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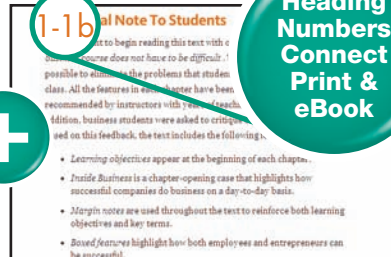
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Brief Contents

Chapter 1 Earth Systems 2

UNIT 1 EARTH MATERIALS AND TIME

Chapter 2 Minerals 16

Chapter 3 Rocks 34

Chapter 4 Geologic Time: A Story in the Rocks 54

Chapter 5 Geologic Resources 74

UNIT 2 INTERNAL PROCESSES

Chapter 6 The Active Earth: Plate Tectonics 100

Chapter 7 Earthquakes and the Earth's Structure 122

Chapter 8 Volcanoes and Plutons 142

Chapter 9 Mountains 168

UNIT 3 SURFACE PROCESSES

Chapter 10 Weathering, Soil, and Erosion 184

Chapter 11 Freshwater: Streams, Lakes, Wetlands, and Groundwater 212

Chapter 12 Water Resources 240

Chapter 13 Glaciers and Glaciations 262

Chapter 14 Deserts and Wind 284

UNIT 4 THE OCEANS

Chapter 15 Ocean Basins 302

Chapter 16 Oceans and Coastlines 328

UNIT 5 THE ATMOSPHERE: EVOLUTION AND COMPOSITION

Chapter 17 The Atmosphere 354

Chapter 18 Energy Balance in the Atmosphere 370

Chapter 19 Moisture, Clouds, and Weather 386

Chapter 20 Climate 414

Chapter 21 Climate Change 430

UNIT 6 (ONLINE ONLY) ASTRONOMY

Chapter 22 Motions in the Heavens 452

Chapter 23 Planets and their Moons 466

Chapter 24 Stars, Space, and Galaxies 488

Index I-1

Tear-Out Cards





Contents

Chapter 1 Earth Systems 2

- 1-1 The Earth's Four Spheres 3
 - The Geosphere 4 The Hydrosphere 6
 - The Atmosphere 7 The Biosphere 7
- 1-2 Earth Systems 7
- 1-3 Time and Rates of Change in Earth Science 9
 - Gradual Change in Earth History 11 Catastrophic Change in Earth History 11
- 1-4 Threshold and Feedback Effects 12
 - Threshold Effects 12 Feedback Mechanisms 13
- 1-5 Humans and Earth Systems 13

UNIT 1 EARTH MATERIALS AND TIME

Chapter 2 Minerals 16

- 2-1 What Is a Mineral? 17
 - Naturally Occurring 18 Inorganic 18 Solid 18
- 2-2 The Chemical Composition of Minerals 18
- 2-3 The Crystalline Nature of Minerals 19
- 2-4 Physical Properties of Minerals 20
 - Crystal Habit 21 Cleavage 21 Fracture 21
 - Hardness 22 Specific Gravity 22 Color 22
 - Streak 23 Luster 23 Other Properties 23
- 2-5 Mineral Classes and the Rock-Forming Minerals 23
 - Silicates 23 Rock-Forming Silicates 25
 - Carbonates 27



- 2-6 Commercially Important Minerals 27
- 2-7 Harmful and Dangerous Rocks and Minerals 28
 - Silicosis and Black Lung 29 Asbestos, Asbestosis, and Cancer 29 Radon and Cancer 30 Acid Mine Drainage and Heavy Metals Contamination 31

DIGGING DEEPER BOX 2.1 Here to Stay: Mercury 32–33

Chapter 3 Rocks 34

- 3-1 Rocks and the Rock Cycle 35
 - The Rock Cycle and Earth Systems Interactions 37
- 3-2 Igneous Rocks 37
 - Magma: The Source of Igneous Rocks 37 Types of Igneous Rocks 37 Naming and Identifying Igneous Rocks 38 Common Igneous Rocks 38 Granite and Rhyolite 39 Basalt and Gabbro 39 Andesite and Diorite 39 Peridotite and Komatiite 39
- 3-3 Sedimentary Rocks 40
 - Clastic Sedimentary Rocks 40 Organic Sedimentary Rocks 42 Chemical Sedimentary Rocks 43 Bioclastic Sedimentary Rocks 43 Carbonate Rocks and Global Climate 44 Physical Sedimentary Structures 44
- 3-4 Metamorphic Rocks 47
 - Metamorphic Grade 47

VIRTUAL FIELD TRIP Sedimentary Rocks: Formation and Correlation 48–49

- Metamorphic Changes 50 Textural Changes 50
- Mineralogical Changes 51 Types of Metamorphism and Metamorphic Rocks 51

Chapter 4 Geologic Time: A Story in the Rocks 54

- 4-1 Earth Rocks, Earth History, and Mass Extinctions 55
 - Extraterrestrial Impacts 55
 - Volcanic Eruptions 58
 - Supercontinents and Earth's Carbon Dioxide Budget 58
- 4-2 Geologic Time 60
- 4-3 Relative Geologic Time 60
 - Interpreting Geologic History From Fossils 62
- 4-4 Unconformities and Correlation 62
 - Unconformities 63
 - Correlation 64
- 4-5 Absolute Geologic Time 67
 - Radioactivity and Half-Life 67
 - Radiometric Dating 67
- 4-6 The Geologic Time Scale 69
 - The Earliest Eons of Geologic Time: Precambrian Time 70
 - The Phanerozoic Eon 70

VIRTUAL FIELD TRIP Geologic Time 72–73

Chapter 5 Geologic Resources 74

- 5-1 Mineral Resources 75
- 5-2 Ore and Ore Deposits 76
 - Magmatic Processes 76
 - Hydrothermal Processes 77
 - Sedimentary Processes 78
 - Weathering Processes 79
- DIGGING DEEPER BOX 5.1** Manganese Nodules 80
- 5-3 Mineral Reserves vs. Mineral Resources 81
 - The Geopolitics of Metal Resources 81
- 5-4 Mines and Mining 82
- 5-5 Energy Resources: Coal, Petroleum, and Natural Gas 84
 - Coal 84
 - Petroleum 84
 - Natural Gas 88
- 5-6 Unconventional Petroleum and Gas Reservoirs 88
 - Coal Bed Methane 89
 - Tar Sands 89
 - Oil Shale 90
- 5-7 Energy Resources: Nuclear Fuels and Reactors 90
- 5-8 Energy Resources: Renewable Energy 91
 - Solar Energy 91
 - Wind Energy 92
 - Geothermal Energy 93
 - Hydroelectric Energy 93
 - Biomass Energy 94
 - The Future of Renewable Energy Resources 94
- 5-9 Conservation as an Alternative Energy Resource 95
 - Technical Solutions 96
 - Social Solutions 97
- 5-10 Energy for the 21st Century 97

UNIT 2 INTERNAL PROCESSES

Chapter 6 The Active Earth: Plate Tectonics 100

- 6-1 Alfred Wegener and the Origin of an Idea: The Continental Drift Hypothesis 101
- 6-2 The Earth's Layers 104
 - The Crust 105
 - The Mantle 105
 - The Lithosphere 105
 - The Asthenosphere 106
 - The Mantle below the Asthenosphere 107
 - The Core 107
- 6-3 The Seafloor Spreading Hypothesis 107
- 6-4 The Theory of Plate Tectonics 109
 - Divergent Plate Boundaries 111
 - The Mid-Oceanic Ridge: Rifting in the Oceans 113
 - Splitting Continents: Rifting in Continental Crust 113
 - Convergent Plate Boundaries 113
 - Transform Plate Boundaries 114
- 6-5 The Anatomy of a Tectonic Plate 114
- 6-6 Why Plates Move: The Earth as a Heat Engine 115
 - Mantle Plumes and Hot Spots 116
- 6-7 Supercontinents 117
- 6-8 Isostasy: Vertical Movement of the Lithosphere 118
- 6-9 How Plate Tectonics Affect Earth's Surface 119
 - Volcanoes 119
 - Earthquakes 119
 - Mountain Building 119
- 6-10 How Plate Tectonics Affect Earth's Climates 120



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Chapter 7 Earthquakes and the Earth's Structure 122

- 7-1 Anatomy of an Earthquake 123
 - 7-2 Earthquake Waves 125
 - Body Waves 126 Surface Waves 127
 - Measurement of Seismic Waves 127
 - Measurement of Earthquake Strength 128
 - Locating the Source of an Earthquake 128
 - 7-3 Earthquakes and Tectonic Plate Boundaries 130
 - Earthquakes at a Transform Plate Boundary:
The San Andreas Fault Zone 130 Earthquakes at
Convergent Plate Boundaries 132 Earthquakes at
Divergent Plate Boundaries 132 Earthquakes in
Plate Interiors 133
 - 7-4 Earthquake Damage and Hazard Mitigation 133
 - How Rock and Soil Influence Earthquake
Damage 133 Construction Design and Earthquake
Damage 134 Tsunamis 134
- DIGGING DEEPER BOX 7.1** Earthquakes in Cascadia 136
- 7-5 Earthquake Prediction 137
 - Long-Term Prediction 137 Short-Term
Prediction 138
 - 7-6 Studying the Earth's Interior 138
 - Discovery of the Crust–Mantle Boundary 138
 - The Structure of the Mantle 139 Discovery of the
Core 139 Density Measurements 140
 - 7-7 Earth's Magnetism 141

Chapter 8 Volcanoes and Plutons 142

- 8-1 Magma 143
 - Processes That Form Magma 143
 - Environments of Magma Formation 144
- 8-2 Basalt and Granite 147
 - Granite and Granitic Magma 147
 - Andesite and Intermediate Magma 147



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- 8-3 Partial Melting and the Origin
of Continents 147
 - When Did Continents Form? 147 Partial Melting
and the Origin of Granitic Continents 148
 - Horizontal Tectonics 149 Vertical Mantle Plume
Tectonics 149
- 8-4 Magma Behavior 149
 - Effects of Silica on Magma Behavior 149
 - Effects of Water on Magma Behavior 149
- 8-5 Plutons 150
- 8-6 Volcanoes 152
 - Lava and Pyroclastic Rocks 152 Fissure Eruptions
and Lava Plateaus 154 Volcano Types 154
- 8-7 Volcanic Explosions: Ash-Flow
Tuffs and Calderas 157
 - Pyroclastic Flows 157

DIGGING DEEPER BOX 8.1 The Destruction of
Pompeii 159

- Calderas 160

DIGGING DEEPER BOX 8.2 The Yellowstone
Volcano 161–163

- 8-8 Risk Assessment: Predicting
Volcanic Eruptions 163
 - Regional Prediction 163 Short-Term Prediction 163
 - 8-9 Volcanic Eruptions and Global Climate 164
- VIRTUAL FIELD TRIP** Hydrothermal Activity 166–167

Chapter 9 Mountains 168

- 9-1 Folds and Faults: Geologic Structures 169
 - How Rocks Respond to Tectonic Stress 169
 - Geologic Structures 169
 - Folds, Faults, and Plate Boundaries 176
- 9-2 Mountains and Mountain Ranges 176



USGS

- 9-3 Island Arcs: Subduction Where Two Oceanic Plates Converge 178
- 9-4 The Andes: Subduction at a Continental Margin 179
- 9-5 The Himalayas: A Collision between Continents 180
Formation of an Andean-Type Margin 180
Continent–Continent Collision 181
The Himalayas Today 181
- 9-6 Mountains and Earth Systems 183

UNIT 3 SURFACE PROCESSES

Chapter 10 Weathering, Soil, and Erosion 184

- 10-1 Weathering and Erosion 185
- 10-2 Mechanical Weathering 186
Pressure-Release Fracturing 186 Frost Wedging 186 Abrasion 188 Organic Activity 188 Thermal Expansion and Contraction 188
- 10-3 Chemical Weathering 189
Dissolution 189 Hydrolysis 190 Oxidation 191
Chemical and Mechanical Weathering Acting Together 191
- 10-4 Soil 193
Components of Soil 193 Soil Horizons 194
Soil Classification 195 Soil-Forming Factors 195



COURTESY OF GRAHAM R. THOMPSON/JONATHAN TURK

- DIGGING DEEPER BOX 10.1** Soil Erosion and Human Activities 204
- 10-5 Mass Wasting and Landslides 205
- 10-6 Types of Rapid Mass Wasting 205
Slide 207 Fall 208
- 10-7 Predicting and Avoiding the Effects of Mass Wasting 209
Why Do Slides, Flows, and Falls Occur? 209

Chapter 11 Freshwater: Streams, Lakes, Wetlands, and Groundwater 212

- 11-1 The Water Cycle 213
- 11-2 Streams 214
Stream Flow and Velocity 214 Stream Erosion and Sediment Transport 215 Downcutting and Base Level 216 Sinuosity of a Stream Channel 218 Drainage Basins and Drainage Divides 220 Stream Erosion and Mountains: How Landscapes Evolve 221
- 11-3 Stream Deposition 221
- 11-4 Floods 223
Flood Control 223 Flood Control, the Mississippi River Delta, and Hurricane Katrina 224
- 11-5 Lakes 227
The Life Cycle of a Lake 227 Nutrient Balance in Lakes 228 Temperature Layering and Turnover in Lakes 228
- 11-6 Wetlands 229
- 11-7 Groundwater 231
Porosity and Permeability 231 The Water Table and Aquifers 232 Groundwater Movement 233
- 11-8 Hot Springs, Geysers, and Geothermal Energy 236

- VIRTUAL FIELD TRIP** Running Water 238–239

Chapter 12 Water Resources 240

- 12-1 Water Supply and Demand 241
Domestic Water Use 242 Industrial Water Use 243
Agricultural Water Use 244
- 12-2 Dams and Diversion 244
Surface Water Diversion 245 Groundwater Diversion 248 Groundwater Depletion 248
- 12-3 The Great American Desert 251
The Colorado River 252

- DIGGING DEEPER BOX 12.1** The Los Angeles Water Project 253

- 12-4 Water and International Politics 253

12-5 Water Pollution 254
Types of Pollutants 254

DIGGING DEEPER BOX 12.2 Love Canal 255

12-6 How Sewage, Detergents, and Fertilizers Pollute Waterways 256

12-7 Toxic Pollutants, Risk Assessment, and Cost–Benefit Analysis 257

12-8 Groundwater Pollution 257
Treating a Contaminated Aquifer 259

DIGGING DEEPER BOX 12.3 Yucca Mountain Controversy 260

12-9 Nuclear Waste Disposal 261

12-10 The Clean Water Act: A Modern Perspective 261

Chapter 13

Glaciers and Glaciations 262

13-1 Formation of Glaciers 263
Alpine Glaciers 264 Continental Glaciers 264

13-2 Glacial Movement 264
The Mass Balance of a Glacier 267

13-3 Glacial Erosion 268
Erosional Landforms Created by Alpine Glaciers 268 Erosional Landforms Created by a Continental Glacier 271

13-4 Glacial Deposits 271
Landforms Composed of Till 272

DIGGING DEEPER BOX 13.1 Glacial Erratics and Canadian Diamonds 273
Landforms Consisting of Stratified Drift 276

13-5 The Pleistocene Glaciation 277
Causes of the Pleistocene Glacial Cycles 278
Effects of Pleistocene Continental Glaciers 279
Sea Level Changes with Glaciation 280

13-6 Snowball Earth: The Greatest Glaciation in Earth's History 280

13-7 The Earth's Disappearing Glaciers 280

Chapter 14

Deserts and Wind 284

14-1 Why Do Deserts Exist? 285
Latitude 285 Mountains: Rain-Shadow Deserts 286 Coastal and Interior Deserts 286

14-2 Water and Deserts 287
Desert Streams 287 Desert Lakes 288 Flash Floods 289 Pediments and Bajadas 289

14-3 Two American Deserts 290
The Colorado Plateau 290 Death Valley and the Great Basin 291

14-4 Wind 292
Wind Erosion 293 Transport and Abrasion 293 Dunes 294 Loess 297

14-5 Desertification 298

VIRTUAL FIELD TRIP Desert Environments 300–301

UNIT 4

THE OCEANS

Chapter 15

Ocean Basins 302

15-1 The Origin of Oceans 303

15-2 The Earth's Oceans 305

15-3 Studying the Seafloor 306
Sampling 306

DIGGING DEEPER BOX 15.1 Invaluable sediment archives recently recovered from the deep ocean 307–309
Remote Sensing 310

15-4 Features of the Seafloor 311
The Mid-Oceanic Ridge System 311
Global Sea-Level Changes and the Mid-Oceanic Ridge System 314 Oceanic Trenches and Island Arcs 315 Seamounts, Oceanic Islands, and Atolls 316

15-5 Sediment and Rocks of the Seafloor 320
Ocean-Floor Sediment 321



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- 15-6 Continental Margins 322
 - Passive Continental Margins 323 The Continental Shelf 324 Active Continental Margins 326

Chapter 16

Oceans and Coastlines 328

- 16-1 Geography of the Oceans 329
- 16-2 Seawater 330
 - Salts and Trace Elements 330 Dissolved Gases 331 Temperature 331
- 16-3 Tides 332
- 16-4 Sea Waves 333
- 16-5 Ocean Currents 334
 - Surface Currents 334 Why Surface Currents Flow in the Oceans 336 Deep-Sea Currents 338 Upwelling 339
- 16-6 The Seacoast 339
 - Weathering and Erosion on the Seacoast 339 Sediment Transport along Coastlines 341 Tidal Currents 342
- 16-7 Emergent and Submergent Coastlines 342
 - Factors That Cause Coastal Emergence and Submergence 343
- 16-8 Beaches 344
 - Sandy Coastlines 345 Rocky Coastlines 348
- 16-9 Life in the Sea 350
 - World Fisheries 350 Reefs 352
- 16-10 Global Warming and Rising Sea Level 353

UNIT 5

THE ATMOSPHERE: EVOLUTION AND COMPOSITION

Chapter 17

The Atmosphere 354

- 17-1 Earth's Early Atmospheres 355
 - The First Atmospheres: 4.6 to 4.0 Billion Years Ago 355 When Life Began: 4.0 to 2.6 Billion Years Ago 356

- 17-2 Life, Iron, and the Evolution of the Modern Atmosphere 357
 - Systems Interactions That Affected Oxygen Concentration in Earth's Early Atmosphere 358 Evolution of the Modern Atmosphere 359

- 17-3 The Modern Atmosphere 360

- 17-4 Atmospheric Pressure 361

- 17-5 Atmospheric Temperature 363

- 17-6 Air Pollution 364
 - Gases Released When Fossil Fuels Are Burned 364 Acid Rain 365 Consequences of Acid Rain 366 Smog and Ozone in the Troposphere 366 Toxic Volatiles 367 Particulates and Aerosols 368

- 17-7 Depletion of the Ozone Layer 368

Chapter 18

Energy Balance in the Atmosphere 370

- 18-1 Incoming Solar Radiation 371
 - Absorption and Emission 372 Reflection 373 Scattering 374

- 18-2 The Radiation Balance 374

- 18-3 Energy Storage and Transfer: The Driving Mechanisms for Weather and Climate 376
 - Heat and Temperature 376 Heat Transport by Conduction and Convection 376 Changes of State 377 Heat Storage 378

- DIGGING DEEPER BOX 18.1** Latitude and Longitude 378

- 18-4 Temperature Changes with Latitude and Season 379
 - Temperature Changes with Latitude 379 The Seasons 379

- 18-5 Temperature Changes with Geography 382
 - Altitude 382 Ocean Effects 383 Wind Direction 384 Cloud Cover and Albedo 384



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Chapter 19 Moisture, Clouds, and Weather 386

- 19-1 Moisture in Air 387
Humidity 387 Supersaturation and Supercooling 388
- 19-2 Cooling and Condensation 388
Radiation Cooling 388 Contact Cooling: Dew and Frost 388 Cooling of Rising Air 388
- 19-3 Rising Air and Precipitation 390
Orographic Lifting 390 Frontal Wedging 390
Convection–Convergence 390 Convective Processes and Clouds 390
- 19-4 Types of Clouds 392
Types of Precipitation 393
- 19-5 Fog 395
- 19-6 Pressure and Wind 395
Pressure Gradient 396 Coriolis Effect 397
Friction 397 Cyclones and Anticyclones 398
Pressure Changes and Weather 399
- 19-7 Fronts and Frontal Weather 399
Warm Fronts and Cold Fronts 399
Occluded Front 402 Stationary Front 402
The Life Cycle of a Midlatitude Cyclone 403
- 19-8 How the Earth’s Surface Features Affect Weather 404
Mountain Ranges and Rain-Shadow Deserts 404
Forests and Weather 405 Sea and Land Breezes 405 Monsoons 405
- 19-9 Thunderstorms 405
Lightning 406
- 19-10 Tornadoes and Tropical Cyclones 407
Tornadoes 407 Tropical Cyclones 407

- 19-11 Hurricane Katrina 410
Scope of the Disaster 410 Brief History of Gulf Hurricanes 410
- 19-12 El Niño 410

Chapter 20 Climate 414

- 20-1 Global Winds and Climate 415
- 20-2 Climate Zones of Earth 417
Humid Tropical Climates: No Winter 420
Dry Climates: Evaporation Greater Than Precipitation 422 Humid Midlatitude Climates with Mild Winters 423 Humid Midlatitude Climate with Severe Winters 425 Polar Climate 426
- 20-3 Urban Climates 426

Chapter 21 Climate Change 430

- 21-1 Climate Change in Earth’s History 431
- 21-2 Measuring Climate Change 434
Historical Records 434 Tree Rings 434
Plant Pollen 435 Oxygen Isotope Ratios in Glacial Ice 435 Glacial Evidence 435 Plankton and Isotopes in Ocean Sediment 435 The Rock and Fossil Record 436
- 21-3 Astronomical Causes of Climate Change 436
Changes in Solar Radiation 437
Bolide Impacts 437
- 21-4 Water and Climate 438
- 21-5 The Natural Carbon Cycle and Climate 438
Carbon in the Atmosphere 439 Carbon in the Biosphere 439 Carbon in the Hydrosphere 439
Carbon in the Crust and Upper Mantle 439
- 21-6 Tectonics and Climate Change 440
Positions of the Continents 440 Mountains and Climate 442 Volcanoes and Climate 442
How Tectonics, Sea Level, Volcanoes, and Weathering Interact to Regulate Climate 442
- 21-7 Greenhouse Effect: The Carbon Cycle and Global Warming 442
Consequences of Greenhouse Warming 446
- 21-8 Feedback and Threshold Mechanisms in Climate Change 448
Albedo Effects 448 Imbalances in Rates of Plant Respiration and Photosynthesis 449 Changes in Ocean Currents 449 Permafrost and Deep-Sea Methane Deposits 450

UNIT 6 (ONLINE ONLY)
ASTRONOMY

Chapter 22

Motions in the Heavens 452

- 22-1 The Motions of the Heavenly Bodies 453
- 22-2 Aristotle and the Earth-Centered Universe 454
- 22-3 The Renaissance and the Heliocentric Solar System 456
 - Copernicus 456 Brahe and Kepler 456
 - Galileo 457 Isaac Newton and the Glue of the Universe 458
- 22-4 The Motions of the Earth and the Moon 458
 - Motion of the Moon 459 Eclipses of the Sun and the Moon 461
- 22-5 Modern Astronomy 462
 - Optical Telescopes 462 Telescopes Using Other Wavelengths 464 Emission and Absorption Spectra 464 Doppler Measurements 465

Chapter 23

Planets and their Moons 466

- 23-1 The Solar System: A Brief Overview 467
- 23-2 The Terrestrial Planets 467
 - Atmospheres and Climates of the Terrestrial Planets 470 Geology and Tectonics of the Terrestrial Planets 472



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- 23-3 The Moon: Our Nearest Neighbor 475
 - Formation of the Moon 476 History of the Moon 478
- 23-4 The Jovian Planets: Size, Compositions, and Atmospheres 478
 - Jupiter 478 Saturn 480 Uranus and Neptune 480
- 23-5 Moons of the Jovian Planets 480
 - The Moons of Jupiter 480 Saturn's Moons 482 The Moons of Uranus and Neptune 483
- 23-6 Planetary Rings 483
- 23-7 Pluto and Other Dwarf Planets 484
- 23-8 Asteroids, Comets, and Meteoroids 484
 - Asteroids 484 Comets 485 Meteoroids 487

Chapter 24

Stars, Space, and Galaxies 488

- 24-1 In the Beginning: The Big Bang 489
- 24-2 The Nonhomogeneous Universe 491
- 24-3 The Birth of a Star 492
- 24-4 The Sun 494
 - The Sun's Inner Structure 494 The Photosphere 497 The Sun's Outer Layers 497
- 24-5 Stars: The Main Sequence 499
- 24-6 The Life and Death of a Star 500
 - Stars about the Same Mass as Our Sun 500
 - Stars with a Large Mass 502
 - First and Second Generation Stars 503
- 24-7 Neutron Stars, Pulsars, and Black Holes 504
 - Neutron Stars and Pulsars 504 Black Holes 506 Gamma Ray Bursts 507
- 24-8 Galaxies 507
 - Galactic Motion 508
- 24-9 The Milky Way 509
 - The Nucleus of the Milky Way 510
 - Galactic Nebulae 511
- 24-10 Quasars 512
 - Looking Backward into Time 512
- 24-11 Dark Matter 512
- 24-12 The End of the Universe 513
- 24-13 Why Are We So Lucky? 513

Index I-1

Tear-Out Cards

Virtual Field Trips of our EARTH: Let's Go!



GOALS OF THE TRIP

1. Improve student understanding of difficult geological concepts
2. Get students into the field
3. Deliver a more meaningful experience to today's technology

GET INTO THE FIELD

With access to the complete set of Virtual Field Trips in Geology, EARTH 2 makes it easier than ever to engage students while educating them on the geologic concepts they need to succeed. Virtual Field Trips provide dynamic panoramas, high-definition videos and photos, key concepts, critical thinking questions, and more to serve diverse learning styles. Now available with all 15 Virtual Field Trips, EARTH 2 enables students to explore famous national parks throughout the United States while being guided by a virtual instructor!

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▲ **Plate Tectonics**
Mount St. Helens and Siding Hill Syncline

▶ **Mineral Resources**
Bingham Canyon Mine



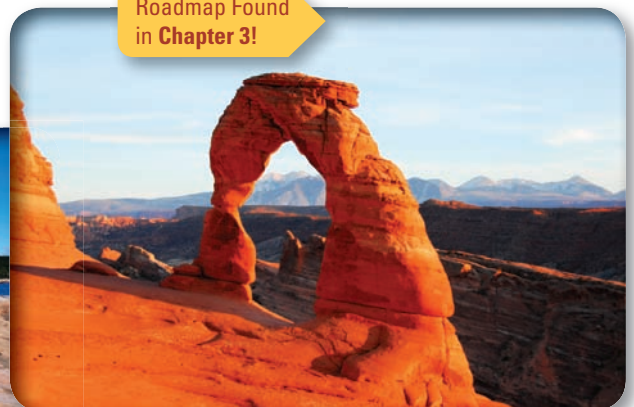
◀ **Volcano Types**
Hawaii Volcanoes National Park and Mount St. Helens



◀ **Igneous Rocks**
Hawaii Volcanoes and Yosemite National Parks

▼ **Sedimentary Rocks**
Arches and Capitol Reef National Parks

Roadmap Found in Chapter 3!



▶ **Metamorphic Rocks**
Acadia National Park





▲ **Earthquakes and Seismicity**
Los Trancos Open Space Preserve
and Pt. Reyes National Seashore

Roadmap Found
in **Chapter 11!**



▲ **Running Water**
Zion National Park

▼ **Groundwater**
Mammoth Cave National Park



Roadmap Found
in **Chapter 4!**

▲ **Geologic Time**
Grand Canyon and Capitol Reef National parks

▲ **Mass Wasting**
Arches and Yosemite
National Parks



◀ **Hydrothermal Activity**
Yellowstone National Park



Roadmap Found
in **Chapter 8!**



▲ **Glaciers and Glaciation**
Kenai Fjords National Park
and Prince William Sound

**Shorelines and
Shoreline Processes** ▶
Bandon Beach



◀ **Desert Environments**
Death Valley National Park



Roadmap Found
in **Chapter 14!**

1 Earth Systems

Northern California coastline showing elements of the geosphere (sea cliffs), atmosphere (sky), hydrosphere (ocean and streams), and biosphere (vegetation).

SECTIONS

- | | |
|--|---|
| 1-1 The Earth's Four Spheres | 1-4 Threshold and Feedback Effects |
| 1-2 Earth Systems | 1-5 Humans and Earth Systems |
| 1-3 Time and Rates of Change in Earth Science | |

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STUDY TOOLS 

“ *When we try to pick out anything by itself, we find it hitched to everything else in the Universe.* ”
John Muir

Earth is sometimes called the water planet or the blue planet because azure seas cover more than two-thirds of its surface. Earth is the only planet or Moon in the Solar System in which water falls from clouds as rain, runs across the land surface, and collects in extensive oceans. It is also the only body we know of that supports life.

1-1 THE EARTH'S FOUR SPHERES

Imagine walking along a sandy beach as a storm blows in from the sea. Wind whips the ocean into white-caps, while large waves crash onto shore. Blowing sand stings your eyes as gulls overhead frantically beat their wings en route to finding shelter.

In minutes, blowing spray has soaked your clothes. A hard rain begins as you hurry back to your vehicle.

During this adventure, you have experienced the four major spheres of Earth.

The beach sand underfoot is the surface of the **geosphere**, or the solid Earth. The rain and sea are parts of the **hydrosphere**, the watery part of our planet. The blowing wind belongs to the **atmosphere**.

Finally, you, the gulls, the beach grasses, and all other forms of life in the sea, on land, and in the air are parts of the **biosphere**, the realm of organisms.

You can readily observe that the atmosphere is in motion,

because clouds drift across the sky and wind blows against your face. In the biosphere, animals—and to a lesser extent plants—also move. Flowing streams, crashing waves, and falling rain are all familiar examples of motion in the hydrosphere. Although it is less apparent on a day-to-day basis, the geosphere is also moving and dynamic. Vast masses of solid rock flow very slowly within the planet's interior. Continents drift, while intervening ocean basins slowly open, then collapse. Mountains rise and then

erode into sediment. Throughout this book we will study many of these phenomena to learn which energy forces set matter in motion and how these motions affect the planet we live on. Figure 1.1 shows schematically all the possible interactions among the spheres.

Figure 1.2 shows that the geosphere is by far the largest of the four spheres. The Earth's radius is about 6,400 kilometers, roughly the same distance as Miami to Anchorage. Despite this great size, nearly all of our direct contact with Earth occurs at or very near its surface. The deepest well penetrates little more than 12 kilometers, less than two-tenths of 1 percent of the

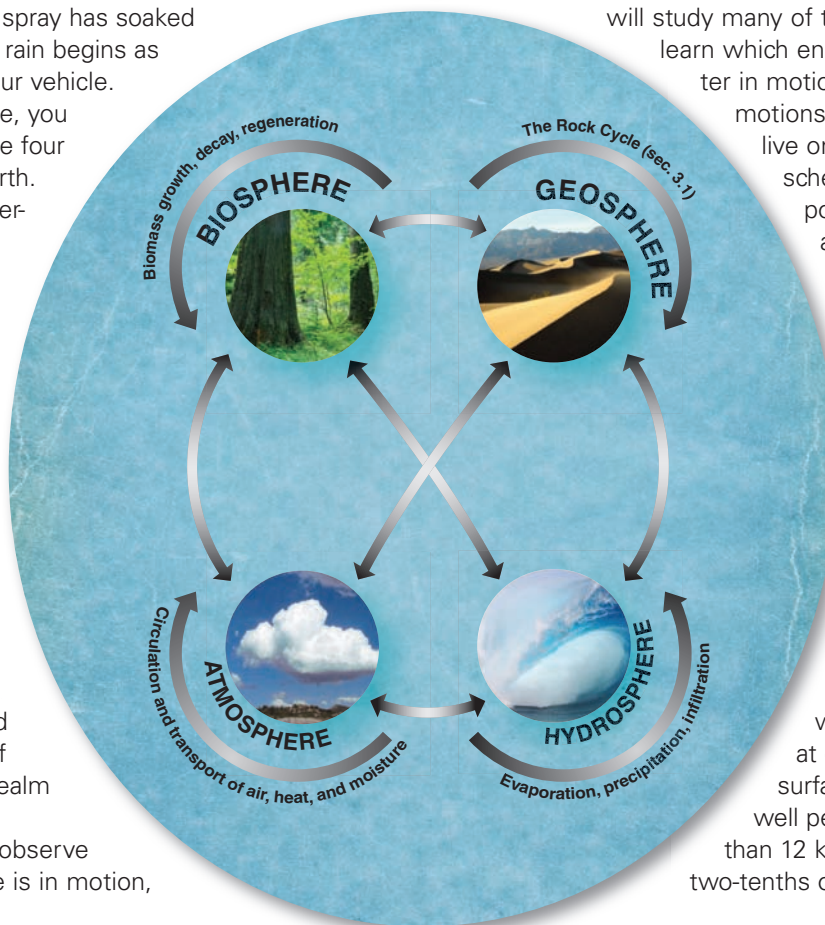


FIGURE 1.1 All of Earth's cycles and spheres are interconnected.

geosphere The solid Earth, consisting of the entire planet from the center of the core to the outer crust.

hydrosphere All of Earth's water, which circulates among oceans, continents, glaciers, and atmosphere.

atmosphere The gaseous layer above the Earth's surface, mostly nitrogen and oxygen, with smaller amounts of argon, carbon dioxide, and other gases. The atmosphere is held to Earth by gravity and thins rapidly with altitude.

biosphere The zone of Earth comprising all forms of life in the sea, on land, and in the air.

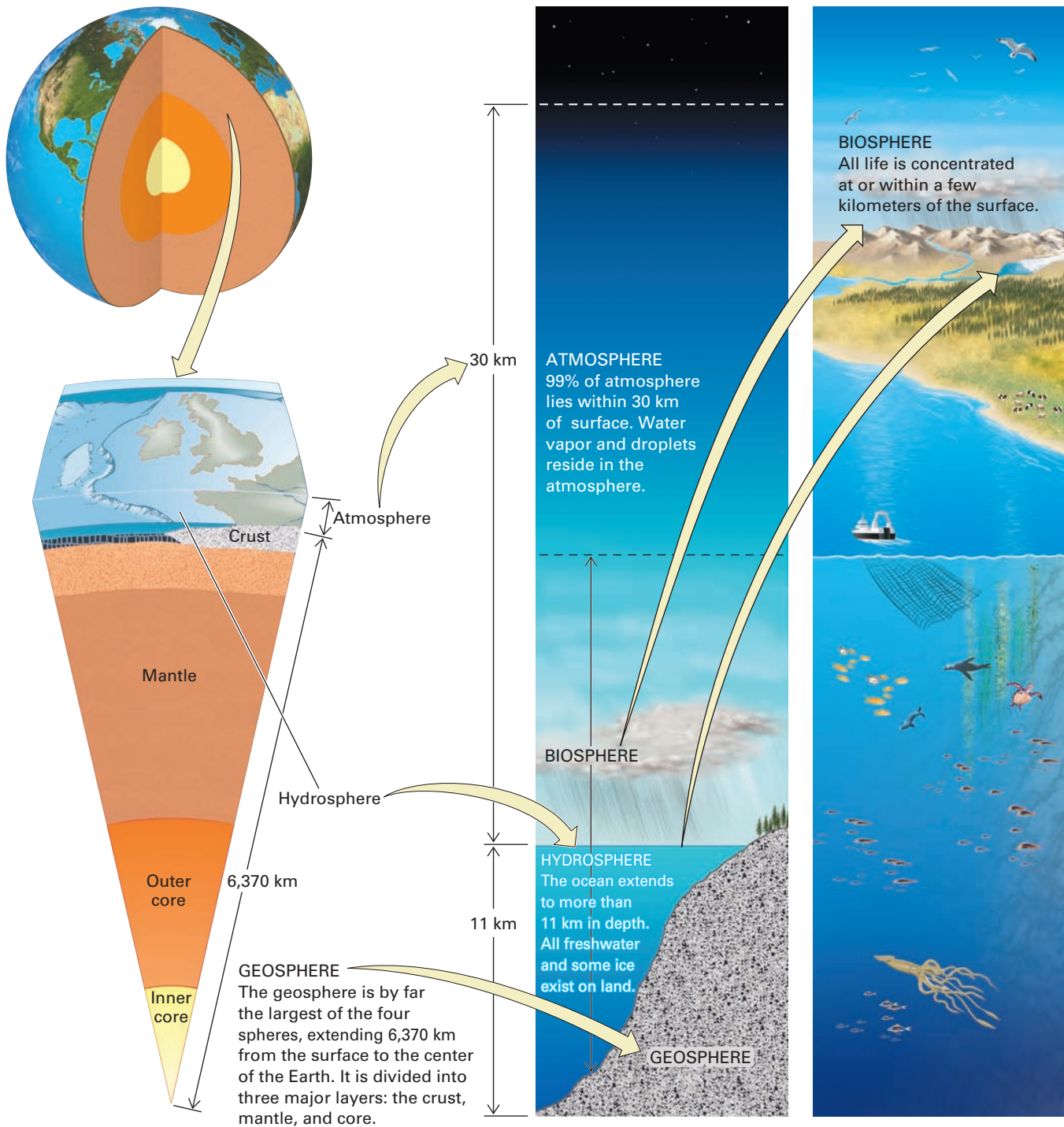


FIGURE 1.2 The geosphere is the largest component of Earth. It is surrounded by the hydrosphere, the biosphere, and the atmosphere.

distance to Earth's center. The oceans make up most of the hydrosphere, and although it can extend as deep as 11 kilometers, the ocean floor averages only about 4 kilometers in depth. Most of Earth's atmosphere lies within 30 kilometers of the surface, and the biosphere is a thin shell about 15 kilometers thick.

1-1a The Geosphere

Our Solar System coalesced from a frigid cloud of dust and gas rotating slowly in space. The Sun formed as gravity pulled material toward the swirling center. At the same time, rotational forces spun material in the outer cloud into a thin disk. Eventually,



FIGURE 1.3 Earth's crust is made up of different kinds of rock (A) A grand view of the sandstones, siltstones, limestones, and shales of the Grand Canyon, as seen from the South Rim. These sedimentary rocks are relatively soft and crumbly and show a marked horizontal layering. Note people for scale. (B) The granite of Baffin Island in the Canadian Arctic is gray, hard, and strong.

core The dense, metallic, innermost region of Earth's geosphere, consisting mainly of iron and nickel. The outer core is molten, but the inner core is solid.

mantle The rocky, mostly solid layer of Earth's geosphere lying beneath the crust and above the core. The mantle extends from the base of the crust to a depth of about 2,900 kilometers.

crust The outermost layer of Earth's geosphere, ranging from 4 to 75 kilometers thick and composed of relative low-density silicate rocks.

lithosphere The cool, rigid, outer part of Earth, which includes the crust and the uppermost mantle, is about 100 kilometers thick, and makes up Earth's tectonic plates.

small grains of matter within the disk stuck together to form fist-sized masses. These planetary "seeds" then accreted to form rocky clumps, which grew to form larger bodies, called *planetesimals*, 100 to 1,000 kilometers in diameter. Finally, the planetesimals consolidated to form the planets. This process was completed about 4.6 billion years ago.

As the Earth coalesced, gravity caused the rocky chunks and planetesimals to accelerate so that they slammed together at high speeds. Particles heat up when they collide, so the early Earth warmed as it formed. Later, asteroids, comets, and more planetesimals crashed into the surface, generating additional heat. At the same time, radioactive decay heated the Earth's interior. These three processes caused the early Earth to become so hot that much of the planet melted as it formed.

Within the molten Earth, the denser materials sunk toward the center, while the less dense materials floated toward the top, creating a layered structure. Today, the geosphere consists of three major layers: a dense metallic **core**, a less dense rocky **mantle**, and an even less dense surface **crust** (Figure 1.2).

The temperature of modern Earth increases with depth. At its center, Earth is 6,000°C—as hot as the Sun's surface. The core is composed mainly of iron and nickel. The outer core is molten metal. However, the inner core, although hotter yet, is solid

because the great pressure compresses the metal to a solid state.

The mantle surrounds the core and lies beneath the crust. The physical characteristics of the mantle vary with depth. From its upper surface to a depth of about 100 kilometers, the outermost mantle is relatively cool, strong, and hard. Below a depth of 100 kilometers, however, rock making up the mantle is so hot that it is *weak*, soft, *plastic* (a solid that will deform permanently), and flows slowly—like cold honey. Even deeper in the mantle, pressure overwhelms temperature, and the rock becomes strong again.

The crust is the outermost layer of rock extending from the ground surface or bottom of the ocean to the top of the mantle. The crust ranges from as little as 4 kilometers thick beneath the oceans to as much as 75 kilometers thick beneath the continents. Even a casual observer sees that the crust includes many different rock types: some are soft, others hard, and they come in many colors, as you can see in Figure 1.3.

The relatively cool, hard, and strong rock of the uppermost mantle is similar to that of the crust. Together these layers make up the **lithosphere**, which averages about 100 kilometers thick.

According to the theory of plate tectonics, developed in the 1960s, the lithosphere is divided into seven major and eight smaller segments called

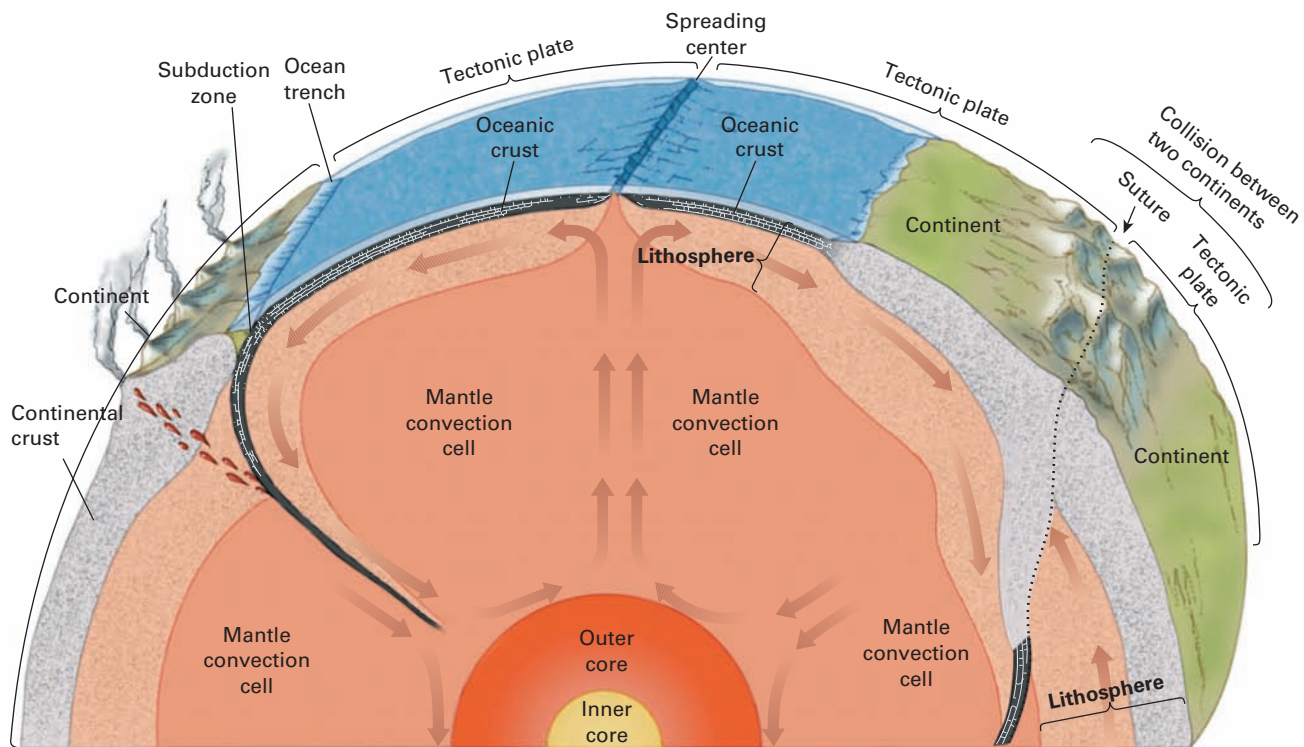
tectonic plates

The segments of Earth's outermost, cool, rigid shell, consisting of the lithosphere. Tectonic plates float on the weak, plastic rock of the asthenosphere beneath.

tectonic plates. These tectonic plates float on the relatively hot, weak, plastic mantle rock beneath and move horizontally with respect to each other (Figure 1.4). For example, North and South America are currently drifting west relative to Eurasia

and Africa about as fast as your fingernails grow. These continental movements are causing the Atlantic Ocean to grow larger and the Pacific Ocean to shrink. In a few hundred million years—almost incomprehensibly long on a human time scale but brief when compared with planetary history—Asia and North America may collide, completely collapsing the Pacific Ocean and crumpling the leading edges of the continents together into a giant mountain range. In later chapters we will learn how the theory of plate tectonics explains earthquakes, volcanic eruptions, and the formation of mountain ranges, as well as many other processes and events that have created our modern Earth and its environment.

FIGURE 1.4 The lithosphere is composed of the crust and the uppermost mantle. It is a 100-kilometer-thick layer of strong rock that floats on the underlying plastic mantle. The lithosphere is broken into seven major segments, called tectonic plates, that glide horizontally over the plastic mantle at rates of a few centimeters per year. In the drawing, the thickness of the mantle and the lithosphere are exaggerated to show detail.



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1-1b The Hydrosphere

The hydrosphere includes all of Earth's water, which circulates among oceans, continents, glaciers, and the atmosphere. Figure 1.5 shows the proportion of water in each of these areas. Oceans cover 71 percent of Earth and contain 97.5 percent of its water. Ocean currents transport heat across vast distances, altering global climate.

About 1.8 percent of Earth's water is frozen in glaciers. Although glaciers cover about 10 percent of Earth's land surface today, they covered much greater portions of the globe as recently as 18,000 years ago. During this glacial period, nearly all of Canada, the British Isles, and Scandinavia were covered with ice that was locally up to 4 kilometers thick. In North America, the ice was so massive that it caused the underlying lithosphere to sag beneath its weight. Hudson Bay in Canada exists because the glacial ice melted faster than the lithosphere was able to bounce back. Today, the Hudson Bay region is undergoing nearly one centimeter of uplift per year as the lithosphere continues to recover from the weight of the ice.

Only about 0.64 percent of Earth's total water exists on the continents as a liquid. Although this is a small proportion, freshwater is essential to life on Earth. Lakes, rivers, and clear, sparkling streams are the most visible reservoirs of continental water, but they constitute only 0.01 percent of Earth's water.

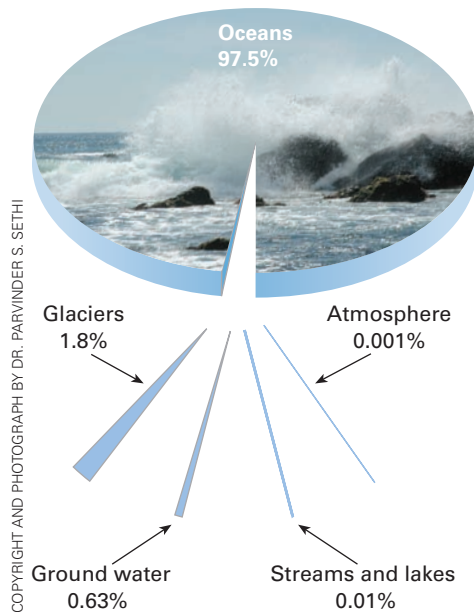


FIGURE 1.5 The oceans contain most of Earth's surface water. Most freshwater is frozen into glaciers. Most available freshwater is stored underground as groundwater.

In contrast, **groundwater**—which occurs in pores, spaces within soil and rock of the upper few kilometers of the geosphere—is much more voluminous and accounts for 0.63 percent of Earth's water. Only a minuscule amount of water, 0.001 percent, exists in the atmosphere, but because it is so mobile, this atmospheric water profoundly affects both the weather and the climate of our planet.

1-1c The Atmosphere

The atmosphere is a mixture of gases: mostly nitrogen and oxygen, with smaller amounts of argon, carbon dioxide, and other gases. It is held to Earth by gravity and thins rapidly with altitude. Ninety-nine percent is concentrated in the first 30 kilometers, but traces of atmospheric gas occur as far as 10,000 kilometers above Earth's surface.

The atmosphere supports life, because animals need oxygen and plants need both carbon dioxide and oxygen. In addition, the atmosphere supports life indirectly by regulating climate. Air serves as both a blanket and a filter, retaining heat at night and shielding us from direct solar radiation during the day. Wind transports heat from the equator toward the poles, cooling equatorial regions and warming temperate and polar zones.

1-1d The Biosphere

The biosphere is the zone that life inhabits. It includes the uppermost geosphere, the hydrosphere, and the

lower parts of the atmosphere. Sea life concentrates near the surface, where sunlight is available. Plants also grow on Earth's surface, with roots penetrating a few meters into the soil. Animals live on the surface, fly a kilometer or two above it, or burrow a few meters underground. Large populations of bacteria live under glacial ice and in rock to depths of as great as 4 kilometers. Some organisms live on the ocean floor, and a few windblown microorganisms drift at heights of 10 kilometers or more. Despite these extremes, the biosphere is a very thin layer at Earth's surface.

Plants and animals are clearly affected by Earth's environment: Organisms breathe air, require water, and thrive in a relatively narrow temperature range. Terrestrial organisms ultimately depend on soil, which is part of the geosphere. But plants and animals also alter the atmosphere through respiration and contribute organic matter to the geosphere when they die.

1-2 EARTH SYSTEMS

A **system** is any assemblage or combination of interacting components that forms a complex whole. For example, the human body is a system composed of bones, nerves, muscles, and a variety of specialized organs. Each organ is discrete, yet all the organs interact to produce a living human. For example, blood nurtures the stomach, and the stomach helps provide energy to maintain the blood.

Systems are driven by the flow of matter and energy. Thus, a person ingests food, which contains both matter and chemical energy, and inhales oxygen. Waste products are released through urine, feces, sweat, and exhaled breath. Some energy is used for respiration and motion, and the remainder is released as heat or stored as fat.

A single system may be composed of many smaller ones. For instance, the human body contains hundreds of millions of bacteria, each of which is its own system. Many of these bacteria are essential to the functioning of human metabolic processes such as digestion.

In addition, humans are part of their local **ecosystem**, which is defined as a complex community of organisms and their environment functioning as an ecological unit in nature. Therefore, to understand the human body system, we must study smaller systems

groundwater

Subsurface water contained in the soil and bedrock of the upper few kilometers of the geosphere, comprising about 0.63 percent of all water in the hydrosphere.

system Any combination of interacting components that form a complex whole.

ecosystem A complex community of individual organisms interacting with each other and with their physical environment and functioning as an ecological unit in nature.

cycle A sequential process or phenomenon that returns to its beginning and then repeats itself over and over.

(e.g., bacteria) that exist within the body, while also exploring how humans interact with their larger ecosystems.

But we're not finished yet.

Individual ecosystems interact with climate systems, ocean currents, and other Earth systems. Thus:

- The size of systems varies dramatically.
- Large systems contain numerous smaller systems.
- Systems interact with one another in complex ways.

As we have learned, Earth is composed of four major systems: geosphere, hydrosphere, atmosphere, and biosphere. Each of these large systems is subdivided into a great many interacting smaller ones. For example, a single volcanic eruption is part of a system. Energy from deep within Earth melts rock, forming magma. Some of this magma escapes during the eruption, along with volcanic gases that react chemically with surface materials. But this volcanic eruption is driven by the distribution and movement of heat within Earth's interior, which is also a system. Volcanic ash and certain gases spewed skyward during the eruption can affect local weather and cool Earth's climate, thereby becoming part of these systems. Heat from the eruption can also rapidly melt glaciers growing near the summit of the volcano, affecting the local hydrologic system. In this book, we will study systems of all sizes and illustrate many of the complex interactions among them.

Earth's surface systems—the atmosphere, hydrosphere, and biosphere—are ultimately powered by the Sun. Wind is powered by uneven solar heating of the atmosphere, ocean waves are driven by the wind, and ocean currents move in response to wind

or differences in water temperature or density. Luckily for us, Earth receives a continuous influx of solar energy, and it will continue to receive this energy for another 5 billion years or so.

In contrast, Earth's interior is powered by the decay of radioactive elements and by residual heat from the primordial coalescence of the planet. We will discuss these sources of heat in later chapters.

Fundamental to our study of Earth systems are several energy and material cycles. A **cycle** is a sequential process or phenomenon that returns to its beginning and then repeats itself over and over. During the course of these cycles, matter is always conserved. It never simply disappears, although it may continuously change form. For example, water evaporates from the ocean into the atmosphere, falls to Earth as rain or snow, and eventually flows back to the oceans. In this book, we will examine the rock cycle (Chapter 3), the hydrologic cycle or water cycle (Chapter 11), the carbon cycle (Chapter 17), and the nitrogen cycle (Chapter 17).

Because matter exists in so many different chemical and physical forms, most materials occur in all four of Earth's major spheres—geosphere, hydrosphere, atmosphere, and biosphere. Water, for example, is chemically bound into clays and other minerals as a component of the geosphere. It is the primary constituent of the hydrosphere and exists in the atmosphere as vapor and clouds. Water is also an essential part of all living organisms. Salt is another example. Thick layers of salt occur as chemical sedimentary rocks; large quantities of salt are dissolved in the oceans; salt aerosols are suspended in the atmosphere; and salt is an essential component of life. As we can see, all the spheres continuously exchange matter and energy. In our study of Earth systems, we categorize the four separate spheres and numerous material cycles independently, but we also recognize that Earth materials and processes are all part of one integrated system (Figure 1.1).

COURTESY OF MATTHEW P. MCGARDLE





“On us who saw these phenomena for the first time, the impression will not easily be forgotten. . . . We felt ourselves necessarily carried back to the time . . . when the sandstone before us was only beginning to be deposited, in the shape of sand and mud, from the waters of an ancient ocean. . . . The mind seemed to grow giddy by looking so far into the abyss of time. . . . We find no vestige of a beginning, no prospect of an end.”

James Hutton¹

1-3 TIME AND RATES OF CHANGE IN EARTH SCIENCE

James Hutton was a gentleman farmer who lived in Scotland in the late 1700s. Although trained as a physician, he never practiced medicine and instead turned to geology. Hutton observed that a certain type of rock, called sandstone, is composed of sand grains cemented together. He also noted that rocks in the Scottish Highlands slowly decompose into sand and that streams carry sand into the Lowlands. He inferred that sandstone is composed of sand grains that originated from the erosion of ancient cliffs and mountains.

Hutton tried to deduce how much time was required to form a thick bed of sandstone. He studied sand grains slowly breaking away from rock outcrops. He watched sand bouncing down streambeds. Finally, he traveled to beaches and river deltas where sand was accumulating. By estimating the time needed for thick layers of sand to accumulate on beaches, Hutton concluded that sandstone must be much older than human history.

Hutton had no way of measuring the magnitude of geologic time. However, modern geologists have learned that certain radioactive materials in rocks can be used as clocks to record the passage of time. Using these “clocks” and other clues embedded in Earth’s crust, the Moon, and in meteorites fallen from the Solar System, geologists estimate that Earth formed 4.6 billion years ago.

The primordial Earth was vastly different from our modern world. There was no crust as we know it today, there were no oceans, and the diffuse atmosphere was vastly different from the modern one. There were no living organisms.

No one knows exactly when or how the first living organisms evolved, but we know that life existed at least as early as 3.8 billion years ago, 800 million years

after the planet formed. For the following 3.3 billion years, life evolved slowly, and although some multicellular organisms developed, most of the biosphere consisted of single-celled organisms. Organisms rapidly became more complex, abundant, and varied about 542 million years ago. The dinosaurs flourished between 225 million and 65 million years ago. *Homo sapiens* and our direct ancestors have been on Earth for 5 to 7 million years, for only about one-tenth of 1 percent of the planet’s history.

In his book *Basin and Range*, John McPhee offers a metaphor for the magnitude of geologic time.² If the history of Earth were represented by the old English measure of a yard—the distance from the king’s nose to the end of his outstretched hand—all of human history could be erased by a single stroke of a file on his middle fingernail. Figure 1.6 summarizes Earth history in graphical form.

Geologists routinely talk about events that occurred millions or even billions of years ago. For example, about 1.7 billion years ago, the granite now forming Mount Rushmore cooled from a melt and crystallized. About a half billion years ago, the Appalachian Mountains began to form from tectonic crumpling of the eastern part of the North American plate. About 150 million years ago, a blanket of mud containing the remains of tiny plankton accumulated in deep water off the West Coast of North America. That sediment has since hardened to form one of the rock units on which the Golden Gate Bridge was built.

There are two significant consequences of the vast span of geologic time:

1. Events that occur slowly become significant. If a continent moves a few centimeters a year, the movement makes no noticeable alteration of Earth systems over decades or centuries.

1. James Hutton, “Theory of the Earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the Globe.” *Transactions of the Royal Society of Edinburgh* 1 (1788): 209–304.

2. John McPhee, *Basin and Range* (New York: Farrar, Straus & Giroux, 1982).