

FOURTEENTH EDITION

GLOBAL EDITION

Earth Science



Edward J. Tarbuck
Frederick K. Lutgens

Illustrated by
Dennis Tasa

PEARSON

Boston Columbus Indianapolis
New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London
Madrid Munich Paris Montréal Toronto
Delhi Mexico City São Paulo Sydney
Hong Kong Seoul Singapore Taipei Tokyo

BRIEF CONTENTS

1 Introduction to Earth Science 23

UNIT ONE | EARTH MATERIALS 52

2 Matter and Minerals 53

3 Rocks: Materials of the Solid Earth 79

UNIT TWO | SCULPTING EARTH'S SURFACE 114

4 Weathering, Soil, and Mass Wasting 115

5 Running Water and Groundwater 151

6 Glaciers, Deserts, and Wind 191

UNIT THREE | FORCES WITHIN 228

7 Plate Tectonics: A Scientific Revolution Unfolds 229

8 Earthquakes and Earth's Interior 265

9 Volcanoes and Other Igneous Activity 297

10 Crustal Deformation and Mountain Building 337

UNIT FOUR | DECIPHERING EARTH'S HISTORY 366

11 Geologic Time 367

12 Earth's Evolution Through Geologic Time 393

UNIT FIVE | THE GLOBAL OCEAN 428

13 The Ocean Floor 429

14 Ocean Water and Ocean Life 453

15 The Dynamic Ocean 473

UNIT SIX | EARTH'S DYNAMIC ATMOSPHERE 504

16 The Atmosphere: Composition, Structure, and Temperature 505

17 Moisture, Clouds, and Precipitation 537

18 Air Pressure and Wind 571

19 Weather Patterns and Severe Storms 597

20 World Climates and Global Climate Change 627

UNIT SEVEN | EARTH'S PLACE IN THE UNIVERSE 658

21 Origins of Modern Astronomy 659

22 Touring Our Solar System 683

23 Light, Astronomical Observations, and the Sun 715

24 Beyond Our Solar System 739

FIND SMART FIGURES AND MOBILE FIELD TRIP FIGURES

In addition to the many informative and colorful illustrations and photos throughout this text, you will find two kinds of special figures that offer additional learning opportunities. These figures contain QR codes which the student can scan with a smart phone to explore exciting expanded online learning materials.



Find **SmartFigures** where you see this icon.



Find **Mobile Field Trip Figures** where you see this icon.

Chapter 1

- 1.1** Internal and External Processes (p. 24)
- 1.6** Magnitude of Geologic Time (p. 28)
- 1.8** Nebular Theory (p. 33)
- 1.15** Earth's Layers (p. 39)
- 1.21** The Continents (p. 44)

Chapter 2

- 2.3** Most Rocks Are Aggregates of Minerals (p. 55)
- 2.12** Color Variations in Minerals (p. 63)
- 2.15** Common Crystal Habits (p. 64)
- 2.16** Hardness Scales (p. 64)
- 2.18** Cleavage Directions Exhibited by Minerals (p. 65)

Chapter 3

- 3.1** The Rock Cycle (p. 81)
- 3.4** Composition of Common Igneous Rocks (p. 84)
- 3.5** Igneous Rock Textures (p. 85)
- 3.7** Classifications of Igneous Rocks, Based on Their Mineral Composition and Texture (p. 87)
- 3.14** Sedimentary Rocks Exposed in Capitol Reef National Park, Utah (p. 91)
- 3.20** Bonneville Salt Flats (p. 95)
- 3.21** From Plants to Coal (p. 96)
- 3.25** Metamorphic Rocks in the Adirondacks, New York. (p. 98)
- 3.27** Confining Pressure and Differential Stress (p. 100)
- 3.35** Common Oil Traps (p. 108)

Chapter 4

- 4.1** Excavating the Grand Canyon (p. 116)
- 4.3** Mechanical Weathering Increases Surface Area (p. 119)
- 4.5** Ice Breaks Rock (p. 119)
- 4.6** Unloading Leads to Sheeting (p. 120)
- 4.8** The Formation of Rounded Boulders (p. 123)
- 4.9** Rock Types Influences Weathering (p. 124)
- 4.11** Monuments to Weathering (p. 125)
- 4.32** Gros Vestre Rockslide (p. 141)
- 4.34** Creep (p. 143)

Chapter 5

- 5.2** The Hydrologic Cycle (p. 153)
- 5.4** Mississippi River Drainage Basin (p. 154)

- 5.9** Channel Changes from Head to Mouth (p. 157)
- 5.13** Formation of Cut Banks and Point Bars (p. 162)
- 5.20** Incised Meanders (p. 166)
- 5.25** Broken Levee (p. 171)
- 5.32** Cone of Depression (p. 177)
- 5.33** Artesian Systems (p. 177)

Chapter 6

- 6.4** Movement of a Glacier (p. 195)
- 6.7** Zones of a Glacier (p. 198)
- 6.11** Glacial Abrasion (p. 200)
- 6.12** Erosional Landforms Created by Alpine Glaciers (p. 201)
- 6.20** Common Depositional Landforms (p. 206)
- 6.27** Orbital Variations (p. 211)
- 6.30** Dry Climates (p. 213)
- 6.32** Landscape Evolution in the Basin and Range Region (p. 215)
- 6.38** White Sands National Monument (p. 219)
- 6.39** Cross Bedding (p. 220)
- 6.40** Types of Sand Dunes (p. 221)

Chapter 7

- 7.2** Reconstructions of Pangaea (p. 231)
- 7.10** Rigid Lithosphere Overlies the Weak Asthenosphere (p. 236)
- 7.15** Continental Rifting (p. 240)
- 7.17** Three Types of Convergent Plate Boundaries (p. 242)
- 7.21** Transform Plate Boundaries (p. 245)
- 7.23** Movement along the San Andreas Fault (p. 246)
- 7.31** Time Scale of Magnetic Reversals (p. 253)

Chapter 8

- 8.5** Elastic Rebound (p. 268)
- 8.10** Body Waves (P and S waves) versus Surface Waves (p. 271)
- 8.23** Turnagain Heights Slide (p. 278)
- 8.31** Seismic Gaps: Tools for Forecasting Earthquakes (p. 285)

Chapter 9

- 9.10** Anatomy of a Volcano (p. 306)
- 9.12** Cinder Cone (p. 310)
- 9.20** Super-Eruptions at Yellowstone (p. 318)
- 9.25** Sill Exposed in Utah's Sinbad Country (p. 322)
- 9.33** Earth's Zones of Volcanism (p. 328)
- 9.34** Subduction of the Juan Fuca Plate Produced the Cascade Volcanoes (p. 330)

Chapter 10

- 10.1** Deformed Sedimentary Strata (p. 338)
- 10.6** Common Types of Folds (p. 342)
- 10.7** Sheep Mountain Wyoming (p. 343)
- 10.8** Domes Versus Basins (p. 343)
- 10.15** Normal Dip-Slip Fault (p. 346)
- 10.16** Normal Faulting in the Basin and Range Province (p. 346)
- 10.26** Collision and Accretion of Small Crustal Fragments to a Continental Margin (p. 353)

- 10.29** India's Continued Northward Migration Severely Deformed Much of China and Southeast Asia (p. 355)
- 10.30** Formation of the Appalachian Mountains (p. 356)
- 10.31** The Valley and Ridge Province (p. 357)
- 10.33** The Effects of Isostatic Adjustment and Erosion on Mountainous Topography (p. 360)

Chapter 11

- 11.7** Inclusions (p. 372)
- 11.8** Formation of an Angular Unconformity (p. 372)
- 11.13** Applying Principles (p. 375)
- 11.18** Fossil Assemblage (p. 380)
- 11.21** Radioactive Decay Curve (p. 382)

Chapter 12

- 12.4** Major Events That Led to the Formation of Early Earth (p. 398)
- 12.10** Growth of Large Continental Masses Through the Collision and Accretion of Smaller Crustal Fragments (p. 403)
- 12.12** The Major Geologic Provinces of North America and Their Ages in Billions of Years (Ga) (p. 404)
- 12.16** Connection Between Oceans Circulation and the Climate in Antarctica (p. 406)
- 12.28** Relationships of Vertebrate Groups and Their Divergence from Lobefin Fish (p. 415)

Chapter 13

- 13.2** Distribution of Land and Water (p. 431)
- 13.6** Satellite Altimeter (p. 433)
- 13.12** Active Continental Margins (p. 438)
- 13.19** Examples of Hydrogenous Sediment (p. 445)

Chapter 14

- 14.2** Variations in Surface Temperature and Salinity with Latitude (p. 455)
- 14.8** Variations in Ocean-Water Density with Depth for Low- and High-Latitude Regions (p. 458)
- 14.12** Benthos (p. 461)
- 14.16** Productivity in Temperate Oceans (Northern Hemisphere) (p. 466)
- 14.19** Ecosystem Energy Flow and Efficiency (p. 468)

Chapter 15

- 15.2** Major Surface-Ocean Currents (p. 475)
- 15.5** Coastal Upwelling (p. 477)
- 15.12** Passage of a Wave (p. 482)
- 15.16** Wave Refraction (p. 484)
- 15.17** The Longshore Transport System (p. 485)
- 15.21** Some Depositional Features (p. 487)
- 15.31** East Coast Estuaries (p. 496)
- 15.35** Tidal Patterns (p. 498)

Chapter 16

- 16.5** Monthly CO₂ Concentrations (p. 509)
- 16.7** Antarctic Ozone Hole (p. 510)
- 16.12** The Changing Sun Angle (p. 515)
- 16.16** Characteristics of the Solstices and Equinoxes (p. 517)
- 16.19** The Three Mechanisms of Heat Transfer (p. 520)
- 16.21** Paths Taken by Solar Radiation (p. 523)
- 16.24** The Greenhouse Effect (p. 524)
- 16.26** Isotherms (p. 526)
- 16.28** Monthly Mean Temperatures for Vancouver, British Columbia, and Winnipeg Manitoba (p. 527)
- 16.32** The Daily Cycle of Temperature at Peoria, Illinois, for Two July Days (p. 529)
- 16.34** World Mean Sea-Level Temperatures in July, in Celsius (°C) and Fahrenheit (°F) (p. 531)

Chapter 17

- 17.2** Changes of State Involve an Exchange of Heat (p. 539)
- 17.8** Map Showing Dew-Point Temperatures on a Typical September Day (p. 543)
- 17.13** Surface Convergence Enhances Cloud Development (p. 547)
- 17.17** Atmospheric Conditions That Result in Absolute Stability (p. 549)
- 17.20** Classification of Clouds, Based on Height and Form (p. 552)
- 17.25** Map Showing the Average Number of Days per Year with Heavy Fog (p. 557)
- 17.30** Formation of Hailstones (p. 561)

Chapter 18

- 18.2** Inches and Millibars (p. 573)
- 18.7** Isobars on a Weather Map (p. 575)
- 18.8** Coriolis Effect (p. 576)
- 18.17** Idealized Global Circulation Proposed for the Three-Cell Circulation Model of a Rotating Earth (p. 581)
- 18.19** Sea and Land Breezes (p. 583)

Chapter 19

- 19.4** Snowfall Map (p. 600)
- 19.8** Cold Front (p. 602)
- 19.11** Idealized Structure of a Large, Mature Midlatitude Cyclone (p. 604)
- 19.19** Thunderstorm Development (p. 609)
- 19.23** The Formation of a Mesocyclone Often Precedes Tornado Formation (p. 611)

Chapter 20

- 20.6** Tropical Rain Forest (p. 633)
- 20.16** Examples of E Climates (p. 641)
- 20.17** Highland Climate (p. 642)
- 20.28** Slope of the Shoreline (p. 652)

Chapter 21

- 21.3** Orientation of the Sun's Rays at Syene (Aswan) and Alexandria, Egypt on June 21 (p. 661)
- 21.6** Ptolemy's Explanation of Retrograde Motion (p. 663)
- 21.15** Using a Telescope, Galileo Discovered That Versus Has Phases Like Earth's Moon (p. 667)
- 21.17** Orbital Motion of Earth and Other Planets (p. 669)
- 21.20** Locating the North Star (Polaris) from the Pointer Stars in the Big Dipper (p. 673)
- 21.23** Precession of Earth's Axis (p. 675)
- 21.25** Phases of the Moon (p. 676)
- 21.27** Lunar Eclipse (p. 678)

Chapter 22

- 22.1** Orbits of the Planets (p. 684)
- 22.3** Bodies with Atmospheres Versus Airless Bodies (p. 687)
- 22.7** Formation and Filling of Large Impact Basins (p. 690)
- 22.14** Olympus Mons (p. 695)
- 22.33** Meteor Crater, Near Winslow, Arizona (p. 708)

Chapter 23

- 23.3** Formation of the Three Types of Spectra (p. 717)
- 23.6** The Doppler Effect (p. 720)
- 23.11** Reflecting Telescope (p. 722)
- 23.20** Diagram of the Sun's Structure (p. 728)

Chapter 24

- 24.8** Hertzsprung–Russell Diagram (p. 745)
- 24.10** Evolutionary Stages of Stars Having Various Masses (p. 748)
- 24.16** Spiral Galaxies (p. 754)
- 24.22** Raisin Bread Analogy for an Expanding Universe (p. 757)

CONTENTS

1 Introduction to Earth Science 23

FOCUS ON CONCEPTS 23

What Is Earth Science? 24

- Geology 24
- Oceanography 25
- Meteorology 25
- Astronomy 25
- Earth Science Is Environmental Science 25
- Scales of Space and Time in Earth Science 27

The Nature of Scientific Inquiry 29

- Hypothesis 29

GEO GRAPHICS | World Population Passes 7 Billion 30

- Theory 30
- Scientific Methods 30

EYE ON EARTH 31

Early Evolution of Earth 32

- Origin of Planet Earth 32
- The Inner Planets Form 33
- The Outer Planets Develop 34

Earth's Spheres 34

GEO GRAPHICS | Solar System: Size and Scale 35

- Hydrosphere 36
- Atmosphere 36
- Biosphere 37

EYE ON EARTH 37

- Geosphere 38

A Closer Look at the Geosphere 38

- Earth's Internal Structure 38
- The Mobile Geosphere 40

The Face of Earth 42

- Major Features of the Continents 43
- Major Features of the Ocean Basins 45

EYE ON EARTH 45

Earth as a System 46

- Earth System Science 46
- The Earth System 47

Concepts in Review 48 | Give It Some Thought 49 |

UNIT ONE | EARTH MATERIALS 52

2 Matter and Minerals 53

FOCUS ON CONCEPTS 53

Minerals: Building Blocks of Rock 54

- Defining a Mineral 54
- What Is a Rock? 55

Atoms: Building Blocks of Minerals 56

- Properties of Protons, Neutrons, and Electrons 56
- Elements: Defined by Their Number of Protons 56

GEO GRAPHICS | Gold 58

Why Atoms Bond 60

- The Octet Rule and Chemical Bonds 60
- Ionic Bonds: Electrons Transferred 60
- Covalent Bonds: Electron Sharing 60
- Metallic Bonds: Electrons Free to Move 61

EYE ON EARTH 62

Properties of a Mineral 62

- Optical Properties 62
- Crystal Shape, or Habit 63
- Mineral Strength 64
- Density and Specific Gravity 66
- Other Properties of Minerals 66

Mineral Groups 66

- Silicate Minerals 67

EYE ON EARTH 67

- Important Nonsilicate Minerals 70

Natural Resources 72

- Renewable Versus Nonrenewable Resources 72
- Mineral Resources 72

GEO GRAPHICS | Gemstones 74

Concepts in Review 75 | Give It Some Thought 76 |

3 Rocks: Materials of the Solid Earth 79

FOCUS ON CONCEPTS 79

Earth as a System: The Rock Cycle 80

- The Basic Cycle 80
- Alternative Paths 80

Igneous Rocks: "Formed by Fire" 82

- From Magma to Crystalline Rock 82
- Igneous Compositions 83
- What Can Igneous Textures Tell Us? 84
- Common Igneous Rocks 86
- How Different Igneous Rocks Form 89

EYE ON EARTH 89

Sedimentary Rocks: Compacted and Cemented Sediment 91

- Classifying Sedimentary Rocks 92
- Lithification of Sediment 95
- Features of Sedimentary Rocks 96

Metamorphic Rocks: New Rock from Old 98

- What Drives Metamorphism? 98



EYE ON EARTH 99

Metamorphic Textures 101
Common Metamorphic Rocks 101

Resources from Rocks and Minerals 103

Metallic Mineral Resources 103

GEO GRAPHICS | Marble 104

Nonmetallic Mineral Resources 107
Energy Resources: Fossil Fuels 107

EYE ON EARTH 109

Concepts in Review 110 | Give It Some Thought 112 |

UNIT TWO | SCULPTING EARTH'S SURFACE 114

4 Weathering, Soil, and Mass Wasting 115

FOCUS ON CONCEPTS 115

Earth's External Processes 116

Weathering 117

GEO GRAPHICS | Some Everyday Examples of Weathering 118

Mechanical Weathering 119
Chemical Weathering 121

EYE ON EARTH 121**GEO GRAPHICS | The Old Man of the Mountain 122****Rates of Weathering 124**

Rock Characteristics 124
Climate 124
Differential Weathering 124

Soil 125

An Interface in the Earth System 125
What Is Soil? 126
Soil Texture and Structure 126

Controls of Soil Formation 127

Parent Material 127
Time 127
Climate 128
Plants and Animals 128
Topography 128

The Soil Profile 129**Classifying Soils 130****EYE ON EARTH 131****Soil Erosion: Losing a Vital Resource 132****Mass Wasting: The Work of Gravity 134**

Landslides as Geologic Hazards 134
The Role of Mass Wasting in Landform Development 134
Slopes Change Through Time 134

GEO GRAPHICS | Landslides as Natural Disasters 135**Controls and Triggers of Mass Wasting 136**

The Role of Water 136
Oversteepened Slopes 137
Removal of Vegetation 137
Earthquakes as Triggers 138

Classifying Mass-Wasting Processes 138

Type of Motion 138
Rate of Movement 139

EYE ON EARTH 139**Rapid Forms of Mass Wasting 140**

Slump 140
Rockslide 141
Debris Flow 141
Earthflow 142

Slow Forms of Mass Wasting 142

Creep 142
Solifluction 143

Concepts in Review 144 | Give It Some Thought 147 |

5 Running Water and Groundwater 151

FOCUS ON CONCEPTS 151**Earth as a System: The Hydrologic Cycle 152**

Earth's Water 152
Water's Paths 152
Storage in Glaciers 153
Water Balance 153

Running Water 153

Drainage Basins 154
River Systems 154
Drainage Patterns 155

Streamflow 156

Factors Affecting Flow Velocity 156
Changes from Upstream to Downstream 157

The Work of Running Water 158

Stream Erosion 158

EYE ON EARTH 158**GEO GRAPHICS | What Are the Largest Rivers? 159**

Transportation of Sediment 160
Deposition of Sediment 161

Stream Channels 161

Bedrock Channels 162
Alluvial Channels 162

Shaping Stream Valleys 164

Base Level and Stream Erosion 164
Valley Deepening 164
Valley Widening 165
Changing Base Level and Incised Meanders 165

Depositional Landforms 167

Deltas 167

EYE ON EARTH 167

Natural Levees 168

Alluvial Fans 169

Floods and Flood Control 169

Causes of Floods 169
Flood Control 169

GEO GRAPHICS | Flash Floods 170

Groundwater: Water Beneath the Surface	172
The Importance of Groundwater	172
Groundwater's Geologic Roles	172
Distribution of Groundwater	172
EYE ON EARTH	173
Factors Influencing the Storage and Movement of Groundwater	174
Groundwater Movement	175
Springs, Wells, and Artesian Systems	175
Springs	175
Artesian Systems	177
EYE ON EARTH	178
Environmental Problems of Groundwater	179
Treating Groundwater as a Nonrenewable Resource	179
Land Subsidence Caused by Groundwater Withdrawal	179
Groundwater Contamination	180
The Geologic Work of Groundwater	182
Caverns	182
Karst Topography	183
Concepts in Review	185 Give It Some Thought 187

6 Glaciers, Deserts, and Wind 191

FOCUS ON CONCEPTS 191

Glaciers and the Earth System	192
Glaciers: A Part of Two Basic Cycles	192
Valley (Alpine) Glaciers	192
Ice Sheets	192
Other Types of Glaciers	194
How Glaciers Move	195
Observing and Measuring Movement	195

GEO GRAPHICS | Antarctica Fact File 196

Budget of a Glacier: Accumulation Versus Wastage	198
Glacial Erosion	199
How Glaciers Erode	200
Landforms Created by Glacial Erosion	200
Glacial Deposits	203
Types of Glacial Drift	203
EYE ON EARTH	203
Moraines, Outwash Plains, and Kettles	204
Drumlins, Eskers, and Kames	206
Other Effects of Ice Age Glaciers	207
Changing Rivers	207
Crustal Subsidence and Rebound	207
Proglacial Lakes Created by Ice Dams	208
Sea-Level Changes	208
Pluvial Lakes	209
Extent of Ice Age Glaciation	209
Causes of Ice Ages	210

Plate Tectonics	210
Variations in Earth's Orbit	211
Other Factors	211
Deserts	212
Distribution and Causes of Dry Lands	213
Geologic Processes in Arid Climates	214
Basin and Range: The Evolution of a Mountainous Desert Landscape	215
EYE ON EARTH	216
Wind Erosion	217
Deflation, Blowouts, and Desert Pavement	217
Wind Abrasion	218
Wind Deposits	218
Loess	219
Sand Dunes	219
Types of Sand Dunes	220
EYE ON EARTH	221
Concepts in Review	222 Give It Some Thought 225

UNIT THREE | FORCES WITHIN 228

7 Plate Tectonics: A Scientific Revolution Unfolds 229

FOCUS ON CONCEPTS 229

From Continental Drift to Plate Tectonics	230
Continental Drift: An Idea Before Its Time	231
Evidence: The Continental Jigsaw Puzzle	231
Evidence: Fossils Matching Across the Seas	232
Evidence: Rock Types and Geologic Features	233
Evidence: Ancient Climates	234
The Great Debate	235
Rejection of the Drift Hypothesis	235
The Theory of Plate Tectonics	236
Rigid Lithosphere Overlies Weak Asthenosphere	236
Earth's Major Plates	237
Plate Boundaries	237
Divergent Plate Boundaries and Seafloor Spreading	238
Oceanic Ridges and Seafloor Spreading	239
Continental Rifting	240
Convergent Plate Boundaries and Subduction	241
Oceanic–Continental Convergence	242
Oceanic–Oceanic Convergence	243
Continental–Continental Convergence	244
Transform Plate Boundaries	245
How Do Plates and Plate Boundaries Change?	247
The Breakup of Pangaea	247
EYE ON EARTH	247
Plate Tectonics in the Future	248
Testing the Plate Tectonics Model	249
Evidence: Ocean Drilling	249
Evidence: Mantle Plumes and Hot Spots	250
Evidence: Paleomagnetism	251
How Is Plate Motion Measured	254
Geologic Evidence for Plate Motion	254
Measuring Plate Motion from Space	256
What Drives Plate Motions?	256
Forces That Drive Plate Motion	256
Models of Plate–Mantle Convection	257
EYE ON EARTH	258
Concepts in Review	259 Give It Some Thought 262



8 Earthquakes and Earth's Interior 265

FOCUS ON CONCEPTS 265

What Is an Earthquake? 266

- Discovering the Causes of Earthquakes 267
- Aftershocks and Foreshocks 268
- Faults and Large Earthquakes 269

EYE ON EARTH 269

Seismology: The Study of Earthquake Waves 270

- Instruments That Record Earthquakes 270
- Seismic Waves 271

Determining the Size of Earthquakes 272

- Intensity Scales 272
- Magnitude Scales 273

GEO GRAPHICS | Finding the Epicenter of an Earthquake 275

Earthquake Destruction 276

- Destruction from Seismic Vibrations 276
- Landslides and Ground Subsidence 278
- Fire 278

EYE ON EARTH 278

- What Is a Tsunami? 279

Earthquake Belts and Plate Boundaries 281

GEO GRAPHICS | Historic Earthquakes East of the Rockies 282

Can Earthquakes Be Predicted? 284

- Short-Range Predictions 284
- Long-Range Forecasts 284

GEO GRAPHICS | Seismic Risks on the San Andreas Fault System 286

Earth's Interior 289

- Formation of Earth's Layered Structure 289
- Probing Earth's Interior: "Seeing" Seismic Waves 289

Earth's Layers 290

- Crust 290
- Mantle 291
- Core 291

Concepts in Review 292 | Give It Some Thought 294 |

9 Volcanoes and Other Igneous Activity 297

FOCUS ON CONCEPTS 297

Mount St. Helens Versus Kilauea 298

The Nature of Volcanic Eruptions 299

- Factors Affecting Viscosity 299
- Quiescent Versus Explosive Eruptions 300

Materials Extruded During an Eruption 301

- Lava Flows 301
- Gases 303
- Pyroclastic Materials 303

Anatomy of a Volcano 304

GEO GRAPHICS | Comparison of Three Types of Volcanic Cones 305

Shield Volcanoes 306

- Mauna Loa: Earth's Largest Shield Volcano 306
- Kilauea, Hawaii: Eruption of a Shield Volcano 307

GEO GRAPHICS | Kilauea's East Rift Zone Eruption 308

Cinder Cones 310

Parícutin: Life of a Garden-Variety Cinder Cone 310

Composite Volcanoes 311

GEO GRAPHICS | Eruption of Mount Vesuvius, AD 79 312

Volcanic Hazards 313

- Pyroclastic Flow: A Deadly Force of Nature 314
- Lahars: Mudflows on Active and Inactive Cones 315
- Other Volcanic Hazards 315

Other Volcanic Landforms 317

- Calderas 317
- Fissure Eruptions and Basalt Plateaus 319

EYE ON EARTH 319

- Volcanic Necks and Pipes 320

Intrusive Igneous Activity 321

- Nature of Intrusive Bodies 321

NATURE ON EARTH 321

- Tabular Intrusive Bodies: Dikes and Sills 322
- Massive Intrusive Bodies: Batholiths, Stocks, and Laccoliths 323

Partial Melting and the Origin of Magma 324

- Partial Melting 324
- Generating Magma from Solid Rock 324
- Decrease in Pressure: Decompression Melting 325

Plate Tectonics and Volcanic Activity 326

- Volcanism at Convergent Plate Boundaries 326
- Volcanism at Divergent Plate Boundaries 327
- Intraplate Volcanism 327

Concepts in Review 331 | Give It Some Thought 333 |

10 Crustal Deformation and Mountain Building 337

FOCUS ON CONCEPTS 337

Crustal Deformation 338

- What Causes Rocks to Deform? 338
- Types of Deformation 339
- Factors That Affect Rock Strength 340

Folds: Rock Structures Formed by Ductile Deformation 341

- Anticlines and Synclines 341

EYE ON EARTH 341

- Domes and Basins 342
- Monoclines 343

Faults and Joints: Rock Structures Formed by Brittle Deformation 345

- Dip-Slip Faults 345
- Strike-Slip Faults 346
- Joints 347

Mountain Building 349

Subduction and Mountain Building 350

- Island Arc-Type Mountain Building 350
- Andean-Type Mountain Building 350

EYE ON EARTH 351

- Sierra Nevada, Coast Ranges, and Great Valley 352

Collisional Mountain Belts 352

- Cordilleran-Type Mountain Building 352
- Alpine-Type Mountain Building: Continental Collisions 354
- The Himalayas 354
- The Appalachians 355

What Causes Earth's Varied Topography? 357

GEO GRAPHICS | The Laramide Rockies 358

- The Principle of Isostasy 360
- How High Is Too High? 360

Concepts in Review 361 | Give It Some Thought 363 |

UNIT FOUR | DECIPHERING EARTH'S HISTORY 366

11 Geologic Time 367

FOCUS ON CONCEPTS 367

A Brief History of Geology 368

- Catastrophism 368
- The Birth of Modern Geology 368
- Geology Today 369

Creating a Time Scale: Relative Dating Principles 369

- The Importance of a Time Scale 369
- Numerical and Relative Dates 369
- Principle of Superposition 370
- Principle of Original Horizontality 370
- Principle of Lateral Continuity 371
- Principle of Cross-Cutting Relationships 371

EYE ON EARTH 371

- Principle of Inclusions 372
- Unconformities 372
- Applying Relative Dating Principles 374

EYE ON EARTH 374

Fossils: Evidence of Past Life 375

- Types of Fossils 376

GEO GRAPHICS | How is Paleontology Different from Archaeology? 377

- Conditions Favoring Preservation 378

Correlation of Rock Layers 378

- Correlation Within Limited Areas 378
- Fossils and Correlation 378

Dating with Radioactivity 380

- Reviewing Basic Atomic Structure 381
- Radioactivity 381
- Half-Life 382
- Using Various Isotopes 382
- Dating with Carbon-14 383

The Geologic Time Scale 384

- Structure of the Time Scale 385
- Precambrian Time 385

EYE ON EARTH 385

- Terminology and the Geologic Time Scale 386

Determining Numerical Dates for Sedimentary Strata 386

EYE ON EARTH 387

GEO GRAPHICS | Did Humans and Dinosaurs Ever Coexist? 388

Concepts in Review 389 | Give It Some Thought 410

12 Earth's Evolution Through Geologic Time 393

FOCUS ON CONCEPTS 393

Is Earth Unique? 394

- The Right Planet 394
- The Right Location 395
- The Right Time 395
- Viewing Earth's History 395

Birth of a Planet 397

- From the Big Bang to Heavy Elements 397
- From Planetesimals to Protoplanets 397
- Earth's Early Evolution 397

Origin and Evolution of the Atmosphere and Oceans 399

- Earth's Primitive Atmosphere 399
- Oxygen in the Atmosphere 399
- Evolution of the Oceans 400

Precambrian History: The Formation of Earth's Continents 401

- Earth's First Continents 401

EYE ON EARTH 401

- The Making of North America 404
- Supercontinents of the Precambrian 404

Geologic History of the Phanerozoic: The Formation of Earth's Modern Continents 406

- Paleozoic History 406
- Mesozoic History 407
- Cenozoic History 409

Earth's First Life 410

- Origin of Life 410
- Earth's First Life: Prokaryotes 410

Paleozoic Era: Life Explodes 411

- Early Paleozoic Life-Forms 411

GEO GRAPHICS | Evolution of Life Through Geologic Time 412

EYE ON EARTH 413

- Vertebrates Move to Land 414
- Reptiles: The First True Terrestrial Vertebrates 414
- The Great Permian Extinction 415

GEO GRAPHICS | Demise of the Dinosaurs 416

Mesozoic Era: Age of the Dinosaurs 418

- Gymnosperms: The Dominant Mesozoic Trees 418
- Reptiles: Dominating the Land, Sea, and Sky 418

Cenozoic Era: Age of Mammals 420

- From Reptiles to Mammals 420
- Marsupial and Placental Mammals 420
- Humans: Mammals with Large Brains and Bipedal Locomotion 421
- Large Mammals and Extinction 421

Concepts in Review 423 | Give It Some Thought 425 |

UNIT FIVE | THE GLOBAL OCEAN 428

13 The Ocean Floor 429

FOCUS ON CONCEPTS 429

The Vast World Ocean 430

- Geography of the Oceans 430
- Comparing the Oceans to the Continents 431

An Emerging Picture of the Ocean Floor 431

- Mapping the Seafloor 431
- Provinces of the Ocean Floor 434

Continental Margins 436

- Passive Continental Margins 436



EYE ON EARTH 437

Active Continental Margins 439

Features of Deep-Ocean Basins 439

Deep-Ocean Trenches 439

GEO GRAPHICS | Explaining Coral Atolls: Darwin's Hypothesis 440

Abyssal Plains 442

Volcanic Structures on the Ocean Floor 442

The Oceanic Ridge 443

Anatomy of the Oceanic Ridge 443

Why Is the Oceanic Ridge Elevated? 443

Seafloor Sediments 444

Types of Seafloor Sediments 444

Seafloor Sediment—A Storehouse of Climate Data 445

Resources from the Seafloor 446

Energy Resources 446

Other Resources 447

EYE ON EARTH 447**Concepts in Review** 448 | **Give It Some Thought** 450 |

14 Ocean Water and Ocean Life 453

FOCUS ON CONCEPTS 453**Composition of Seawater 454**

Salinity 454

Sources of Sea Salts 454

Processes Affecting Seawater Salinity 455

Recent Increase in Ocean Acidity 456

Variations in Temperature and Density with Depth 456

Temperature Variations 457

Density Variations 457

EYE ON EARTH 457

Ocean Layering 458

The Diversity of Ocean Life 459

Classification of Marine Organisms 459

Marine Life Zones 461

GEO GRAPHICS | Deep-Sea Hydrothermal Vents 462**EYE ON EARTH 464****Ocean Productivity 465**

Productivity in Polar Oceans 465

Productivity in Tropical Oceans 465

Productivity in Midlatitude Oceans 466

Oceanic Feeding Relationships 467

Trophic Levels 467

Transfer Efficiency 467

Food Chains and Food Webs 467

Concepts in Review 469 | **Give It Some Thought** 470 |

15 The Dynamic Ocean 473

FOCUS ON CONCEPTS 473**The Ocean's Surface Circulation 474**

The Pattern of Ocean Currents 474

Upwelling and Deep-Ocean Circulation 477

Coastal Upwelling 477

Deep-Ocean Circulation 477

The Shoreline: A Dynamic Interface 478

The Coastal Zone 479

Basic Features 479

Beaches 480

Ocean Waves 481

Wave Characteristics 481

EYE ON EARTH 481

Circular Orbital Motion 482

Waves in the Surf Zone 482

The Work of Waves 483

Wave Erosion 483

Sand Movement on the Beach 483

Shoreline Features 486

Erosional Features 486

Depositional Features 486

The Evolving Shore 487

Stabilizing the Shore 488

Hard Stabilization 489

Alternatives to Hard Stabilization 490

EYE ON EARTH 491**Contrasting America's Coasts 492**

Atlantic and Gulf Coasts 492

Pacific Coast 492

Coastal Classification 493

EYE ON EARTH 493**GEO GRAPHICS** | A Brief Tour of America's Coasts 494**Tides 496**

Causes of Tides 496

Monthly Tidal Cycle 497

Tidal Patterns 498

Tidal Currents 498

Concepts in Review 499 | **Give It Some Thought** 502 |

UNIT SIX | EARTH'S DYNAMIC ATMOSPHERE 504

16 The Atmosphere: Composition, Structure, and Temperature 505

FOCUS ON CONCEPTS 505**Focus on the Atmosphere 506**

Weather in the United States 506

Weather and Climate 506

EYE ON EARTH 507**Composition of the Atmosphere 508**

Major Components 508

Carbon Dioxide (CO₂) 508

Variable Components 509

Ozone Depletion: A Global Issue 510

GEO GRAPHICS | Acid Precipitation 511

Vertical Structure of the Atmosphere 512

- Pressure Changes 512
- Temperature Changes 513

Earth–Sun Relationships 514

- Earth's Motions 515
- What Causes the Seasons? 515
- Earth's Orientation 516
- Solstices and Equinoxes 516

EYE ON EARTH 519**Energy, Heat, and Temperature 520**

- Mechanism of Heat Transfer: Conduction 520

EYE ON EARTH 520

- Mechanism of Heat Transfer: Convection 521
- Mechanism of Heat Transfer: Radiation 521

Heating the Atmosphere 522

- What Happens to Incoming Solar Radiation? 522
- Reflection and Scattering 522
- Absorption 523
- Heating the Atmosphere: The Greenhouse Effect 524

For the Record: Air Temperature Data 525**Why Temperatures Vary: The Controls of Temperature 526**

- Land and Water 526
- Altitude 528
- Geographic Position 528
- Cloud Cover and Albedo 528

EYE ON EARTH 529**World Distribution of Temperature 530**

Concepts in Review 531 | **Give It Some Thought** 534 |

17 Moisture, Clouds, and Precipitation 537

FOCUS ON CONCEPTS 537**Water's Changes of State 538**

- Ice, Liquid Water, and Water Vapor 538
- Latent Heat 538

EYE ON EARTH 539**Humidity: Water Vapor in the Air 540**

- Saturation 540
- Mixing Ratio 541
- Relative Humidity 541
- Dew-Point Temperature 542
- Measuring Humidity 543

The Basis of Cloud Formation: Adiabatic Cooling 544

- Fog and Dew Versus Cloud Formation 544
- Adiabatic Temperature Changes 545
- Adiabatic Cooling and Condensation 545

Processes That Lift Air 546

- Orographic Lifting 546
- Frontal Wedging 546
- Convergence 547
- Localized Convective Lifting 547

The Weathermaker: Atmospheric Stability 548

- Types of Stability 548
- Stability and Daily Weather 550

Condensation and Cloud Formation 551

- Types of Clouds 552

EYE ON EARTH 553**Fog 555**

- Fogs Caused by Cooling 556
- Evaporation Fogs 557

How Precipitation Forms 558

- Precipitation from Cold Clouds: The Bergeron Process 558
- Precipitation from Warm Clouds: The Collision–Coalescence Process 559

Forms of Precipitation 559

- Rain 560
- Snow 560
- Sleet and Glaze 560
- Hail 561

GEO GRAPHICS | Our Water Supply 562

- Rime 564

Measuring Precipitation 564

- Measuring Snowfall 564
- Precipitation Measurement by Weather Radar 564

Concepts in Review 565 | **Give It Some Thought** 568 |

18 Air Pressure and Wind 571

FOCUS ON CONCEPTS 571**Understanding Air Pressure 572**

- Visualizing Air Pressure 572
- Measuring Air Pressure 573

Factors Affecting Wind 574

- Pressure Gradient Force 574
- Coriolis Effect 575
- Friction with Earth's Surface 576

Highs and Lows 578

- Cyclonic and Anticyclonic Winds 578
- Weather Generalizations About Highs and Lows 578

General Circulation of the Atmosphere 580

- Circulation on a Nonrotating Earth 580
- Idealized Global Circulation 580
- Influence of Continents 580

EYE ON EARTH 580

- The Westerlies 582

Local Winds 583

- Land and Sea Breezes 583
- Mountain and Valley Breezes 583
- Chinook and Santa Ana Winds 584

Measuring Wind 585**EYE ON EARTH 585****El Niño and La Niña and the Southern Oscillation 586**

- Impact of El Niño 586
- Impact of La Niña 587

GEO GRAPHICS | The 1930s Dust Bowl 589

- Southern Oscillation 590

Global Distribution of Precipitation 590

- The Influence of Pressure and Wind Belts 590
- Other Factors 591

EYE ON EARTH 591

Concepts in Review 592 | **Give It Some Thought** 594 |





19 Weather Patterns and Severe Storms 597

FOCUS ON CONCEPTS 597

Air Masses 598

- What Is an Air Mass? 598
- Source Regions 599
- Weather Associated with Air Masses 599

EYE ON EARTH 600

Fronts 601

- Warm Fronts 602
- Cold Fronts 602
- Stationary Fronts and Occluded Fronts 603

Midlatitude Cyclones 604

- Idealized Weather of a Midlatitude Cyclone 604
- The Role of Airflow Aloft 606

EYE ON EARTH 606

Thunderstorms 607

- What's in a Name? 607
- Thunderstorm Occurrence 608
- Stages of Thunderstorm Development 608

Tornadoes 610

- Tornado Occurrence and Development 610
- Tornado Destruction and Loss of Life 612

EYE ON EARTH 612

- Tornado Forecasting 613

Hurricanes 615

- Profile of a Hurricane 615

GEO GRAPHICS | Hurricane Katrina from Space 617

- Hurricane Formation and Decay 618
- Hurricane Destruction 618
- Tracking Hurricanes 620

Concepts in Review 621 | Give It Some Thought 623 |

20 World Climates and Global Climate Change 627

FOCUS ON CONCEPTS 627

The Climate System 628

World Climates 629

EYE ON EARTH 629

- Climate Classification 630
- The Köppen Classification 630

Humid Tropical (A) Climates 632

- The Wet Tropics 632
- Tropical Wet and Dry 634

Dry (B) Climates 635

- Low-Latitude Deserts and Steppes 635
- Middle-Latitude Deserts and Steppes 636

EYE ON EARTH 636

Humid Middle-Latitude Climates (C and D Climates) 637

- Humid Middle-Latitude Climates with Mild Winters (C Climates) 637
- Humid Middle-Latitude Climates with Severe Winters (D Climates) 638

Polar (E) Climates 640

Highland Climates 641

Human Impact on Global Climate 643

- Rising CO₂ Levels 643

EYE ON EARTH 643

- The Atmosphere's Response 644
- The Role of Trace Gases 645

GEO GRAPHICS | Greenhouse Gas (GHG) Emissions 646

Climate-Feedback Mechanisms 648

- Types of Feedback Mechanisms 648
- Computer Models of Climate: Important yet Imperfect Tools 649

How Aerosols Influence Climate 649

Some Possible Consequences of Global Warming 650

- Sea-Level Rise 651
- The Changing Arctic 652
- The Potential for "Surprises" 653

Concepts in Review 653 | Give It Some Thought 656 |

UNIT SEVEN

EARTH'S PLACE IN THE UNIVERSE 658

21 Origins of Modern Astronomy 659

FOCUS ON CONCEPTS 659

Ancient Astronomy 660

- The Golden Age of Astronomy 660
- Ptolemy's Model 662

The Birth of Modern Astronomy 663

- Nicolaus Copernicus 663
- Tycho Brahe 664
- Johannes Kepler 665
- Galileo Galilei 666
- Sir Isaac Newton 668

Positions in the Sky 669

- Constellations 669

GEO GRAPHICS | Orion the Hunter 670

- The Equatorial System 672

The Motions of Earth 673

- Rotation 673
- Revolution 674

EYE ON THE UNIVERSE 674

- Precession 675

Motions of the Earth–Moon System 675

- Lunar Motions 675
- Phases of the Moon 677

Eclipses of the Sun and Moon 677

Concepts in Review 679 | Give It Some Thought 680 |

22 Touring Our Solar System 683

FOCUS ON CONCEPTS 683

Our Solar System: An Overview 684

- Nebular Theory: Formation of the Solar System 685
- The Planets: Internal Structures and Atmospheres 686
- Planetary Impacts 687

Earth's Moon: A Chip Off the Old Block 689

- How Did the Moon Form? 689

EYE ON THE UNIVERSE 689

Terrestrial Planets 692

- Mercury: The Innermost Planet 692

EYE ON THE UNIVERSE 692

- Venus: The Veiled Planet 693
- Mars: The Red Planet 694

GEO GRAPHICS | Mars Exploration 696

Jovian Planets 699

- Jupiter: Lord of the Heavens 699
- Saturn: The Elegant Planet 701
- Uranus and Neptune: Twins 703

Small Solar System Bodies 705

- Asteroids: Leftover Planetesimals 705
- Comets: Dirty Snowballs 706
- Meteoroids: Visitors to Earth 707
- Dwarf Planets 709

Concepts in Review 710 | Give It Some Thought 712 |

23 Light, Astronomical Observations, and the Sun 715

FOCUS ON CONCEPTS 715

Signals from Space 716

- Nature of Light 716
- Light as Evidence of Events and Processes 718

Spectroscopy 718

- Continuous Spectrum 718
- Dark-Line Spectrum 719
- Bright-Line Spectrum 719
- The Doppler Effect 719

Collecting Light Using Optical Telescopes 720

- Refracting Telescopes 720
- Reflecting Telescopes 720
- Light Collection 722

Radio- and Space-Based Astronomy 724

- Radio Telescopes 724
- Orbiting Observatories 725

The Sun 726

- Photosphere 727
- Chromosphere 728
- Corona 728



The Active Sun 729

- Sunspots 729
- Prominences 731
- Solar Flares 731

EYE ON THE UNIVERSE 731

GEO GRAPHICS | Hubble Space Telescope 732

The Source of Solar Energy 734

Concepts in Review 735 | Give It Some Thought 737 |

24 Beyond Our Solar System 739

FOCUS ON CONCEPTS 739

The Universe 740

- How Large Is It? 740
- A Brief History of the Universe 741

Interstellar Matter: Nursery of the Stars 742

- Bright Nebulae 742
- Dark Nebulae 744

Classifying Stars: Hertzsprung–Russell Diagrams (H-R Diagrams) 744

Stellar Evolution 746

- Stellar Birth 746
- Protostar Stage 747
- Main-Sequence Stage 747
- Red Giant Stage 747

EYE ON THE UNIVERSE 747

- Burnout and Death 748

Stellar Remnants 749

- White Dwarfs 749
- Neutron Stars 750
- Black Holes 750

Galaxies and Galactic Clusters 751

GEO GRAPHICS | The Milky Way 752

- Types of Galaxies 754
- Galactic Clusters 755
- Galactic Collisions 756

The Big Bang Theory 756

- Evidence for an Expanding Universe 756
- Predictions of the Big Bang Theory 757
- What Is the Fate of the Universe? 757

Concepts in Review 759 | Give It Some Thought 761 |

APPENDIX A Metric and English Units Compared 763

APPENDIX B Relative Humidity and Dew-Point Tables 764

APPENDIX C Stellar Properties 765

GLOSSARY 768

INDEX 781

