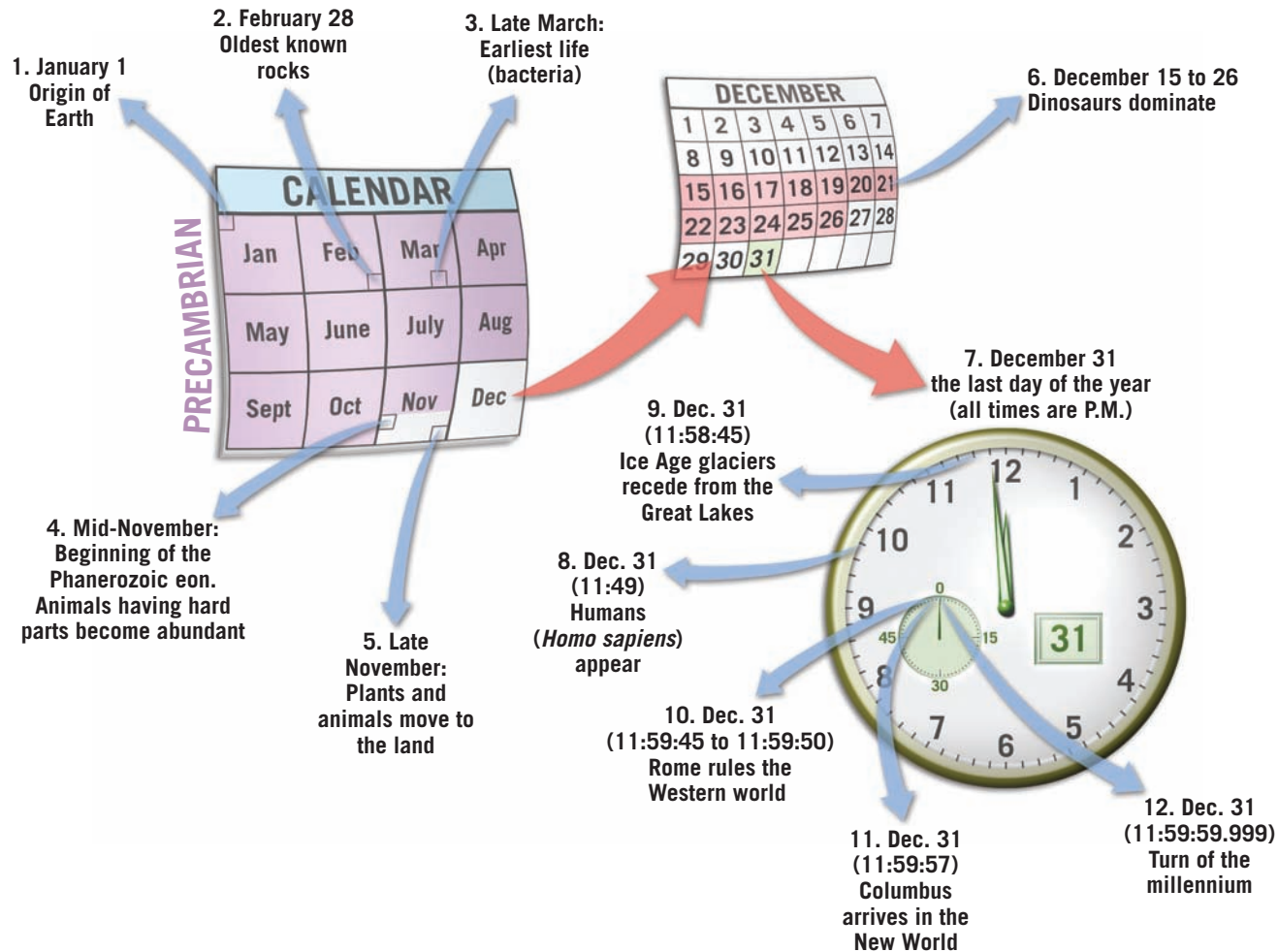
Those who study Earth science must routinely deal with vast time periods—millions or billions (thousands of millions) of years. When viewed in the context of Earth's 4.6-billion-year history, an event that occurred 100 million years ago may be characterized as “recent” by a geologist, and a rock sample that has been dated at 10 million years may be called “young.”

An appreciation for the magnitude of geologic time is important in the study of our planet because many processes are so gradual that vast spans of time are needed before significant changes occur. How long is 4.6 billion years? If you were to begin counting at the rate of one number per second and continued 24 hours a day, seven

SmartFigure 1.6
Magnitude of Geologic Time



What if we compress the 4.6 billion years of Earth history into a single year?



days a week and never stopped, it would take about two lifetimes (150 years) to reach 4.6 billion!

The preceding analogy is just one of many that have been conceived in an attempt to convey the magnitude of geologic time. Although helpful, all of them, no matter how clever, only begin to help us comprehend the vast expanse of Earth history. **FIGURE 1.6** provides another interesting way of viewing the age of Earth.

Over the past 200 years or so, Earth scientists have developed the *geologic time scale* of Earth history. It divides the 4.6-billion-year history of Earth into many different units and provides a meaningful time frame within which the events of the geologic past are arranged (see Figure 11.24, page 364). The principles used to develop the geologic time scale are examined in some detail in Chapter 11.

1.1 CONCEPT CHECKS

- 1 List and briefly describe the sciences that collectively make up Earth science.
- 2 Name the two broad subdivisions of geology and distinguish between them.
- 3 List at least four different natural hazards.
- 4 Aside from natural hazards, describe another important connection between people and Earth science.
- 5 List two examples of size/space scales in Earth science that are at opposite ends of the spectrum.
- 6 How old is Earth?
- 7 If you compress geologic time into a single year, how much time has elapsed since Columbus arrived in the New World?

1.2 THE NATURE OF SCIENTIFIC INQUIRY Discuss the nature of scientific inquiry and distinguish between a hypothesis and a theory.

As members of a modern society, we are constantly reminded of the benefits derived from science. But what exactly is the nature of scientific inquiry? Developing an understanding of how science is done and how scientists work is another important theme that appears throughout this book. You will explore the difficulties in gathering data and some of the ingenious methods that have been developed to overcome these difficulties. You will also see many examples of how hypotheses are formulated and tested, as well as learn about the evolution and development of some major scientific theories.

All science is based on the assumption that the natural world behaves in a consistent and predictable manner that is comprehensible through careful, systematic study. The overall goal of science is to discover the underlying patterns in nature and then to use this knowledge to make predictions about what should or should not be expected, given certain facts or circumstances. For example, by understanding the processes that produce certain cloud types, meteorologists are often able to predict the approximate time and place of their formation.

The development of new scientific knowledge involves some basic logical processes that are universally accepted. To determine what is occurring in the natural world, scientists collect scientific facts through observation and measurement (FIGURE 1.7). The types of facts or data that are collected generally seek to answer a well-defined question about the natural world. Because some error is inevitable, the accuracy of a particular measurement or observation is always open to question. Nevertheless, these data are essential to science and serve as the springboard for the development of scientific hypotheses and theories.

Hypothesis

Once facts have been gathered and principles have been formulated to describe a natural phenomenon, investigators try to explain how or why things happened in the manner observed. They often do this by constructing a tentative (or untested) explanation, which is called a scientific **hypothesis**. It is best if an investigator can formulate more than one hypothesis to explain a given set of observations. If an individual scientist is unable to devise multiple hypotheses, others in the scientific community will almost always develop alternative explanations. A spirited debate frequently ensues. As a result, extensive research is conducted by proponents of opposing hypotheses, and the results are made available to the wider scientific community in scientific journals.

This paleontologist is collecting fossils in Antarctica. Later, a detailed analysis will occur in the lab.



This Automated Surface Observing System (ASOS) installation is one of nearly 900 in use for data gathering as part of the U.S. primary surface observing network.



FIGURE 1.7 Observation and Measurement Gathering data and making careful observations are basic parts of scientific inquiry. (Instrument photo by Bobbé Christopherson; paleontologist photo by British Antarctic Survey/Science Source)

Before a hypothesis can become an accepted part of scientific knowledge, it must pass objective testing and analysis. If a hypothesis cannot be tested, it is not scientifically useful, no matter how interesting it might seem. The verification process requires that *predictions* be made based on the hypothesis being considered and that the predictions be tested by comparing them against objective observations of nature. Put another way, hypotheses must fit observations other than those used to formulate them in the first place. Hypotheses that fail rigorous testing are ultimately discarded. The history of science is littered with discarded hypotheses. One of the best known is the Earth-centered model of the universe—a proposal that was supported by the apparent daily motion of the Sun, Moon, and stars around Earth. As the mathematician Jacob Bronowski so ably stated, “Science is a great many things, but in the end they all return to this: Science is the acceptance of what works and the rejection of what does not.”