An aerial photograph of a farm situated on rolling green hills. The scene is captured at sunrise or sunset, with a warm, golden light illuminating the landscape. A layer of mist or fog hangs in the valleys between the hills, creating a soft, ethereal atmosphere. The farm itself consists of several red-roofed buildings, a prominent white silo, and a barn, all nestled among lush green fields and clusters of trees. The overall composition emphasizes the beauty and tranquility of a rural landscape.

exploring physical geography

Second Edition

**Mc
Graw
Hill**
Education

Stephen J.
REYNOLDS

Robert V.
ROHLI

Julia K.
JOHNSON

Peter R.
WAYLEN

Mark A.
FRANCEK

exploring physical
geography

About the Cover

This photograph by Michael Collier shows farms atop a hill in West Virginia. Morning mist hanging down in the valleys outlines the network of streams, like Grove Creek and Fish Creek, that collect and drain into the Ohio River near Moundsville. The underlying rocks are sedimentary and in places contain seams of coal that were formed from ancient swamps that covered the area during the Pennsylvanian Period. This area is part of the Appalachian Plateau Province, which was uplifted to its current elevation of about 1,200 feet above sea level by tectonic compression that created the Appalachian Mountains. In addition to coal mining, agriculture has always been important to this region. Hardwood forests have been removed along the ridges to create fields for crops and cattle.

Michael Collier received his B.S. in geology at Northern Arizona University, M.S. in structural geology at Stanford, and M.D. from the University of Arizona. He rowed boats commercially in Grand Canyon in the late 1970s and early 1980s. He now lives in Flagstaff, Arizona, where he practices family medicine. Collier has published books about the geology of Grand Canyon National Park, Death Valley, Denali National Park, and Capitol Reef National Park. He has done books on the Colorado River basin, glaciers of Alaska, and climate change in Alaska. He recently completed a three-book series on American mountains, rivers, and coastlines, designed around his spectacular photographs taken from the air. As a special-projects writer with the USGS, he wrote books about the San Andreas fault, climate change, and downstream effects of dams, with each book featuring his many photographs. Collier has produced an iPad app about seeing landscapes from the air. He received the USGS Shoemaker Communication Award in 1997, the National Park Service Director's Award in 2000, and the American Geological Institute's Public Contribution to Geosciences Award in 2005.



STEPHEN J. REYNOLDS

Arizona State University

ROBERT V. ROHLI

Louisiana State University

JULIA K. JOHNSON

Arizona State University

PETER R. WAYLEN

University of Florida

MARK A. FRANCEK

Central Michigan University

exploring physical
geography

CYNTHIA C. SHAW

Lead Illustrator, Art Director

**Mc
Graw
Hill**
Education



EXPLORING PHYSICAL GEOGRAPHY, SECOND EDITION

Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121. Copyright © 2018 by McGraw-Hill Education. All rights reserved. Printed in the United States of America. Previous edition © 2015. No part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written consent of McGraw-Hill Education, including, but not limited to, in any network or other electronic storage or transmission, or broadcast for distance learning.

Some ancillaries, including electronic and print components, may not be available to customers outside the United States.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LWI 21 20 19 18 17

ISBN 978-1-259-54243-5

MHID 1-259-54243-2

Chief Product Officer, SVP Products & Markets: *G. Scott Virkler*
Vice President, General Manager, Products & Markets: *Marty Lange*
Vice President, Content Design & Delivery: *Betsy Whalen*
Managing Director: *Thomas Timp*
Senior Director, Content Design & Delivery: *Linda Avenarius*
Brand Manager: *Michael Ivanov, Ph.D.*
Director, Product Development: *Rose Koos*
Director of Digital Content: *Philip Janowicz, Ph.D.*
Product Developer: *Jodi Rhomberg*
Market Development Manager: *Tamara Hodge*
Marketing Manager: *Noah Evans*
Digital Product Analyst: *Patrick Diller*
Digital Product Developer: *Joan Weber*
Program Manager: *Lora Neyens*
Content Project Managers: *Laura Bies, Tammy Juran & Sandy Schnee*
Buyer: *Sandy Ludovissy*
Design: *Matt Backhaus*
Content Licensing Specialists: *Lori Hancock & Melisa Seegmiller*
Cover Image: *Michael Collier*
Compositor: *SPi Global*
Printer: *LSC Communications*

All credits appearing on page or at the end of the book are considered to be an extension of the copyright page.

Library of Congress Cataloging-in-Publication Data

Names: Reynolds, Stephen J., author.

Title: Exploring physical geography / Stephen J. Reynolds, Arizona State University, Robert V. Rohli, Louisiana State University, Julia K. Johnson, Arizona State University, Peter R. Waylen, University of Florida, Mark A. Francek, Central Michigan University.

Description: Second edition. | New York, NY : McGraw-Hill, [2017]

Identifiers: LCCN 2016034542 | ISBN 9781259542435 (alk. paper)

Subjects: LCSH: Physical geography—Textbooks.

Classification: LCC GB54.5 .R49 2017 | DDC 910/.02—dc23 LC record available at <https://lccn.loc.gov/2016034542>

The Internet addresses listed in the text were accurate at the time of publication. The inclusion of a website does not indicate an endorsement by the authors or McGraw-Hill Education, and McGraw-Hill Education does not guarantee the accuracy of the information presented at these sites.

BRIEF CONTENTS

CHAPTER 1:	THE NATURE OF PHYSICAL GEOGRAPHY	2
CHAPTER 2:	ENERGY AND MATTER IN THE ATMOSPHERE.....	34
CHAPTER 3:	ATMOSPHERIC MOTION.....	74
CHAPTER 4:	ATMOSPHERIC MOISTURE.....	108
CHAPTER 5:	WEATHER SYSTEMS AND SEVERE WEATHER	142
CHAPTER 6:	ATMOSPHERE-OCEAN-CRYOSPHERE INTERACTIONS.....	180
CHAPTER 7:	CLIMATES AROUND THE WORLD	212
CHAPTER 8:	WATER RESOURCES.....	246
CHAPTER 9:	UNDERSTANDING LANDSCAPES.....	272
CHAPTER 10:	PLATE TECTONICS AND REGIONAL FEATURES	306
CHAPTER 11:	VOLCANOES, DEFORMATION, AND EARTHQUAKES	344
CHAPTER 12:	WEATHERING AND MASS WASTING	384
CHAPTER 13:	STREAMS AND FLOODING.....	416
CHAPTER 14:	GLACIERS AND GLACIAL LANDFORMS	452
CHAPTER 15:	COASTS AND CHANGING SEA LEVELS.....	476
CHAPTER 16:	SOILS	502
CHAPTER 17:	ECOSYSTEMS AND BIOGEOCHEMICAL CYCLES	534
CHAPTER 18:	BIOMES.....	564

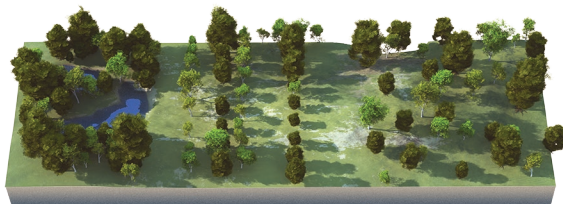
CONTENTS

Preface	xiv
Connect	xxiv
Acknowledgments	xxvi
About the Authors	xxix

CHAPTER 1: THE NATURE OF PHYSICAL GEOGRAPHY

2

1.1 What Is Physical Geography?	4
1.2 How Do We Investigate Geographic Questions?	6
1.3 How Do Natural Systems Operate?	8
1.4 What Are Some Important Earth Cycles?	10
1.5 How Do Earth's Four Spheres Interact?	12
1.6 How Do We Depict Earth's Surface?	14
1.7 What Do Latitude and Longitude Indicate?	16
1.8 What Are Some Other Coordinate Systems?	18
1.9 How Do Map Projections Influence the Portrayal of Spatial Data?	20
1.10 How Do We Use Maps and Photographs?	22
1.11 How Do We Use Global Positioning Systems and Remote Sensing?	24
1.12 How Do We Use GIS to Explore Spatial Issues?	26
1.13 What Is the Role of Time in Geography?	28
1.14 CONNECTIONS: How Did Geographers Help in the 2010 Gulf of Mexico Oil-Spill Cleanup?	30
1.15 INVESTIGATION: What Might Happen If This Location Is Deforested?	32

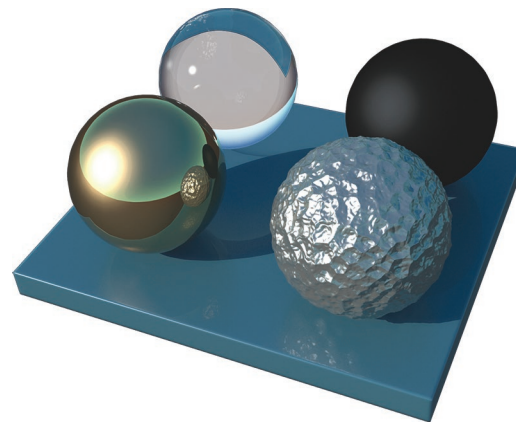


CHAPTER 2: ENERGY AND MATTER IN THE ATMOSPHERE

34

2.1 What Is the Atmosphere?	36
2.2 What Is Energy and How Is It Transmitted?	38
2.3 What Are Heat and Temperature?	40
2.4 What Is Latent Heat?	42

2.5 What Is Electromagnetic Radiation?	44
2.6 What Controls Wavelengths of Radiation?	46
2.7 What Causes Changes in Insolation?	48
2.8 Why Does Insolation Vary from Place to Place?	50
2.9 Why Do We Have Seasons?	52
2.10 What Controls When and Where the Sun Rises and Sets?	54
2.11 How Does Insolation Interact with the Atmosphere?	56
2.12 What Is Ozone and Why Is It So Important?	58
2.13 How Much Insolation Reaches the Surface?	60
2.14 What Happens to Insolation That Reaches the Surface?	62
2.15 How Does Earth Maintain an Energy Balance?	64
2.16 How Do Insolation and Outgoing Radiation Vary Spatially?	66
2.17 Why Do Temperatures Vary Between Oceans and Continents?	68
2.18 CONNECTIONS: How Are Variations in Insolation Expressed Between the North and South Poles?	70
2.19 INVESTIGATION: How Do We Evaluate Sites for Solar-Energy Generation?	72

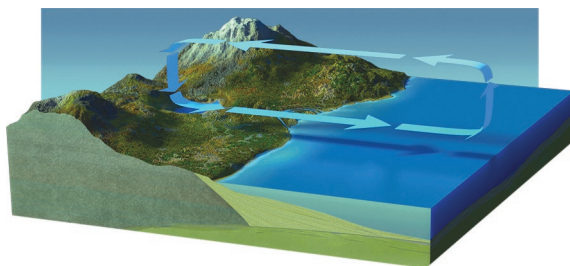


CHAPTER 3: ATMOSPHERIC MOTION

74

3.1 How Do Gases Respond to Changes in Temperature and Pressure?	76
3.2 What Is Air Pressure?	78
3.3 What Causes Pressure Variations and Winds?	80
3.4 How Do Variations in Temperature and Pressure Cause Local Atmospheric Circulation?	82

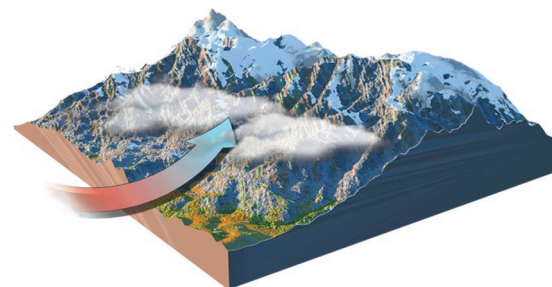
3.5	What Are Some Significant Regional Winds?	84
3.6	How Do Variations in Insolation Cause Global Patterns of Air Pressure and Circulation?	86
3.7	What Is the Coriolis Effect?	88
3.8	How Does the Coriolis Effect Influence Wind Direction at Different Heights?	90
3.9	How Do the Coriolis Effect and Friction Influence Atmospheric Circulation?	92
3.10	How Does Air Circulate in the Tropics?	94
3.11	How Does Air Circulate in High Latitudes?	96
3.12	How Does Surface Air Circulate in Mid-Latitudes?	98
3.13	How Does Air Circulate Aloft over the Mid-Latitudes?	100
3.14	What Causes Monsoons?	102
3.15	CONNECTIONS: How Have Global Pressures and Winds Affected History in the North Atlantic?	104
3.16	INVESTIGATION: What Occurs During Seasonal Circulation Shifts?	106



CHAPTER 4: ATMOSPHERIC MOISTURE 108

4.1	How Does Water Occur in the Atmosphere?	110
4.2	What Is Humidity?	112
4.3	How Does Specific Humidity Vary Globally and Seasonally?	114
4.4	What Is the Dew Point?	116
4.5	What Happens When Air Rises or Sinks?	118
4.6	How Does the Surface Affect the Rising of Air?	120
4.7	What Mechanisms Can Force Air to Rise?	122
4.8	What Do Clouds Tell Us About Weather?	124
4.9	What Conditions Produce Fog?	126

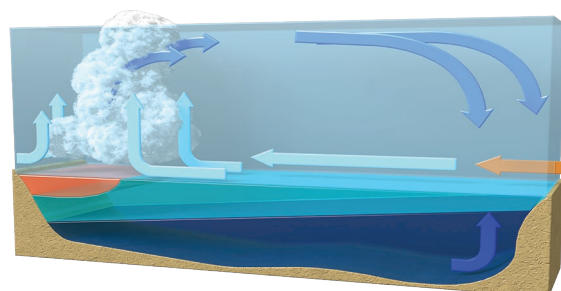
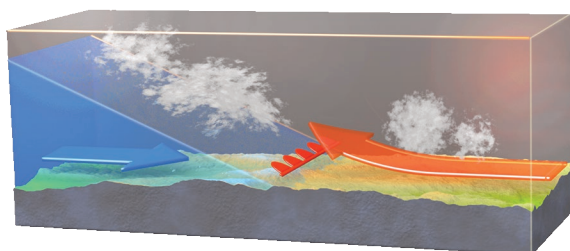
4.10	Where and When Is Fog Most Likely?	128
4.11	How Does Precipitation Form?	130
4.12	How Do Sleet and Freezing Rain Form?	132
4.13	What Is the Distribution of Precipitation?	134
4.14	How Can Moisture Extremes Be Characterized?	136
4.15	CONNECTIONS: What Caused the Recent Great Plains Drought?	138
4.16	INVESTIGATION: How Do Global Patterns of Humidity, Water Vapor, and Precipitation Compare?	140



CHAPTER 5: WEATHER SYSTEMS AND SEVERE WEATHER 142

5.1	Why Does Weather Change?	144
5.2	What Are Fronts?	146
5.3	Where Do Mid-Latitude Cyclones Form and Cross North America?	148
5.4	How Do Mid-Latitude Cyclones Move and Evolve?	150
5.5	How Do Migrating Anticyclones Form and Affect North America?	152
5.6	What Conditions Produce Thunderstorms?	154
5.7	Where Are Thunderstorms Most Common?	156
5.8	What Causes Hail?	158
5.9	What Causes Lightning and Thunder?	160
5.10	What Is a Tornado?	162
5.11	Where and When Do Tornadoes Strike?	164
5.12	What Are Some Other Types of Wind Storms?	166
5.13	What Is a Tropical Cyclone?	168
5.14	What Affects the Strength of a Tropical Cyclone?	170
5.15	How Are Weather Forecasts Made?	172

- 5.16** How Are We Warned About Severe Weather? 174
- 5.17 CONNECTIONS:** What Happened During Hurricane Sandy? 176
- 5.18 INVESTIGATION:** Where Would You Expect Severe Weather? 178

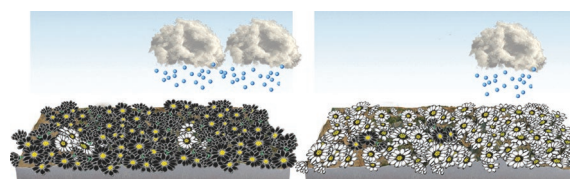


CHAPTER 6: ATMOSPHERE-OCEAN- CRYOSPHERE INTERACTIONS 180

- 6.1** What Causes Ocean Currents? 182
- 6.2** What Is the Global Pattern of Surface Currents? 184
- 6.3** How Do Sea-Surface Temperatures Vary from Place to Place and Season to Season? 186
- 6.4** What Causes Water to Rise or Sink? 188
- 6.5** What Are the Global Patterns of Temperature and Salinity? 190
- 6.6** What Processes Affect Ocean Temperature and Salinity in Tropical and Polar Regions? 192
- 6.7** How Are the Atmosphere, Oceans, and Cryosphere Coupled? 194
- 6.8** What Connects Equatorial Atmospheric and Oceanic Circulation? 196
- 6.9** What Are El Niño and the Southern Oscillation? 198
- 6.10** What Are the Phases of ENSO? 200
- 6.11** Do Impacts of ENSO Reach Beyond the Tropics? 202
- 6.12** How Does an El Niño Start and Stop? 204
- 6.13** Do Other Oceans Display Oscillations? 206
- 6.14 CONNECTIONS:** What Influences Climates Near the Southern Isthmus of Central America? 208
- 6.15 INVESTIGATION:** What Oceanic and Atmospheric Patterns Are Predicted for a Newly Discovered Planet? 210

CHAPTER 7: CLIMATES AROUND THE WORLD 212

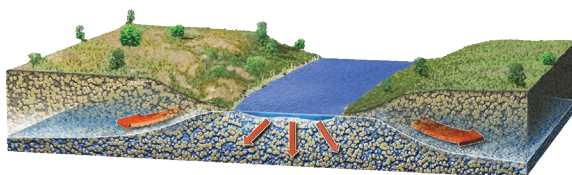
- 7.1** How Do We Classify Climates? 214
- 7.2** Where Are Different Climate Types Located? 216
- 7.3** What Are the Most Common Climate Types? 218
- 7.4** What Is the Setting of Tropical Climates? 220
- 7.5** What Conditions Cause Arid Climates? 222
- 7.6** What Causes Warm Temperate Climates? 224
- 7.7** What Are the Settings of Mid-Latitude Climates? 226
- 7.8** What Causes Subarctic and Polar Climates? 228
- 7.9** How Does Air Quality Relate to Climate? 230
- 7.10** How Do Air Pollution and Urbanization Affect and Respond to the Local Climate? 232
- 7.11** What Is the Evidence for Climate Change? 234
- 7.12** What Factors Influence Climate Change? 236
- 7.13** What Are the Consequences of Climate Change? 238
- 7.14** How Do We Use Computers to Study Climate Change? 240
- 7.15 CONNECTIONS:** How Does the Climate System Sustain Life? 242
- 7.16 INVESTIGATION:** What Climates and Weather Would Occur Here? 244



CHAPTER 8: WATER RESOURCES

246

- 8.1 Where Does Water Occur on the Planet? 248
- 8.2 What Is the Global Water Budget? 250
- 8.3 How Do We Evaluate Water Balances? 252
- 8.4 How Do Water Balances Vary Spatially? 254
- 8.5 How Do We Use Freshwater Resources? 256
- 8.6 How and Where Does Groundwater Flow? 258
- 8.7 What Is the Relationship Between Surface Water and Groundwater? 260
- 8.8 What Problems Are Associated with Groundwater Pumping? 262
- 8.9 How Can Water Become Contaminated? 264
- 8.10 How Does Groundwater Contamination Move and How Do We Clean It Up? 266
- 8.11 **CONNECTIONS:** What Is Happening with the Ogallala Aquifer? 268
- 8.12 **INVESTIGATION:** Who Polluted Surface Water and Groundwater in This Place? 270

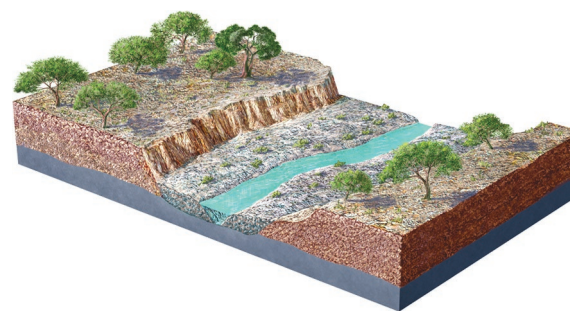


CHAPTER 9: UNDERSTANDING LANDSCAPES

272

- 9.1 What Materials Compose Landscapes? 274
- 9.2 How Do Rocks Form? 276
- 9.3 What Can Happen to a Rock? 278
- 9.4 What Are Some Common Sedimentary Rocks? 280
- 9.5 What Are Igneous Processes and Rocks? 282
- 9.6 What Are Metamorphic Processes and Rocks? 284
- 9.7 How Are Different Rock Types Expressed in Landscapes? 286
- 9.8 What Controls the Appearance of Landscapes? 288

- 9.9 How Are Landscapes Weathered and Eroded? 290
- 9.10 How Do Landscapes Record Transport and Deposition by Gravity, Streams, Ice, and Waves? 292
- 9.11 How Do Landscapes Record Transport and Deposition by Wind? 294
- 9.12 How Do We Infer the Relative Ages of Events? 296
- 9.13 How Do We Determine the Ages of Events? 298
- 9.14 How Do We Study Ages of Landscapes? 300
- 9.15 **CONNECTIONS:** What Is the Natural History of the Grand Canyon? 302
- 9.16 **INVESTIGATION:** What Is the History of This Landscape? 304

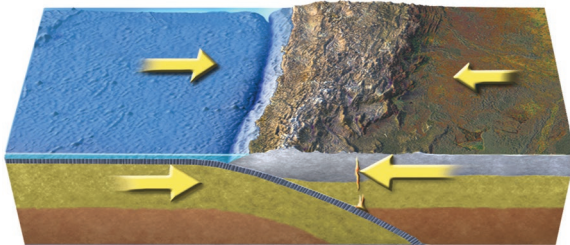


CHAPTER 10: PLATE TECTONICS AND REGIONAL FEATURES

306

- 10.1 What Is Inside Earth? 308
- 10.2 What Are the Major Features of Earth? 310
- 10.3 Why Do Some Continents Have Matching Shapes? 312
- 10.4 What Is the Distribution of Earthquakes, Volcanoes, and Mountain Belts? 314
- 10.5 What Causes Tectonic Activity to Occur in Belts? 316
- 10.6 What Happens at Divergent Boundaries? 318
- 10.7 What Happens at Convergent Boundaries? 320
- 10.8 What Happens Along Transform Boundaries? 322
- 10.9 Why and How Do Plates Move? 324
- 10.10 How Is Paleomagnetism Used to Determine Rates of Seafloor Spreading? 326
- 10.11 What Features Form at Oceanic Hot Spots? 328
- 10.12 What Features Form at Continental Hot Spots? 330
- 10.13 What Are Continents and How Do They Form? 332

10.14 How Did the Continents Join and Split Apart?	334
10.15 Where Do Mountain Belts and High Regions Form?	336
10.16 How Do Internal and External Processes Interact to Form Landscapes?	338
10.17 CONNECTIONS: Why Is South America Lopsided?	340
10.18 INVESTIGATION: What Is the Plate Tectonics of This Place?	342

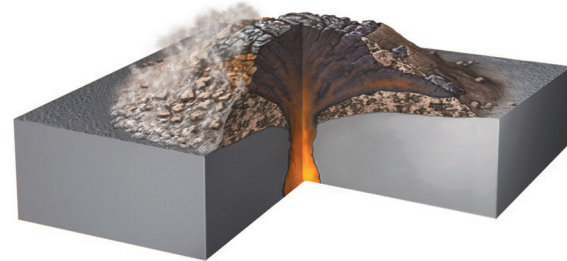


CHAPTER 11: VOLCANOES, DEFORMATION, AND EARTHQUAKES

344

11.1 What Is a Volcano?	346
11.2 How Do Volcanoes Erupt?	348
11.3 What Volcanic Features Consist of Basalt?	350
11.4 What Are Composite Volcanoes and Volcanic Domes?	352
11.5 What Are Calderas?	354
11.6 What Hazards Are Associated with Volcanoes?	356
11.7 What Areas Have the Highest Potential for Volcanic Hazards?	358
11.8 How Are Magmatic Conduits Exposed?	360
11.9 What Is Deformation and How Is It Expressed in Landscapes?	362
11.10 How Are Fractures Expressed in Landscapes?	364
11.11 How Are Folds Expressed in Landscapes?	366
11.12 How Do Local Mountains and Basins Form?	368
11.13 What Is an Earthquake?	370
11.14 Where Do Most Earthquakes Occur?	372
11.15 What Causes Earthquakes Along Plate Boundaries and Within Plates?	374
11.16 How Do Earthquakes Cause Damage?	376

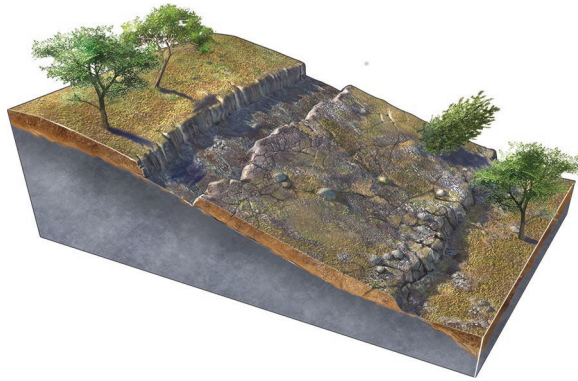
11.17 What Were Some Recent Large Earthquakes?	378
11.18 CONNECTIONS: What Happened During the Great Alaskan Earthquake of 1964?	380
11.19 INVESTIGATION: Where Is the Safest Place to Live in This Area?	382



CHAPTER 12: WEATHERING AND MASS WASTING

384

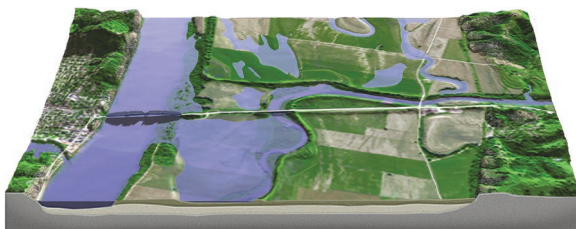
12.1 How Does Physical Weathering Affect Earth's Surface?	386
12.2 How Does Chemical Weathering Affect Earth's Surface?	388
12.3 How Do Climate, Slope, Vegetation, and Time Influence Weathering?	390
12.4 How Does the Type of Earth Material Influence Weathering?	392
12.5 How Is Weathering Expressed?	394
12.6 How Do Caves Form?	396
12.7 What Is Karst Topography?	398
12.8 What Controls the Stability of Slopes?	400
12.9 How Do Slopes Fail?	402
12.10 How Does Material on Slopes Fall and Slide?	404
12.11 How Does Material Flow Down Slopes?	406
12.12 Where Do Slope Failures Occur in the U.S.?	408
12.13 How Do We Study Slope Failures and Assess the Risk for Future Events?	410
12.14 CONNECTIONS: What Is Happening with the Slumgullion Landslide in Colorado?	412
12.15 INVESTIGATION: Which Areas Have the Highest Risk of Slope Failure?	414



CHAPTER 13: STREAMS AND FLOODING

416

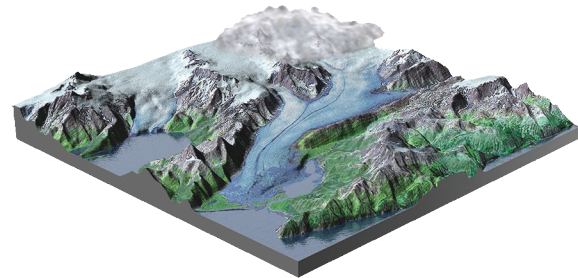
- 13.1** What Are Stream Systems? 418
- 13.2** How Do Streams Transport Sediment and Erode Their Channels? 420
- 13.3** How Do Streams Change Downstream or Over Short Time Frames? 422
- 13.4** What Factors Influence Profiles of Streams? 424
- 13.5** Why Do Streams Have Curves? 426
- 13.6** What Happens in the Headwaters of Streams? 428
- 13.7** What Features Characterize Braided Streams? 430
- 13.8** What Features Characterize Low-Gradient Streams? 432
- 13.9** What Happens When a Stream Reaches Its Base Level? 434
- 13.10** How Do Streams Change Over Time? 436
- 13.11** What Happens During Stream Incision? 438
- 13.12** What Is and What Is Not a Flood? 440
- 13.13** What Were Some Devastating Floods? 442
- 13.14** How Do We Measure Floods? 444
- 13.15** How Do Streams Affect People? 446
- 13.16 CONNECTIONS:** How Does the Colorado River Change as It Flows Across the Landscape? 448
- 13.17 INVESTIGATION:** How Would Flooding Affect This Place? 450



CHAPTER 14: GLACIERS AND GLACIAL LANDFORMS

452

- 14.1** What Are Glaciers? 454
- 14.2** What Is the Distribution of Present and Past Glaciers? 456
- 14.3** How Do Glaciers Form, Move, and Vanish? 458
- 14.4** How Do Glaciers Erode, Transport, and Deposit? 460
- 14.5** What Are the Landforms of Alpine Glaciation? 462
- 14.6** What Are the Landforms of Continental Glaciation? 464
- 14.7** What Features Are Peripheral to Glaciers? 466
- 14.8** What Is the Evidence for Past Glaciations? 468
- 14.9** What Starts and Stops Glaciations? 470
- 14.10 CONNECTIONS:** What Would Happen to Sea Level if the Ice in West Antarctica Melted? 472
- 14.11 INVESTIGATION:** How Could Global Warming or a Glacial Period Affect Sea Level in North America? 474

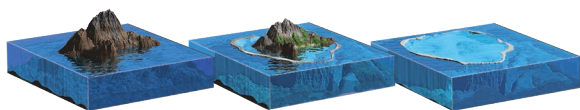


CHAPTER 15: COASTS AND CHANGING SEA LEVELS

476

- 15.1** What Processes Occur Along Coasts? 478
- 15.2** What Causes High Tides and Low Tides? 480
- 15.3** How Do Waves Form and Propagate? 482
- 15.4** How Is Material Eroded, Transported, and Deposited Along Coasts? 484
- 15.5** What Landforms Occur Along Coasts? 486
- 15.6** How Do Reefs and Coral Atolls Form? 488

15.7 What Are Some Challenges of Living in a Coastal Zone?	490
15.8 How Do We Assess the Relative Risks of Different Stretches of Coastline?	492
15.9 What Happens When Sea Level Changes?	494
15.10 What Causes Changes in Sea Level?	496
15.11 CONNECTIONS: What Coastal Damage Was Caused by These Recent Atlantic Hurricanes?	498
15.12 INVESTIGATION: What Is Happening Along the Coast of This Island?	500



CHAPTER 16: SOILS

502

16.1 What Is Soil?	504
16.2 What Are the Physical Properties of Soil?	506
16.3 What Is the Role of Water in Soil?	508
16.4 What Are the Chemical and Biological Properties of Soil?	510
16.5 How Do Climate and Vegetation Affect Soil?	512
16.6 How Do Terrain, Parent Material, and Time Affect Soil?	514
16.7 What Are the Major Layers of Soil?	516
16.8 What Are the Major Types of Soil?	518
16.9 What Types of Soils Largely Reflect the Local Setting or Initial Stages in Soil Formation?	520
16.10 What Types of Soils Form Under Relatively Warm Conditions?	522
16.11 What Types of Soils Form Under Temperate and Polar Conditions?	524
16.12 Where Do the Various Soil Types Exist?	526
16.13 What Are the Causes and Impacts of Soil Erosion?	528
16.14 CONNECTIONS: How Does Soil Impact the Way We Use Land?	530

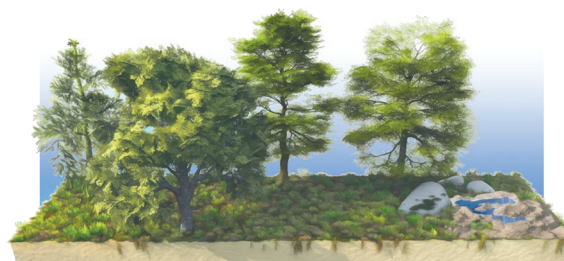
16.15 INVESTIGATION: Where Do These Soils Originate?	532
---	-----



CHAPTER 17: ECOSYSTEMS AND BIOGEOCHEMICAL CYCLES

534

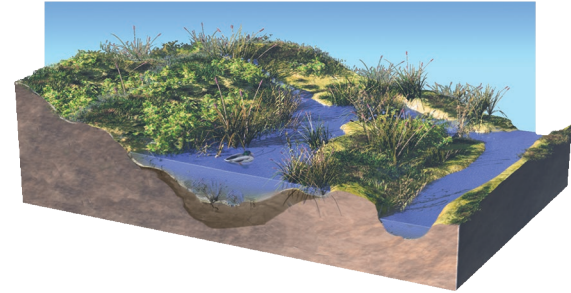
17.1 How Is the Ecosystem Approach Useful in Understanding the Biosphere?	536
17.2 What Types of Organisms Inhabit Ecosystems?	538
17.3 What Interactions Occur in Ecosystems?	540
17.4 How Can Biodiversity Be Assessed?	542
17.5 How Does Energy Flow Through Ecosystems?	544
17.6 How Do We Describe Ecosystem Productivity?	546
17.7 How Do Ecosystems React to Disturbance?	548
17.8 What Is the Role of Carbon in Ecosystems?	550
17.9 What Is the Role of Nitrogen in Ecosystems?	552
17.10 What Is the Role of Phosphorus in Ecosystems?	554
17.11 What Is the Role of Sulfur in the Environment?	556
17.12 How Does a Lack of Oxygen Harm Ecosystems?	558
17.13 CONNECTIONS: How Do Invasive Species Impact U.S. Gulf Coast Ecosystems?	560
17.14 INVESTIGATION: What Factors Influence the Desert Ecosystems of Namibia in Southern Africa?	562



CHAPTER 18: BIOMES

564

18.1 What Biomes Exist on Earth?	566	
18.2 Where Are Each of the Biomes Distributed?	568	
18.3 What Factors Influence Biome Distribution?	570	
18.4 How Does Topography Influence Biomes?	572	
18.5 What Characterizes the Rain Forest Biome?	574	
18.6 How Are Tropical Rain Forests Threatened?	576	
18.7 What Are Deserts and How Do They Form?	578	
18.8 How Do Desert Organisms Survive?	580	
18.9 What Are the Features of the Grassland Biome?	582	
18.10 What Characterizes the Subtropical Scrub and Woodland Biome?	584	
18.11 What Characterizes the Temperate Forest Biome?	586	
18.12 What Characterizes the Boreal Forest Biome?	588	
18.13 What Characterizes the Tundra Biome?	590	
18.14 What Characterizes the Freshwater Biome?	592	
18.15 What Ecosystems Exist in the Saltwater Biome?	594	
18.16 How Do Animal Realms Overlap with Biomes?	596	
		18.17 What Are the Issues with Sustainability?
		598
		18.18 CONNECTIONS: How Do the Atmosphere, Hydrosphere, and Cryosphere Interact with Land to Form Biomes?
		600
		18.19 INVESTIGATION: What Factors Might Control the Biomes in This Location?
		602
		Glossary
		G-1
		Credits
		C-1
		Index
		I-1
		Shaded-Relief Map of the United States
		Inside Back Cover



PREFACE

TELLING THE STORY . . .

WE WROTE *EXPLORING PHYSICAL GEOGRAPHY* so that students could learn from the book on their own, freeing up instructors to teach the class in any way they want. I (Steve Reynolds) first identified the need for this type of book while I was a National Association of Geoscience Teachers' (NAGT) distinguished speaker. As part of my NAGT activities, I traveled around the country conducting workshops on how to infuse active learning and scientific inquiry into introductory college science courses, including those with upwards of 200 students. In the first part of the workshop, I asked the faculty participants to list the main goals of an introductory science course, especially for non-majors. At every school I visited, the main goals were similar to those listed below:

- to engage students in the process of scientific inquiry so that they learn what science is and how it is conducted,
- to teach students how to observe and interpret landscapes and other aspects of their physical environment,
- to enable students to learn and apply important concepts of science,
- to help students understand the relevance of science to their lives, and
- to enable students to use their new knowledge, skills, and ways of thinking to become more informed citizens.

I then asked faculty members to rank these goals and estimate how much time they spent on each goal in class. At this point, many instructors recognized that their activities in class were not consistent with their own goals. Most instructors were spending nearly all of class time teaching content. Although this was one of their main goals, it commonly was not their top goal.

Next, I asked instructors to think about why their activities were not consistent with their goals. Inevitably, the answer was that most instructors spend nearly all of class time covering content because (1) textbooks

include so much material that students have difficulty distinguishing what is important from what is not, (2) instructors needed to lecture so that students would know what is important, and (3) many students have difficulty learning independently from the textbook.

In most cases, textbooks drive the curriculum, so my coauthors and I decided that we should write a textbook that (1) contains only important material, (2) indicates clearly to the student what is important and what they need to know, and (3) is designed and written in such a way that students can learn from the book on their own. This type of book would give instructors freedom to teach in a way that is more consistent with their goals, including using local examples to illustrate geographic concepts and their relevance. Instructors would also be able to spend more class time teaching students to observe and interpret landscapes, atmospheric phenomena, and ecosystems, and to participate in the process of scientific inquiry, which represents the top goal for many instructors.

COGNITIVE AND SCIENCE-EDUCATION RESEARCH

To design a book that supports instructor goals, we delved into cognitive and science-education research, especially research on how our brains process different types of information, what obstacles limit student learning from textbooks, and how students use visuals versus text while studying. We also conducted our own research on how students interact with textbooks, what students see when they observe photographs showing landscape features, and how they interpret different types of scientific illustrations, including maps, cross sections, and block diagrams that illustrate the evolution of environments. *Exploring Physical Geography* is the result of our literature search and of our own science-education research. As you examine *Exploring Physical Geography*, you will notice that it is stylistically different from most other textbooks, which will likely elicit a few questions.

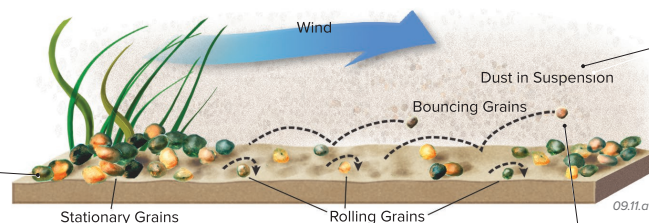
A How Does Wind Transport Sediment?

Wind is generated by differences in air pressure and at times is strong enough to transport material, but only relatively small and lightweight fragments, like sand and clay. Transport of these materials by the wind is most efficient in dry climates, where there is limited vegetation to bind materials together and hold them on the ground.

1. Wind is capable of transporting sand and finer sediment, as well as lightweight plant fragments and other materials lying on the surface. It generally moves material in one of three ways and can deposit sediment in various settings, some of which are shown in photographs on these two pages.

2. Most materials on Earth's surface are not moved by the wind because they are too firmly attached to the land (such as rock outcrops), are too large or heavy to be moved, or are both.

3. If wind velocity is great enough, it can roll or slide grains of sand and silt and other loose materials across the ground.



5. Wind can pick up and carry finer material, such as dust, silt, and salt. This mode of transport is called *suspension*, and wind can keep some particles in the air for weeks, transporting them long distances, even across the oceans.

4. Very strong winds can lift sand grains, carry them short distances, and drop them. This process is akin to bouncing a grain along the surface and is called *saltation*.

HOW DOES THIS BOOK SUPPORT STUDENT CURIOSITY AND INQUIRY?

CHAPTER

12

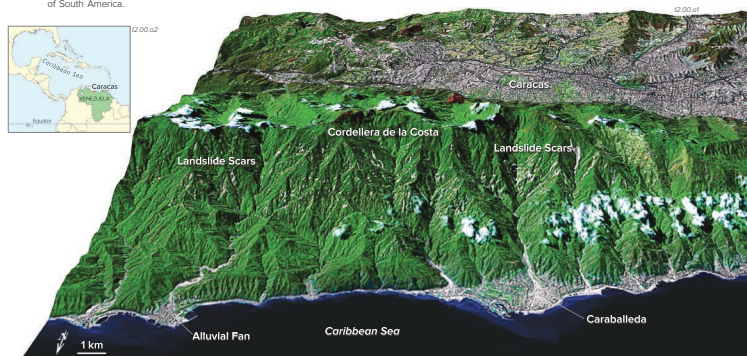
Weathering and Mass Wasting

THE BREAKDOWN OF SURFACE MATERIALS—weathering—produces soils and can lead to unstable slopes. Such slope instability is called *mass wasting*, which is the movement of material downslope in response to gravity. Mass wasting can be slow and barely perceptible, or it can be catastrophic, involving thick, dangerous slurries of mud and debris. It is a type of erosion that strips material off a landscape and transports that material away. What physical and chemical weathering processes loosen material from solid rocks and lead to mass wasting? What factors determine if a slope is stable, and how do slopes fail? In this chapter, we explore weathering and mass wasting, which help sculpt natural landscapes.

The **Cordillera de la Costa** is a steep 2 km-high mountain range that runs along the coast of Venezuela, separating the capital city of Caracas from the sea. This image, looking south, has topography overlain with a satellite image taken in 2000. The white areas are clouds and the purple areas are cities. The Caribbean Sea is in the foreground. The map below shows the location of Venezuela on the northern coast of South America.

In December 1999, torrential rains in the mountains caused landslides and mobilized soil and other loose material as debris flows and flash floods that buried parts of the coastal cities. Some light-colored landslide scars are visible on the hillsides in this image.

How does soil and other loose material form on hillslopes? What factors determine whether a slope is stable or is prone to landslides and other types of downhill movement?



The mountain slopes are too steep for buildings, so people built the coastal cities on the less steep fan-shaped areas at the foot of each valley. These flatter areas are alluvial fans composed of mountain-derived sediment that has been transported down the canyons and deposited along the mountain front.

What are some potential hazards of living next to steep mountain slopes, especially in a city built on an active alluvial fan?

The city of **Caraballeda**, built on one such alluvial fan, was especially hard hit in 1999 by debris flows and flash floods that tore a swath of destruction through the town. Landslides, debris flows, and flooding killed more than 19,000 people and caused up to \$30 billion in damage in the region. The damage is visible as the light-colored strip through the center of town.

How can loss of life and destruction of property by debris flows and landslides be avoided or at least minimized?

384

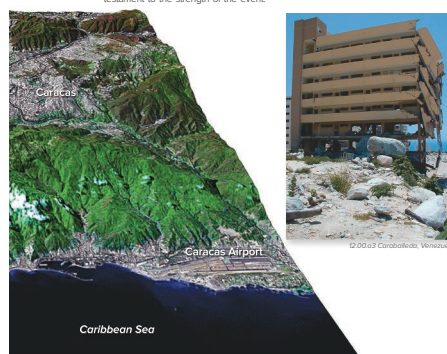
Weathering and Mass Wasting 385



TOPICS IN THIS CHAPTER

12.1	How Does Physical Weathering Affect Earth's Surface?	386	12.8	What Controls the Stability of Slopes?	400
12.2	How Does Chemical Weathering Affect Earth's Surface?	388	12.9	How Do Slopes Fail?	402
12.3	How Does the Type of Earth Material Influence Weathering?	390	12.10	How Does Material on Slopes Fall and Slide?	404
12.4	How Do Climate, Slope, Vegetation, and Time Influence Weathering?	392	12.11	How Does Material Flow Down Slopes?	406
12.5	How Is Weathering Expressed?	394	12.12	Where Do Slope Failures Occur in the U.S.?	408
12.6	How Do Caves Form?	396	12.13	How Do We Study Slope Failures and Assess the Risk for Future Events?	410
12.7	What Is Karst Topography?	398	12.14	CONNECTIONS: What Is Happening with the Slinguillon Landslide in Colorado?	412
			12.15	INVESTIGATION: Which Areas Have the Highest Risk of Slope Failure?	414

Huge boulders smashed through the lower two floors of this building in Caraballeda and ripped away part of the right side (▼). The mud and water that transported these boulders are no longer present, but the boulders remain as a testament to the strength of the event.



This aerial photograph (▲) of Caraballeda, looking south up the canyon, shows the damage in the center of the city caused by the debris flows and flash floods. Many houses were completely demolished by the fast-moving, boulder-rich mud.

1999 Venezuelan Disaster

A **debris flow** is a slurry of water and debris, including mud, sand, gravel, pebbles, boulders, vegetation, and even cars and small structures. Debris flows can move at speeds up to 80 km/hr (50 mph), but most are slower. In December 1999, two storms dumped as much as 1.1 m (42 in.) of rain on the coastal mountains of Venezuela. The rain loosened soil on the steep hillsides, causing many landslides and debris flows that coalesced in the steep canyons and raced downhill toward the cities built on the alluvial fans.

In Caraballeda, the debris flows carried boulders up to 10 m (33 ft) in diameter and weighing 300 to 400 tons each. The debris flows and flash floods raced across the city, flattening cars and smashing houses, buildings, and bridges. They left behind a jumble of boulders and other debris along the path of destruction through the city.

After the event, USGS geoscientists went into the area to investigate what had happened and why. They documented the types of material that were carried by the debris flows, mapped the extent of the flows, and measured boulders (▼) to investigate processes that occurred during the event. When the scientists examined what lay beneath the foundations of destroyed houses, they discovered that much of the city had been built on older debris flows. These deposits should have provided a warning of what was to come.



12.0

Exploring Physical Geography promotes inquiry and science as an active process. It encourages student curiosity and aims to activate existing student knowledge by posing the title of every two-page spread and every subsection as a question. In addition, questions are dispersed throughout the book. Integrated into the book are opportunities for students to observe patterns, features, and examples before the underlying concepts are explained. That is, we employ a *learning-cycle approach* where student exploration precedes the introduction of geographic terms and the application of knowledge to a new situation. For example, chapter 12 on slope stability, pictured above, begins with a three-dimensional image of northern Venezuela and asks readers to observe where people are living in this area and what natural processes might have formed these sites.

Wherever possible, we introduce terms after students have an opportunity to observe the feature or concept that is being named. This approach is consistent with several educational philosophies, including a learning cycle and just-in-time teaching. Research on learning cycles shows that

students are more likely to retain a term if they already have a mental image of the thing being named (Lawson, 2003). For example, this book presents students with maps showing the spatial distribution of earthquakes, volcanoes, and mountain ranges and asks them to observe the patterns and think about what might be causing the patterns. Only then does the textbook introduce the concept of tectonic plates.

Also, the figure-based approach in this book allows terms to be introduced in their context rather than as a definition that is detached from a visual representation of the term. We introduce new terms in italics rather than in boldface, because boldfaced terms on a textbook page cause students to immediately focus mostly on the terms, rather than build an understanding of the concepts. The book includes a glossary for those students who wish to look up the definition of a term to refresh their memory. To expand comprehension of the definition, each entry in the glossary references the pages where the term is defined in the context of a figure.

WHY ARE THE PAGES DOMINATED BY ILLUSTRATIONS?

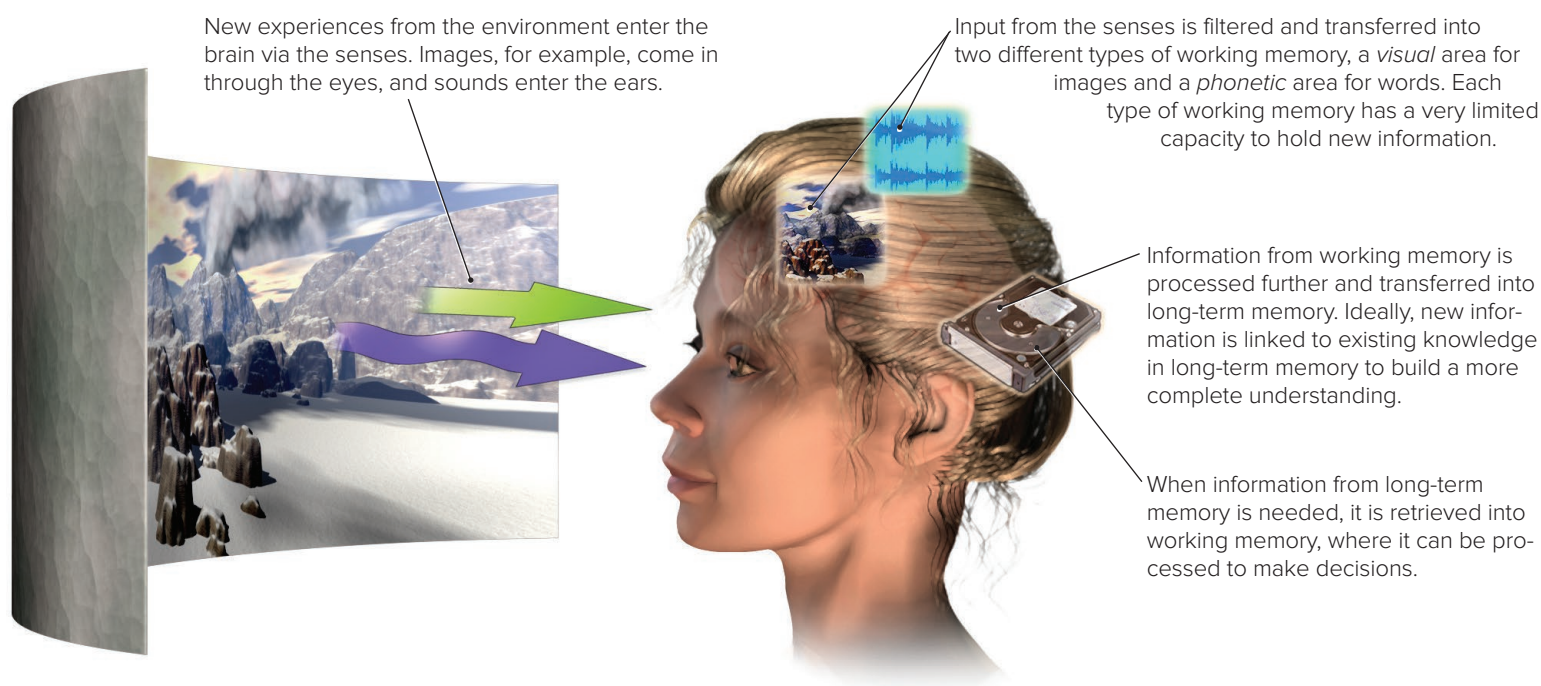
Physical geography is a visual science. Geography textbooks contain a variety of photographs, maps, cross sections, block diagrams, and other types of illustrations. These diagrams help portray the spatial distribution and geometry of features in the landscape, atmosphere, oceans, and biosphere in ways words cannot. In geography, a picture really is worth a thousand words.

Exploring Physical Geography contains a wealth of figures to take advantage of the visual and spatial nature of geography and the efficiency of figures in conveying geographic concepts. This book contains few large blocks of text—most text is in smaller blocks that are specifically linked to illustrations. Examples of our integrated figure-text approach are shown throughout the book. In this approach, each short block of text is one or more complete sentences that succinctly describe a geographic feature, geographic process, or both of these. Most of these text blocks are connected to their illustrations with leader lines so that readers know exactly which feature or part of the diagram is being referenced in the text block. A reader does not have to search for the part of the figure that corresponds to a text passage, as occurs when a student reads a traditional textbook with large blocks of text referencing a figure that may appear on a different page. The short blocks are numbered if they should be read in a specific order.

This approach is especially well suited to covering geographic topics, because it allows the text to have a precise linkage to the geographic location of the aspect being described. A text block discussing the

Intertropical Convergence Zone in Costa Rica can have a leader that specifically points to the location of this feature. A cross section of atmospheric circulation can be accompanied by short text blocks that describe each part of the system and that are linked by leaders directly to specific locations on the figure. This allows the reader to concentrate on the concepts being presented, not deciding what part of the figure is being discussed.

The approach in *Exploring Physical Geography* is consistent with the findings of cognitive scientists, who conclude that our minds have two different processing systems, one for processing pictorial information (images) and one for processing verbal information (speech and written words). This view of cognition is illustrated in the figure below. Cognitive scientists also speak about two types of memory: *working memory* involves holding and processing information in short-term memory, and *long-term memory* stores information until we need it (Baddeley, 2007). Both the verbal and pictorial processing systems have a limited amount of working memory, and our minds have to use much of our mental processing space to reconcile the two types of information in working memory. For information that has both pictorial and verbal components, as most geographic information does, the amount of knowledge we retain depends on reconciling these two types of information, on transferring information from working memory to long-term memory, and on linking the new information with our existing mental framework. For this reason, this book integrates text and figures, as in the example shown here.



WHY ARE THERE SO MANY FIGURES?

This textbook contains more than 2,600 figures, which is two to three times the number in most introductory geography textbooks. One reason for this is that the book is designed to provide a concrete example of each process, environment, or landscape feature being illustrated. Research shows that many college students require concrete examples before they can begin to build abstract concepts (Lawson, 1980). Also, many students have limited travel experience, so photographs and other figures allow them to observe places, environments, and processes they have not been able to observe firsthand. The numerous photographs, from geographically diverse places, help bring the sense of place into the student's reading. The inclusion of an illustration for each text block reinforces the notion that the point being discussed is important. In many cases, as in the example on this page, conceptualized figures are integrated with photographs and text so that students can build a more coherent view of the environment or process.

Exploring Physical Geography focuses on the most important geographic concepts and makes a deliberate attempt to eliminate text that is not essential for student learning of these concepts. Inclusion of information that is not essential tends to distract and confuse students rather than illuminate the concept; thus, you will see fewer words. Cognitive and science-education research has identified a redundancy effect, where information that restates and expands upon a more succinct description actually results in a decrease in student learning (Mayer, 2001). Specifically, students learn less if a long figure caption restates information contained elsewhere on the page, such as in a long block of text that is detached from

the figure. We avoid the redundancy effect by including only text that is integrated with the figure.

The style of illustrations in *Exploring Physical Geography* was designed to be more inviting to today's visually oriented students who are used to photo-realistic, computer-rendered images in movies, videos, and computer games. For this reason, many of the figures were created by world-class scientific illustrators and artists who have worked on award-winning textbooks, on Hollywood movies, on television shows, for *National Geographic*, and in the computer-graphics and gaming industry. In most cases, the figures incorporate real data, such as satellite images, weather and climatological data, and aerial photographs. Our own research shows that many students do not understand cross sections and other subsurface diagrams, so nearly every cross section in this book has a three-dimensional aspect, and many maps are presented in a perspective view with topography. Research findings by us and other researchers (Roth and Bowen, 1999) indicate that including people and human-related items on photographs and figures attracts undue attention, thereby distracting students from the features being illustrated. As a result, our photographs have nondistracting indicators of scale, like dull coins and plain marking pens. Figures and photographs do not include people or human-related items unless we are trying to (1) illustrate how geographers study geographic processes and features, (2) illustrate the relevance of the processes on humans, or (3) help students connect and relate to the human dimension of the issue.

396
Weathering and Mass Wasting 397

12.6 How Do Caves Form?

WATER IS AN ACTIVE CHEMICAL AGENT and can dissolve rock and other materials. Weathering near the surface and groundwater at depth can work together to completely dissolve limestone and other soluble rocks, leaving openings in places where the rocks have been removed. Such dissolution of limestone forms most caves, but caves form in many other ways. Once a cave is formed, dripping and flowing water can deposit a variety of beautiful and fascinating cave formations that grow from the ceilings, walls, and floor of the cave.

A How Do Limestone Caves Form?

Water near the surface or at depth as groundwater can dissolve limestone and other carbonate rocks, to form large caves, especially if the water is acidic. Cave systems generally form in limestone because most other rock types do not easily dissolve. A few other rocks, such as gypsum or rock salt, dissolve too easily—they completely disappear and cannot maintain caves. The figure below illustrates how limestone caves form.

- Limestone is primarily made of calcite (calcium carbonate), a relatively soluble mineral that dissolves in acidic water. Rainwater is typically slightly acidic due to dissolved carbon dioxide (CO₂), sulfur dioxide (SO₂), and organic material. Water reacts with calcite in limestone, dissolving it. This dissolution can be aided by acidic water coming from deeper in the Earth, by microbes, and by acids that microbes produce.
- Groundwater dissolves limestone and other carbonate rocks, often starting along fractures and boundaries between layers, and then progressively widening them over time. Open spaces become larger and more continuous, allowing more water to flow through and accelerating the dissolution and widening. If the openings become continuous, they may accommodate underground pools or underground streams.
- Most caves form below the water table, but some form from downward-flowing water above the water table. In either case, dissolution over millions of years can form a network of interconnected caves and tunnels in the limestone. If the water table falls, groundwater drains out of the tunnels and dries out part of the cave system.
- If the roof of the cave collapses, the cave can be exposed to the air. This can further dry out the cave. Such a roof collapse commonly forms a pitlike depression, called a sinkhole, on the surface.
- Limestone caves range in size from minuscule to huge. The Mammoth Cave System of Kentucky is the longest cave in the world, with an explored length of over 640 km (400 mi), with some parts still largely unexplored.

B What Are Some Other Types of Caves?

Most but not all caves developed in limestone. Caves in volcanic regions are commonly lava tubes, which were originally subsurface channels of flowing lava within a partially solidified lava flow. When the lava drained out of the tube, it left behind a long and locally branching cave. Such caves tend to have a curved, tube-like appearance with walls that have been smoothed and grooved by the flowing lava.

Most any rock type can host a cave, as long as it is strong enough to support a roof over the open space. Granite, not known as a soluble rock, can form caves, especially where physical and chemical weathering has enlarged areas along fractures. Many non-limestone caves are along a contact between a stronger rock above, which holds up the roof, and a weaker rock below, to form the opening.

C What Features Are Associated with Caves?

Caves are beautiful and interesting places to explore. Some contain twisty, narrow passages connecting open chambers. Others are immense rooms full of cave formations, such as stalactites and stalagmites. Caves can be decorated with intricate features formed by dissolution and precipitation of calcite and several other minerals.

- Most caves form by dissolution of limestone. Certain features on the land surface can indicate that there is a cave at depth. These include the presence of limestone, sinkholes, and other features. Collapse of part of the roof can open the cave to the surface, forming a skylight that lets light into the cave.
- Caves contain many features formed by minerals precipitated from dripping or flowing water. Water flowing down the walls or along the floor can precipitate *travertine* (a banded form of calcium carbonate) in thin layers that build up to create formations called *flowstone* or *draperies*.
- Probably the most recognized features of caves are stalactites and stalagmites, which are formed when calcium-rich water dripping from the roof evaporates and leaves calcium carbonate behind. Stalactites hang from the roof. Stalagmites form when water drips to the floor, building mounds upward.
- As mineral-rich water drips from the roof and flows from the walls, it leaves behind coatings, ribbons, and straw-like tubes. The water can accumulate in underground pools on the floor of the cave, precipitating rims of cream-colored *travertine* along their edges.
- In humid environments, weathering at the surface commonly produces reddish, clay-rich soil. The soil, along with pieces of limestone, can be washed into crevices and sinkholes, where it forms a residual matrix around limestone fragments.
- Dissolution of limestone along fractures and bedding planes, along with formation of sinkholes and skylights, disrupts streams and other drainages. Streams may disappear into the ground, adding more water to the cave system.

Carlsbad Caverns

About 260 million years ago (260 Ma), Carlsbad, New Mexico, was an area covered by a shallow inland sea. A huge reef, lush with sea life, thrived in this warm-water tropical environment. Eventually, the sea retreated, leaving the reef buried under other rock layers.

While buried, the limestone was dissolved by water rich in sulfuric acid generated from hydrogen sulfide that leaked upward from deeper accumulations of petroleum. Later, erosion of overlying layers uplifted the once-buried and groundwater-filled limestone cave and eventually exposed it at the surface. Groundwater dripped and trickled into the partially dry cave, where it deposited calcium carbonate to make the cave's famous formations.

While buried, the limestone was dissolved by water rich in sulfuric acid generated from hydrogen sulfide that leaked upward from deeper accumulations of petroleum. Later, erosion of overlying layers uplifted the once-buried and groundwater-filled limestone cave and eventually exposed it at the surface. Groundwater dripped and trickled into the partially dry cave, where it deposited calcium carbonate to make the cave's famous formations.

Before You Leave This Page

- Summarize the character and formation of caves, sinkholes, skylights, and travertine along streams.
- Briefly summarize how stalactites, stalagmites, and flowstone form.
- Describe features on the surface that might indicate an area may contain caves at depth.

WHY DOES THE BOOK CONSIST OF TWO-PAGE SPREADS?

This book consists of two-page spreads, most of which are further subdivided into sections. Research has shown that because of our limited amount of working memory, much new information is lost if it is not incorporated into long-term memory. Many students keep reading and highlighting their way through a textbook without stopping to integrate the new information into their mental framework. New information simply displaces existing information in working memory before it is learned and retained. This concept of cognitive load (Sweller, 1994) has profound implications for student learning during lectures and while reading textbooks. Two-page spreads and sections help prevent cognitive overload by providing natural breaks that allow students to stop and consolidate the new information before moving on.

Each spread has a unique number, such as 6.10 for the tenth topical two-page spread in chapter 6. These numbers help instructors and students keep track of where they are and what is being covered. Each two-page spread, except for those that begin and end a chapter, contains a *Before You Leave This Page* checklist that indicates what is important and what is expected of students before they move on. This list contains learning objectives for the spread and provides a clear way for the instructor to indicate to the student what is important. The items on these lists are compiled into a master *What-to-Know List* provided to the instructor, who then deletes or adds entries to suit the instructor's learning goals and distributes the list to students before the students begin reading the book. In this way, the *What-to-Know List* guides the students' studying.

200

6.10 What Are the Phases of ENSO?

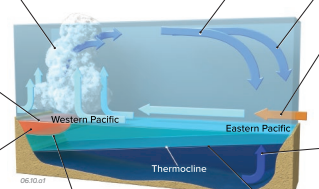
THE ATMOSPHERE-OCEAN SYSTEM in the equatorial Pacific is constantly changing. Although each year has its own unique characteristics, certain atmosphere-ocean patterns repeat, displaying a limited number of modes. We can use surface-water temperatures in the eastern equatorial Pacific to designate conditions as one of three phases of the *El Niño-Southern Oscillation* (ENSO) system—neutral (or “normal”), warm (*El Niño*), and cold (*La Niña*).

A What Are Atmosphere-Ocean Conditions During the Three Phases of ENSO?

El Niño and *La Niña* phases represent the end-members of ENSO, but sometimes the region does not display the character of either phase. Instead, conditions are deemed to be neither and are therefore assigned to the *neutral phase* of ENSO. To understand the extremes (*El Niño* and *La Niña*), we begin with the neutral situation.

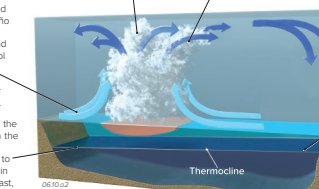
Neutral Phase of ENSO

1. Warm, unstable, rising air over the western equatorial Pacific warm pool produces low atmospheric pressures near the surface.
2. Walker cell circulation in the equatorial troposphere brings cool, dry air eastward along the tropopause.
3. Cool, descending air over the eastern equatorial Pacific produces dominantly high atmospheric pressure at the surface and stable conditions in the atmosphere.
4. Easterly trade winds flow over the Andes mountain range and then continue to the west across the ocean, pushing west against the surface waters along the coast of South America. The easterlies continue propelling the warm water westward toward Australia and southeast Asia, allowing the waters to warm even more as they are heated by insolation along the equator.
5. Westward displacement of surface waters, and offshore winds, induces upwelling of cold, deep ocean waters just off the coast of western South America. Abundant insolation under clear skies warms these rising waters somewhat, so there is no density-caused return of surface waters to depth.
6. The thermocline slopes to the west, being over three times deeper in the western Pacific than in the eastern Pacific. This condition can only be maintained by a series of feedbacks, including the strength of the trade winds.
7. In the western Pacific, surface waters are warm (over 28°C) and less saline because of abundant precipitation and stream runoff from heavy precipitation that falls on land. The warm surface waters (the warm pool) overlie cooler, deeper ocean water—a stable situation.
8. Warm waters blown to the west not only depress the thermocline to about 150 m below the surface, but also physically raise the height of the western equatorial Pacific, compared to the eastern Pacific.
9. The warm, moist air above the warm pool rises under the influence of low pressures, producing intense tropical rainfalls that maintain the less saline, less dense fresh water on the surface of the warm pool.



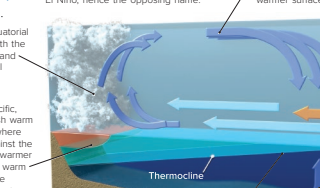
Warm Phase of ENSO (El Niño)

1. During a warm phase (*El Niño*), the warm pool and associated convective rainfalls move toward the central Pacific.
2. *El Niño* conditions are also characterized by weakened Walker cell circulation over the equatorial Pacific. This is expressed by decreased winds aloft and by a reduction in the strength and geographic range of the easterly trade winds near the surface.
3. Upon reaching South America, the cool air descends over equatorial parts of the Andes, increasing atmospheric pressure, limiting convective uplift, and reducing associated rainfall in Colombia and parts of the Amazon.
4. Weakening of the trade winds reduces coastal upwelling of cold water, which, combined with the eastern displacement of the descending air, promotes a more southerly location of the ITCZ in the Southern summer and increased precipitation in the normally dry coastal regions of Peru and Ecuador.
5. Changes in the strength of the winds, in temperatures, and in the movements of near-surface waters cause the thermocline to become somewhat shallower in the west and deeper in the east, but it still slopes to the west.
6. For Australia, Indonesia, and the westernmost Pacific, *El Niño* brings higher atmospheric pressures, reduced rainfall, and westerly winds. The warm pool and associated convective rainfalls move toward the central Pacific, allowing cooler surface waters in the far west.



Cold Phase of ENSO (La Niña)

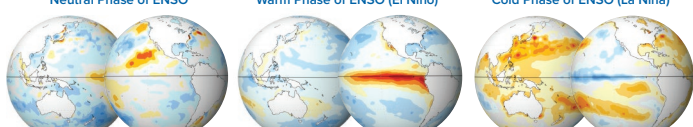
1. In many ways, the cold phase of ENSO (*La Niña*) displays conditions opposite to an *El Niño*, hence the opposing name.
2. During a cold phase of ENSO (*La Niña*), Walker cell circulation strengthens over the equatorial Pacific. This increases winds aloft and causes near-surface easterly trade winds to strengthen, driving warmer surface waters westward toward Australasia and Indonesia.
3. Enhanced easterly trade winds bring more moisture to the equatorial parts of the Andes and to nearby areas of the Amazon basin. Orographic effects cause heavy precipitation on the Amazon (east side of the mountain range (not shown)).
4. Partially depleted of moisture and driven by stronger trade winds, dry air descends westward off the Andes and onto the coast. The flow of dry air, combined with the descending limb of the Walker cell, produces clear skies and dry conditions along the coast.
5. As surface waters push westward and the Humboldt Current turns west, deep waters rise (strong upwelling). The resulting cool SST and descending dry, stable air conspire to produce excessive drought in coastal regions of Peru.
6. The upwelling near South America raises the thermocline and causes it to slope steeper to the west. Cold water is now closer to the surface, producing favorable conditions for cold-water fish.
7. In the western Pacific, strong easterlies push warm waters to the west where they accumulate against the continent, forming a warmer and more expansive warm pool. In response, the thermocline of the western equatorial Pacific is pushed much deeper, further increasing the slope of the thermocline to the west.
8. The region of equatorial rainfall associated with the warm pool expands and the amount of rainfall increases.



B How Are ENSO Phases Expressed in Sea-Surface Temperatures?

As the Pacific region shifts between the warm (*El Niño*), cold (*La Niña*), and neutral phases, sea-surface temperatures (SST), atmospheric pressures, and winds interact all over the equatorial Pacific. These variations are recorded by numerous types of historical data, especially in SST. The globes below show SST for the western Pacific (near Asia) and eastern Pacific (near the Americas) for each phase of ENSO—neutral, warm, and cold. The colors represent whether SST is warmer than normal (red and orange), colder than normal (blue), or about average (light).

Neutral Phase of ENSO **Warm Phase of ENSO (El Niño)** **Cold Phase of ENSO (La Niña)**



During the *neutral phase* of ENSO, SST along the equator in the Pacific are about average, with no obvious warmer or colder than normal waters near the Western Pacific Warm Pool (left globe) or South America (right globe). An area of warmer than normal SST occurs southwest of North America, but this is not obviously related to ENSO.

During the *warm phase* of ENSO, a belt of much warmer than normal water appears along the equator west of South America. This warm water is the signature of an *El Niño*, causing the decrease in cold-water fishes. SST in the western Pacific are a little cooler than average, but an *El Niño* is most strongly expressed in the eastern Pacific (right globe).

During the *cold phase* of ENSO (*La Niña*), a belt of colder than normal water occurs along the equator west of South America, hence the name “cold phase.” The western Pacific (left globe), however, now has waters that are warmer than normal. These warm waters are quite widespread in this region, extending from Japan to Australia.

Before You Leave This Page

- ✓ Sketch and explain atmosphere-ocean conditions for each of the three typical phases of ENSO, noting typical vertical and horizontal air circulation, sea-surface temperatures, relative position of the thermocline, and locations of areas of excess rain and drought.
- ✓ Summarize how each of the three phases of ENSO (neutral, warm, and cold) are expressed in SST of the equatorial Pacific Ocean.

201

Two-page spreads and integrated *Before You Leave This Page* lists offer the following advantages to the student:

- Information is presented in relatively small and coherent chunks that allow a student to focus on one important aspect or geographic system at a time.
- Students know when they are done with this particular topic and can self-assess their understanding with the *Before You Leave This Page* list.

- Two-page spreads allow busy students to read or study a complete topic in a short interval of study time, such as the breaks between classes.
- All test questions and assessment materials are tightly articulated with the *Before You Leave This Page* lists so that exams and quizzes cover precisely the same material that was assigned to students via the *What-to-Know* list.

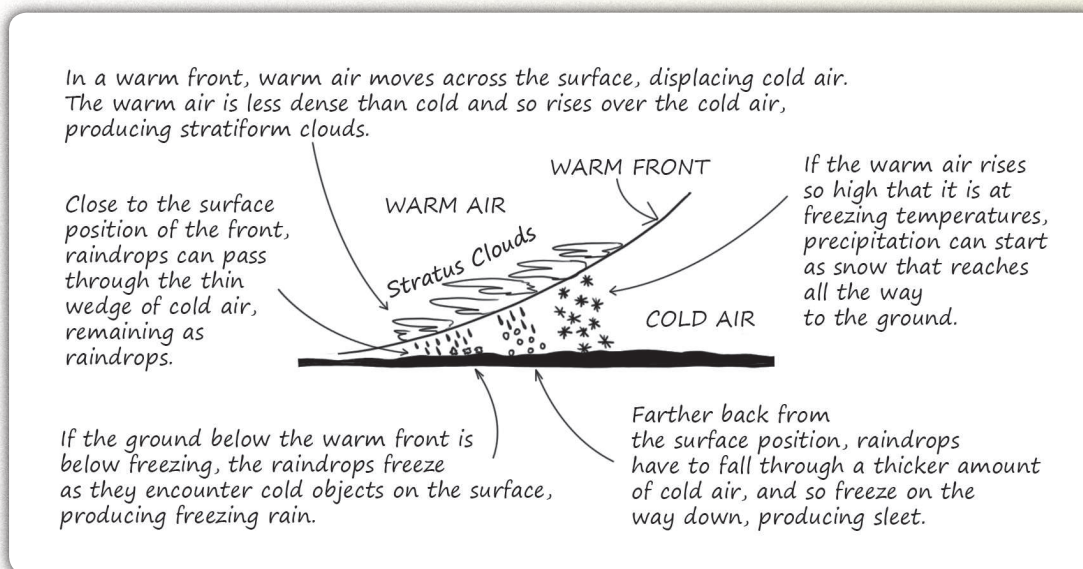
The two-page spread approach also has advantages for the instructor. Before writing this book, the authors wrote most of the items for the *Before You Leave This Page* lists. We then used this list to decide what figures were needed, what topics would be discussed, and in what order. In other words, *the textbook was written from the learning objectives*. The *Before You Leave This Page* lists provide a straightforward way for an instructor to tell students what information is important. Because we provide the instructor with a master *What-to-Know* list, an instructor can selectively assign or eliminate content

by providing students with an edited *What-to-Know* list. Alternatively, an instructor can give students a list of assigned two-page spreads or sections within two-page spreads. In this way, the instructor can identify content for which students are responsible, even if the material is not covered in class. Two-page spreads provide the instructor with unparalleled flexibility in deciding what to assign and what not to cover. It allows this book to be easily used for one-semester and two-semester courses.

CONCEPT SKETCHES

Most items on the *Before You Leave This Page* list are by design suitable for student construction of concept sketches. Concept sketches are sketches that are annotated with complete sentences that identify geographic features, describe how the features form, characterize the main geographic processes, and summarize histories of landscapes (Johnson and Reynolds, 2005). An example of a concept sketch is shown to the right.

Concept sketches are an excellent way to actively engage students in class and to assess their understanding of geographic features, processes, and history. Concept sketches are well suited to the visual nature of geography, especially cross sections, maps, and block diagrams. Geographers are natural sketchers using field notebooks, blackboards, publications, and even napkins, because sketches are an important way to record observations and thoughts, organize knowledge, and try to visualize the evolution of landscapes, circulation in the atmosphere and oceans, motion and precipitation along weather fronts, layers within soils, and biogeochemical cycles. Our research data show that a student who can draw, label, and explain a concept sketch generally has a good understanding of that concept.



REFERENCES CITED

- Baddeley, A. D. 2007. *Working memory, thought, and action*. Oxford: Oxford University Press, 400 p.
- Johnson, J. K., and Reynolds, S. J. 2005. Concept sketches—Using student- and instructor-generated annotated sketches for learning, teaching, and assessment in geology courses. *Journal of Geoscience Education*, v. 53, pp. 85–95.
- Lawson, A. E. 1980. Relationships among level of intellectual development, cognitive styles, and grades in a college biology course. *Science Education*, v. 64, pp. 95–102.
- Lawson, A. 2003. *The neurological basis of learning, development & discovery: Implications for science & mathematics instruction*. Dordrecht, The Netherlands: Kluwer Academic Publishers, 283 p.
- Mayer, R. E. 2001. *Multimedia learning*. Cambridge: Cambridge University Press, 210 p.
- Roth, W. M., and Bowen, G. M. 1999. Complexities of graphical representations during lectures: A phenomenological approach. *Learning and Instruction*, v. 9, pp. 235–255.
- Sweller, J. 1994. Cognitive Load Theory, learning difficulty, and instructional design. *Learning and Instruction*, v. 4, pp. 295–312.

HOW IS THIS BOOK ORGANIZED?

Two-page spreads are organized into 18 chapters that are arranged into five major groups: (1) introduction to Earth, geography, and energy and matter; (2) atmospheric motion, weather, climate, and water resources; (3) introduction to landscapes, earth materials, sediment transport, plate tectonics, and tectonic processes (e.g., volcanoes and earthquakes); (4) processes, such as stream flow and glaciation, that sculpt and modify landscapes; and (5) soils, biogeography, and biogeochemical cycles. The first chapter provides an overview of geography, including the scientific approach to geography, how we determine and represent location, the tools and techniques used by geographers, and an introduction to *natural systems*—a unifying theme interwoven throughout the rest of the book. Chapter 2 covers energy and matter in the Earth system, providing a foundation for all that follows in the book.

The second group of chapters begins with an introduction to atmospheric motion (chapter 3), another theme revisited throughout the book. It features separate two-page spreads on circulation in the tropics, high latitudes, and mid-latitudes, allowing students to concentrate on one part of the system at a time, leading to a synthesis of lower-level and upper-level winds. Chapter 3 also covers air pressure, the Coriolis effect, and seasonal and regional winds. This leads naturally into chapter 4, which is a thorough introduction to atmospheric moisture and the consequences of rising and sinking air, including clouds and precipitation. Chapter 5 follows with a visual, map-oriented discussion of weather, including cyclones, tornadoes, and other severe weather. The next chapter (chapter 6), unusual for an introductory geography textbook, is devoted entirely to interactions between the atmosphere, oceans, and cryosphere. It features sections on ocean currents, sea-surface temperatures, ocean salinity, and a thorough treatment of ENSO and other atmosphere-ocean oscillations. This leads into a chapter on climate (chapter 7), which includes controls on climate and a climate classification, featuring a two-page spread on each of the main climate types, illustrated with a rich blend of figures and photographs. These spreads are built around globes that portray a few related climate types, enabling students to concentrate on their spatial distribution and control, rather than trying to extract patterns from a map depicting all the climate types (which the chapter also has). The climate chapter also has a data-oriented presentation of climate change. This second part of the book concludes with chapter 8, which presents the hydrologic cycle and water resources, emphasizing the interaction between surface water and groundwater.

The third part of the book focuses on landscapes and tectonics. It begins with chapter 9, a visually oriented introduction to understanding landscapes, starting with familiar landscapes as an introduction to rocks and minerals. The chapter has a separate two-page spread for each family of rocks and how to recognize each type in the landscape. It presents a brief introduction to weathering, erosion, and transport, aspects that are covered in more detail in later chapters on geomorphology. Wind transport, erosion, and landforms are integrated into chapter 9, rather than being a

separate, sparse-content chapter that forcibly brings in non-wind topics, as is done in other textbooks. It also covers relative and numeric dating and how we study the ages of landscapes. It is followed by chapter 10 on plate tectonics and regional features. Chapter 10 begins with having students observe large-scale features on land and on the seafloor, as well as patterns of earthquakes and volcanoes, as a lead-in to tectonic plates. Integrated into the chapter are two-page spreads on continental drift, paleomagnetism, continental and oceanic hot spots, evolution of the modern oceans and continents, the origin of high elevations, and the relationship between internal and external processes. The last chapter in this third part (chapter 11) presents the processes, landforms, and hazards associated with volcanoes, deformation, and earthquakes. It also explores the origin of local mountains and basins, another topic unique to this textbook.

The fourth group of chapters concerns the broad field of geomorphology—the form and evolution of landscapes. It begins with chapter 12, a more in-depth treatment of weathering, mass wasting, and slope stability. This chapter also has two-page spreads on caves and karst topography. Chapter 13 is about streams and flooding, presenting a clear introduction to drainage networks, stream processes, different types of streams and their associated landforms and sediment, and how streams change over time. It ends with sections on floods, calculating stream discharges, some examples of devastating local and regional floods, and the many ways in which streams affect people. Chapter 14 covers glaciers and glacial movement, landforms, and deposits. It also discusses the causes of glaciation and the possible consequences of melting of ice sheets and glaciers. Chapter 15 covers the related topic of coasts and changing sea levels. It introduces the processes, landforms, and hazards of coastlines. It also covers the consequences of changing sea level on landforms and humans.

The fifth and final group of chapters focuses on the biosphere and begins with chapter 16, which explores the properties, processes, and importance of soil. This chapter covers soil characterization and classification, including globes showing the spatial distribution of each main type of soil. It ends with a discussion of soil erosion and how soil impacts the way we use land. Chapter 17 provides a visual introduction to ecosystems and biogeochemical cycles. It addresses interactions between organisms and resources within ecosystems, population growth and decline, biodiversity, productivity, and ecosystem disturbance. The last part of chapter 17 covers the carbon, nitrogen, phosphorus, and sulfur cycles, the role of oxygen in aquatic ecosystems, and invasive species. The final chapter in the book, chapter 18, is a synthesis chapter on biomes. It discusses factors that influence biomes and then contains a two-page spread on each major biome, with maps, globes, photographs, and other types of figures to convey where and why each biome exists. It includes a section on sustainability and ends with a synthesis that portrays biomes in the context of many topics presented in the book, including energy balances, atmospheric moisture and circulation, climate types, and soils.

TWO-PAGE SPREADS

Most of the book consists of *two-page spreads*, each of which is about one or more closely related topics. Each chapter has four main types of two-page spreads: opening, topical, connections, and investigation.

Opening Two-Page Spread

Opening spreads introduce the chapter, engaging the student by highlighting some interesting and relevant aspects and posing questions to activate prior knowledge and curiosity.

CHAPTER 3 Atmospheric Motion

MOTION OF THE EARTH'S ATMOSPHERE has a great influence on human life by controlling climate, creating weather patterns, and providing transportation. It is driven largely by differences in insolation, with differences from solar insolation, including topographic, coastal, and regional variations of the planet. These drivers create pressure and density differences, which in turn create wind. Wind is the primary mechanism for moving heat and moisture from one place to another on the planet.

TOPICS IN THIS CHAPTER

3.1 How Do Waves Respond to Changes in Temperature and Pressure?	76
3.2 What Are Pressure Variations and How Do They Affect the Atmosphere?	88
3.3 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.4 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.5 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.6 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.7 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.8 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.9 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.10 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.11 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.12 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.13 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.14 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.15 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92
3.16 How Do the Coriolis Effect and Friction Affect Wind Direction and Speed?	92

Topical Two-Page Spread

Topical spreads comprise most of the book. They convey the geographic content, help organize knowledge, describe and illustrate processes, and provide a specific spatial context. The first topical spread in a chapter usually includes some aspects that are familiar to most students, as a bridge or scaffold into the rest of the chapter. Each chapter has at least one two-page spread illustrating how geography impacts society and commonly another two-page spread that specifically describes how geographers study typical problems.

340 How Does Air Circulate in the Tropics?

TROPICAL CIRCULATION is driven by the intense solar heating of land and sea near the equator. The heated air rises and spreads out from the equator, setting up large, circulating cells of flowing air. The rising air results in a belt of tropical low pressure, and where the air descends back toward the surface is a belt of subtropical high pressure. What determines where the rising and sinking occur, and how does the Coriolis effect influence this flow?

Formation of Hadley Cells

1. Insolation of air rises in the tropics, causing it to expand and rise.
2. The rising air is deflected by the Coriolis effect, creating a belt of low pressure at the equator.
3. The air then descends back toward the surface, creating a belt of high pressure at the equator.
4. The air then moves back toward the poles, creating a belt of low pressure at the poles.
5. The air then descends back toward the surface, creating a belt of high pressure at the poles.

Influence of the Coriolis Effect

1. The Coriolis effect causes moving air to be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.
2. The Coriolis effect is strongest at the poles and weakest at the equator.
3. The Coriolis effect causes wind to flow at an angle to the right of the pressure gradient in the Northern Hemisphere and to the left in the Southern Hemisphere.

Seasonal Variations in the Position of the Intertropical Convergence Zone

1. The ITCZ moves north and south of the equator throughout the year.
2. The ITCZ is located at the equator during the equinoxes.
3. The ITCZ is located in the Northern Hemisphere during the summer months.
4. The ITCZ is located in the Southern Hemisphere during the winter months.

Connections Two-Page Spread

The next-to-last two-page spread in each chapter is a *Connections spread* designed to help students connect and integrate the various concepts from the chapter and to show how these concepts can be applied to an actual location. *Connections* are about real places that illustrate the geographic concepts and features covered in the chapter, often explicitly illustrating how we investigate a geographic problem and how geographic problems have relevance to society.

345 How Have Global Pressures and Winds Affected History in the North Atlantic?

INTERCONTINENTAL TRAVEL AND TRADE have relied upon moving currents in the air and ocean. Before the 20th century, when transoceanic travel and shipping relied on wind-driven global winds, such as the trade winds and westerlies, distant which directions of travel were possible at different latitudes. The direction of global winds then has greatly influenced the exploration and colonization of the Americas, and even of that influence can be directed in part and present climate. The Atlantic, called down the larger central globe spanning these two pages represents the path of explorers or trade routes, as described below.

Before You Leave This Page

1. Research the location of the North Atlantic Ocean and the Gulf Stream.
2. Research the location of the North Atlantic Ocean and the Gulf Stream.
3. Research the location of the North Atlantic Ocean and the Gulf Stream.

Investigation Two-Page Spread

Each chapter ends with an *Investigation* spread that is an exercise in which students apply the knowledge, skills, and approaches learned in the chapter. These exercises mostly involve virtual places that students explore and investigate to make observations and interpretations and to answer a series of geographic questions. Investigations are modeled after the types of problems geographers investigate, and they use the same kinds of data and illustrations encountered in the chapter. The Investigation includes a list of goals for the exercises and step-by-step instructions, including calculations and methods for constructing maps, graphs, and other figures. These investigations can be completed by students in class, as worksheet-based homework, or as online activities.

346 What Occurs During Seasonal Circulation Shifts?

SEASONAL CIRCULATION is driven by the intense solar heating of land and sea near the equator. The heated air rises and spreads out from the equator, setting up large, circulating cells of flowing air. The rising air results in a belt of tropical low pressure, and where the air descends back toward the surface is a belt of subtropical high pressure. What determines where the rising and sinking occur, and how does the Coriolis effect influence this flow?

Goals of This Exercise

1. Identify the major features of the global atmospheric circulation in each season.
2. Research the location of the North Atlantic Ocean and the Gulf Stream.
3. Research the location of the North Atlantic Ocean and the Gulf Stream.

Procedures

1. Study the map showing an average pressure for the month of January and the month of July. Locate the high and low pressure areas on the map.
2. Study the map showing an average wind velocity for the month of January and the month of July. Locate the high and low wind velocity areas on the map.
3. Study the map showing an average cloud cover for the month of January and the month of July. Locate the high and low cloud cover areas on the map.

NEW IN THE SECOND EDITION

The second edition of *Exploring Physical Geography* represents a significant revision. The style, approach, and sequence of chapters are unchanged, but every chapter received new photographs, revised figures, major to minor editing of text blocks and, in some cases, minor reorganization. We revised text blocks to improve clarity and conciseness and to present recent discoveries and events. Most chapters contain the same number of two-page spreads, but the content on some spreads was extensively revised. Nearly all changes were made in response to comments by reviewers, students, and instructors who are using the materials. The most important revisions are listed below.

- This edition features completely different fonts from the first edition. The new fonts were chosen partly to improve the readability on portable electronic devices, while retaining fidelity to a quality printed book. This font replacement resulted in countless small changes in the layout of individual text blocks on every two-page spread. In addition to replacing all of the fonts within the text, all figure labels were replaced with the new font, a process that required opening, editing, and commonly resizing every illustration. In addition, all labels were incorporated into the actual artwork, rather than overlaying text on the artwork using the page-layout program, as was done for many figures in the first edition. This involved adding labels to hundreds of illustrations, but has the benefit of having every label as an integral part of its associated art file, a useful feature for constructing PowerPoint files.
- This edition contains more than 100 new photographs, with a deliberate intention to represent a wider geographic diversity, providing students with local examples from their region. For the geomorphology chapters, many photographs from the first edition were reprocessed from the original to improve clarity and provide more detail.
- This edition contains 120 new and heavily revised illustrations. Figures from the first edition were replaced with new versions to update information so that it is more recent, to improve student understanding of certain complex topics, and for improved appearance. Investigations in several chapters were completely revised.

CHAPTER 1: There are six new photographs and minor revisions to several illustrations. As with other chapters in the book, there are numerous minor edits to the text.

CHAPTER 2: For this chapter we replaced three photographs, including one of the Earth from the Moon. In addition, we produced new versions of 14 figures, including new globes for the investigation. A number of these revisions reflect the decision to refer to the Sun using Sun angle instead of Zenith angle, which some students found confusing.

CHAPTER 3: This chapter has one new photograph, and we revised or created ten figures, mostly concerning flow between the upper and

lower parts of the troposphere. We also added labels showing the locations of important high- and low-pressure zones.

CHAPTER 4: One photograph was replaced in this chapter, and we revised 21 figures, mostly for font changes. Heavily revised figures include new maps and rendered globes of specific humidity and precipitation, upper-level convergence, and extreme precipitation. The Investigation for this chapter was completely redone, now having students observe and explain global patterns of humidity, water vapor, and land cover.

CHAPTER 5: For this chapter, we replaced four photos and revised more than a dozen figures (30 if you count all the font replacements). Revised figures include revisions to several maps, figures related to the formation of lightning, and figures depicting upper-level divergence. In addition, we replaced a world map of tornado frequency with more visually appealing and less distorting globes of these data. The Connections spread received a change in layout, and the Investigation was heavily revised with six new maps and new procedures.

CHAPTER 6: Chapter 6 contains 24 revised figures, mostly for fonts, but including a number of new versions for important figures. These include new renders of globes for the opening two-page spread, globes about the relationship of winds to ocean currents, and globes about ENSO. There are new figures about the Walker cell, El Niño SST anomalies, and other topics. We deleted a figure and associated text on salinity in Section 6.7.

CHAPTER 7: In this chapter we replaced just one new photograph, but we revised 54 figures, mostly for fonts. There are new versions of globes in the opening two-page spread and in the introduction to the climate types, as well as newly rendered globes of every type of climate. There are new maps of the urban heat islands and new graphs depicting the data for climate change, revising the graphs to incorporate the most recent data. There are new figures for sea-level change, the decrease of Arctic ice, and the frequency of storms over time. We also revised the maps in the Investigation.

CHAPTER 8: We deleted one photograph from this chapter, and incorporated six new photographs. New photographs are from Central Texas, Maryland, the Black Hills, and the state of Washington. Most of the figure revisions were font replacements and adding labels to globes, but larger revisions included figures about global water budgets and newly rendered water-balance globes. There is also a new map of the Ogallala aquifer and water-level changes in the aquifer. We changed some values in the table for the Investigation.

CHAPTER 9: This chapter has 19 new photographs, including new multi-specimen photographs of common minerals. There are also new close-ups of rocks and new photographs of landscapes. We also revised the geologic timescale to reflect new dates. We made minor revisions to three figures.

CHAPTER 10: Chapter 10 has one new photograph, but a number of photographs were reprocessed from the original. As with all other chapters, all figures with labels were revised, including 16 in this chapter, and more extensive revisions occurred in figures regarding paleomagnetism.

CHAPTER 11: For this chapter we deleted one photograph and two satellite images, and replaced five photographs. The layout and text were revised for the opening two-page spread and for floods associated with volcanic eruptions. Legends were added to the global earthquake maps, and there are new versions of two illustrations of the Alaskan earthquake. A number of other figures were revised, mostly as a result of replacing fonts.

CHAPTER 12: This chapter has seven new photographs, and a number of existing photographs were reprocessed for clarity. The new photographs expand the geographic diversity, including photographs from Central Texas and Florida. There is a new map showing the location of Venezuela and a new map of the global distribution of karst. There are a number of minor revisions to other figures.

CHAPTER 13: There are nine new photographs for this chapter, including ones from Alaska, Central Texas, and the Potomac River. Twenty-nine illustrations in the chapter were significantly revised or had fonts replaced. For example, all the hydrographs were revised, as were the figures for the Upper Mississippi flood.

CHAPTER 14: Chapter 14 has 13 new photographs from Alaska, Wyoming, Colorado, and other states. Text was revised in conjunction with the new photographs.

CHAPTER 15: For this chapter there are 11 new photographs, mostly from Florida and coastal Alabama. Figure revisions for this chapter consisted mostly of font replacements, of which there were many.

CHAPTER 16: We replaced four photographs for this chapter. The position of Sections 16.5 and 16.6 were swapped, putting the discussion of climate and soil ahead of the discussion of terrain, parent material, and time.

CHAPTER 17: Chapter 17 has five new photographs, with accompanying word changes. Significant changes were made to more than a dozen figures, including the opening 3D perspective. There are new figures in the sections regarding biogeochemical cycles for nitrogen, sulfur, and oxygen.

CHAPTER 18: We replaced 17 photographs in this chapter, adding photographs from the Everglades, Mississippi, Alaska, and the southern Rocky Mountains. There are also new photographs of coral reefs. For figure revisions, there is a new version of maps of tropical rain-forest deforestation, coral-reef distribution, and the Panama connection.



McGraw-Hill Connect® Learn Without Limits

Connect is a teaching and learning platform that is proven to deliver better results for students and instructors.

Connect empowers students by continually adapting to deliver precisely what they need, when they need it, and how they need it, so your class time is more engaging and effective.

73% of instructors who use **Connect** require it; instructor satisfaction increases by 28% when **Connect** is required.

Analytics

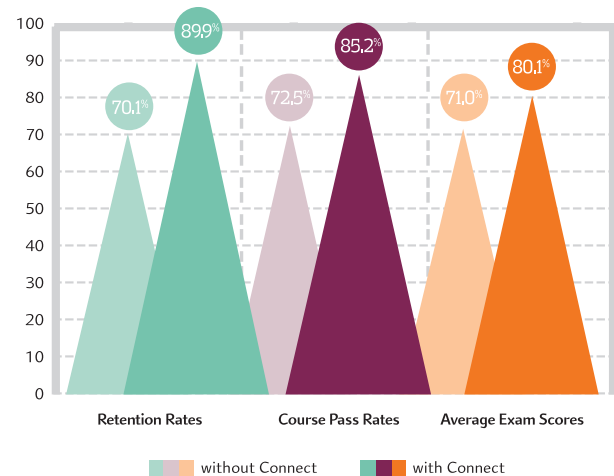
Connect Insight®

Connect Insight is Connect's new one-of-a-kind visual analytics dashboard—now available for both instructors and students—that provides at-a-glance information regarding student performance, which is immediately actionable. By presenting assignment, assessment, and topical performance results together with a time metric that is easily visible for aggregate or individual results, Connect Insight gives the user the ability to take a just-in-time approach to teaching and learning, which was never before available. Connect Insight presents data that empowers students and helps instructors improve class performance in a way that is efficient and effective.

Mobile

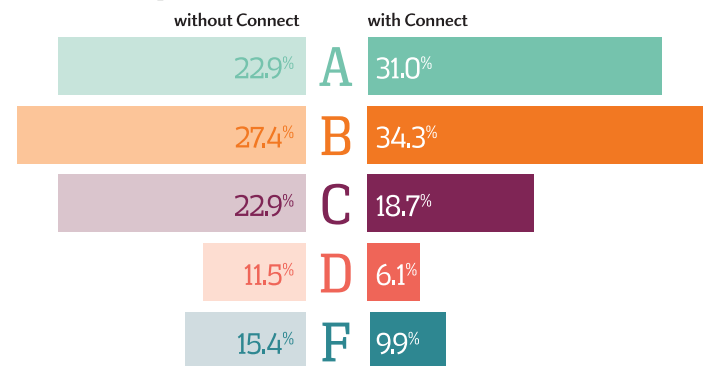
Connect's new, intuitive mobile interface gives students and instructors flexible and convenient, anytime-anywhere access to all components of the Connect platform.

Connect's Impact on Retention Rates, Pass Rates, and Average Exam Scores

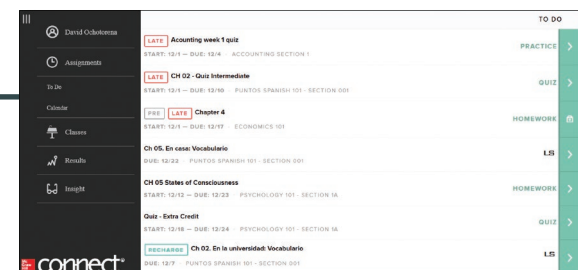


Using **Connect** improves retention rates by **19.8%**, passing rates by **12.7%**, and exam scores by **9.1%**.

Impact on Final Course Grade Distribution



Students can view their results for any **Connect** course.



Adaptive



More students earn **A's** and **B's** when they use McGraw-Hill Education **Adaptive** products.

SmartBook®

Proven to help students improve grades and study more efficiently, SmartBook contains the same content within the print book, but actively tailors that content to the needs of the individual. SmartBook's adaptive technology provides precise, personalized instruction on what the student should do next, guiding the student to master and remember key concepts, targeting gaps in knowledge and offering customized feedback, and driving the student toward comprehension and retention of the subject matter. Available on tablets, SmartBook puts learning at the student's fingertips—anywhere, anytime.

Over **8 billion** questions have been answered, making McGraw-Hill Education products more intelligent, reliable, and precise.

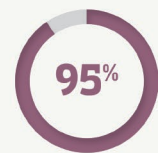
www.mheducation.com

THE ADAPTIVE READING EXPERIENCE DESIGNED TO TRANSFORM THE WAY STUDENTS READ

STUDENTS WANT

Mc
Graw
Hill
Education

SMARTBOOK®



of students reported **SmartBook** to be a more effective way of reading material.



of students want to use the Practice Quiz feature available within **SmartBook** to help them study.



of students reported having reliable access to off-campus wifi.



of students say they would purchase **SmartBook** over print alone.



of students reported that **SmartBook** would impact their study skills in a positive way.

Mc
Graw
Hill
Education

*Findings based on 2015 focus group results administered by McGraw-Hill Education

ACKNOWLEDGMENTS

Writing a totally new type of introductory geography textbook would not be possible without the suggestions and encouragement we received from instructors who reviewed various drafts of this book and its artwork. We are especially grateful to people who contributed entire days either reviewing the book or attending symposia to openly discuss the vision, challenges, and refinements of this kind of new approach. Our colleagues Paul Morin and Mike Kelly contributed materials in various chapters, for which we continue to be grateful.

This book contains over 2,600 figures, several times more than a typical introductory geography textbook. This massive art program required great effort and artistic abilities from the illustrators and artists who turned our vision and sketches into what truly are pieces of art. We are especially appreciative of Cindy Shaw, who was lead illustrator, art director, and a steady hand that helped guide a diverse group of authors. For many figures, she extracted data from NOAA and NASA websites and then converted the data into exquisite maps and other illustrations. Cindy also fine-tuned the authors' layouts, standardized illustrations, and prepared the final figures for printing. Chuck Carter produced many spectacular pieces of art, including virtual places featured in the chapter-ending Investigations. Susie Gillatt contributed many of her wonderful photographs of places, plants, and creatures from around the world, photographs that helped us tell the story in a visual way. She also color corrected and retouched most of the photographs in the book. We also used visually unique artwork by Daniel Miller, David Fierstein, and Susie Gillatt. Suzanne Rohli performed magic with GIS files, did the initial work on the glossary, and helped in many other ways. We were ably assisted in data compilation and other tasks by geography students Emma Harrison, Abeer Hamden, Peng Jia, and Javier Vázquez, and by Courtney Merjil. Terra Chroma, Inc., of Tucson, Arizona, supported many aspects in the development of this book, including funding parts of the extensive art program and maintenance of the ExploringPhysicalGeography.com website.

Many people went out of their way to provide us with photographs, illustrations, and advice. These helpful people included Susie Gillatt, Vladimir Romanovsky, Paul McDaniel, Lawrence McGhee, Charles Love, Cindy Shaw, Sandra Londono, Lynda Williams, Ramón Arrowsmith, John Delaney, Nancy Penrose, Dan Trimble, Bixler McClure, Michael Forster, Vince Matthews, Ron Blakey, Doug Bartlett, Ed DeWitt, Phil Christensen, Scott Johnson, Peg Owens, Emma Harrison, Skye Rodgers, Steve Semken, and David Walsh.

We used a number of data sources to create many illustrations. Reto Stöckli of the Department of Environmental Sciences at ETH Zürich and NASA Goddard produced the Blue Marble and Blue Marble Next Generation global satellite composites. We are very appreciative of the NOAA Reanalysis Site, which we used extensively, and for other sites of the USDA, NASA, USGS, NRCS, and NPS.

We have treasured our interactions with the wonderful Iowans at McGraw-Hill Higher Education, who enthusiastically supported our vision, needs, and progress. We especially thank our current and previous publishers and brand managers Michelle Vogler, Michael Ivanov, Ryan Blankenship, and Marge Kemp for their continued encouragement and excellent support. Jodi Rhomberg and Laura Bies skillfully and cheerfully guided the development of the book during the entire publication process, making it all happen. Lori Hancock helped immensely with our ever-changing photographic needs. We also appreciate the support, cooperation, guidance, and enthusiasm of Thomas Timp, Marty Lange, Kurt Strand, Noah Evans, Matt Garcia, Lisa Nicks, David Hash, Traci Andre, Tammy Ben, and many others at McGraw-Hill who worked hard to make this book a reality. Kevin Campbell provided thorough copy editing, and reviewed the glossary and index. Angie Sigwarth and Rose Kramer provided excellent proofreading that caught small gremlins before they escaped. Our wonderful colleague Gina Szablewski expertly directed the development of LearnSmart materials and provided general encouragement.

Finally, a project like this is truly life consuming, especially when the author team is doing the writing, illustrating, photography, near-final page layout, media development, and development of assessments, teaching ancillaries, and the instructor's website. We are extremely appreciative of the support, patience, and friendship we received from family members, friends, colleagues, and students who shared our sacrifices and successes during the creation of this new vision of a textbook. Steve Reynolds thanks the ever-cheerful, supportive, and talented Susie Gillatt; John and Kay Reynolds; and our mostly helpful book-writing companions, Widget, Jasper, and Ziggy. Julia Johnson thanks Annabelle Louise and Hazel Johnson, and the rest of her family for enthusiastic support and encouragement. Steve and Julia appreciate the support of their wonderful colleagues at ASU and elsewhere.

Robert Rohli is grateful to his wife Suzanne, a geographer herself, for her patient and unflagging assistance with so many aspects of this project. In addition, their son, Eric, and daughter, Kristen, also contributed in various direct and indirect ways. Their support and enthusiasm, and the encouragement of so many other family members and friends, particularly Bob's and Suzanne's parents, was an important motivator. Rohli also feels deep appreciation for so many dedicated mentors who stimulated his interest in physical geography while he was a student. These outstanding educators include John Arnfield, David Clawson, Carville Earle, Keith Henderson, Jay Hobgood, Merrill Johnson, Ricky Nuesslein, Kris Preston, John Rayner, Jeff Rogers, Rose Sauder, and many others. And finally, Rohli thanks the many students over the years whose interest in the world around them makes his job fun.

Peter Waylen thanks his wife, Marilyn, for her continued unstinting support and encouragement in this and all his other academic endeavors. He would also like to acknowledge geographers who have been very influential in guiding his satisfying and rewarding career, the late John

Thornes, Ming-ko Woo, and César Caviades. He also thanks Germán Poveda for the stream of stimulating new ideas, including Daisy World with a hydrologic cycle. Peter thanks his coauthors, especially Steve Reynolds and Julia Johnson, for providing the opportunity to participate in this novel and exciting project.

Mark Francek wishes to thank his wife, Suezell, who from the onset, said, “You can do this!” despite his initial doubts about being able to find the time to complete this project. His five kids and two grandkids have also been supportive, making him smile and helping him not to take his work too seriously. Mark’s academic mentors over the years, including Ray Lougeay, Lisle Mitchell, Barbara Borowiecki, and Mick Day, have instilled in him a love of field work and physical geography. He also thanks the hundreds of students he taught over the years. Their eagerness to learn has always pushed him to explore new academic horizons. Finally, Mark appreciates working with all his coauthors. He marvels at their patience, kindness, and academic pedigrees.

Cindy Shaw, lead illustrator, is grateful to John Shaw and Ryan Swain, who were of enormous help with final art-file preparation. She particularly appreciates the support of her ever-patient husband, Karl Pitts, who during the project adapted to her long working hours and a steady diet of take-out food. As a scientist, he was always interested and happy to bounce ideas around and clarify any questions. Finally, Cindy thanks all the authors for being a pleasure to work with.

All the authors are very grateful for the thousands of students who have worked with us on projects, infused our classrooms with energy and enthusiasm, and provided excellent constructive feedback about what works and what doesn’t work. We wrote this book to help instructors, including us, make students’ time in our classes even more interesting, exciting, and informative. Thank you all!

REVIEWERS

Special thanks and appreciation go out to all reviewers. This book was improved by many beneficial suggestions, new ideas, and invaluable advice provided by these reviewers. We appreciate all the time they devoted to reviewing manuscript chapters, attending focus groups, surveying students, and promoting this text to their colleagues.

We would like to thank the following individuals who wrote and/or reviewed learning goal-oriented content for *LearnSmart*.

Florida Atlantic University, Jessica Miles
Northern Arizona University, Sylvester Allred
Roane State Community College, Arthur C. Lee
State University of New York at Cortland, Noelle J. Relles
University of North Carolina at Chapel Hill, Trent McDowell
University of Wisconsin—Milwaukee, Gina Seegers Szablewski

University of Wisconsin—Milwaukee, Tristan J. Kloss
Elise Uphoff

Special thanks and appreciation go out to all reviewers, focus group and Symposium participants. This first edition (through several stages of manuscript development) has enjoyed many beneficial suggestions, new ideas, and invaluable advice provided by these individuals. We appreciate all the time they devoted to reviewing manuscript chapters, attending focus groups, reviewing art samples, and promoting this text to their colleagues.

PHYSICAL GEOGRAPHY REVIEWERS

Antelope Valley College, Michael W. Pesses
Arizona State University, Bohumil Svoma
Austin Peay State University, Robert A. Sirk
Ball State University, David A. Call
California State University—Los Angeles, Steve LaDochy
California State University—Sacramento, Tomas Krabacker
College of Southern Idaho, Shawn Willsey
College of Southern Nevada, Barry Perlmutter
Eastern Washington University, Richard Orndorff
Eastern Washington University, Jennifer Thomson
Florida State University, Holly M. Widen
Florida State University, Victor Mesev
Frostburg State University, Phillip P. Allen
Frostburg State University, Tracy L. Edwards
George Mason University, Patricia Boudinot
Las Positas College, Thomas Orf
Lehman College, CUNY, Stefan Becker
Long Island University, Margaret F. Boorstein
Mesa Community College, Steve Bass
Mesa Community College, Clemenc Ligocki
Metro State, Kenneth Engelbrecht
Metro State, Jon Van de Grift
Minnesota State University, Forrest D. Wilkerson
Monroe Community College, SUNY, Jonathon Little
Moorpark College, Michael T. Walegur
Normandale Community College, Dave Berner
Northern Illinois University, David Goldblum
Oklahoma State University, Jianjun Ge
Oregon State University, Roy Haggerty
Pasadena City College, James R. Powers
Rhodes College, David Shankman
Samford University, Jennifer Rahn
San Francisco State University, Barbara A. Holzman
South Dakota State University, Trisha Jackson
South Dakota State University, Jim Peterson
Southern Illinois University—Edwardsville, Michael J. Grossman
Southern Utah University, Paul R. Larson
State University of New York at New Paltz, Ronald G. Knapp
Texas State University—San Marcos, David R. Butler
The University of Memphis, Hsiang-te Kung
Towson University, Kent Barnes
United States Military Academy, Peter Siska
University of Calgary, Lawrence Nkendirim

University of Cincinnati, Teri Jacobs
University of Colorado–Boulder, Jake Haugland
University of Colorado–Colorado Springs, Steve Jennings
University of Georgia, Andrew Grundstein
University of Missouri, C. Mark Cowell
University of Nevada–Reno, Franco Biondi
University of North Carolina–Charlotte, William Garcia
University of Oklahoma, Scott Greene
University of Saskatchewan, Dirk de Boer
University of Southern Mississippi, David Harms Holt
University of Tennessee, Derek J. Martin
University of Tennessee–Knoxville, Julie Y. McKnight
University of Wisconsin–Eau Claire, Christina M. Hupy
University of Wisconsin–Eau Claire, Joseph P. Hupy

University of Wisconsin–Eau Claire, Garry Leonard Running
University of North Dakota, Paul Todhunter
Weber State University, Eric C. Ewert

PHYSICAL GEOGRAPHY FOCUS GROUP AND SYMPOSIUM PARTICIPANTS

Ball State University, Petra Zimmermann
Blinn College, Rhonda Reagan
California State University–Los Angeles, Steve LaDochy
Georgia State University, Leslie Edwards

Indiana Purdue University–Indianapolis (IUPUI), Andrew Baker
Kansas State University, Doug Goodin
Mesa Community College, Steven Bass
Minnesota State University, Ginger L. Schmid
Northern Illinois University, Lesley Rigg
Northern Illinois University, Mike Konen
South Dakota State University, Bruce V. Millett
Texas A&M University, Steven Quiring
University of Alabama, Amanda Epsy-Brown
University of Colorado–Boulder, Peter Blanken
University of North Carolina–Greensboro, Michael Lewis
University of Oklahoma, Scott Greene
University of Wisconsin–Oshkosh, Stefan Becker

ABOUT THE AUTHORS

STEPHEN J. REYNOLDS



Stephen J. Reynolds received an undergraduate degree from the University of Texas at El Paso, and M.S. and Ph.D. degrees in geosciences from the University of Arizona. He then spent ten years directing the geologic framework and mapping program of the Arizona Geological Survey, completing a new *Geologic Map of Arizona*. Steve currently is a professor in the School of Earth and Space Exploration at Arizona State University, where he has taught various courses about regional geology, earth resources, evolution of landscapes, field studies, and teaching methods. He was president of the Arizona Geological Society and has authored or edited nearly 200 maps, articles, and reports on the evolution of Western North America. He also coauthored several widely used textbooks, including the award-winning *Exploring Geology* and *Exploring Earth Science*. His current science research focuses on regional geology, geomorphology, and resources of the Southwest. He has done science-education research on student learning in college science courses, especially the role of visualization. He was the first geoscientist with his own eye-tracking laboratory, where he and his students have researched student learning, including the role of textbooks and other educational materials. Steve is known for innovative teaching methods, has received numerous teaching awards, and has an award-winning website. As a National Association of Geoscience Teachers (NAGT) distinguished speaker, he traveled across the country presenting talks and workshops on how to infuse active learning and inquiry into large introductory geology classes. He is commonly an invited speaker to national workshops and symposia on active learning, visualization, and teaching.

ROBERT V. ROHLI



Robert Rohli received a B.A. in geography from the University of New Orleans, an M.S. degree in atmospheric sciences from The Ohio State University, and a Ph.D. in geography from Louisiana State University (LSU). He currently serves as professor of geography at LSU, coordinator of the Louisiana Geographic Education Alliance, and faculty director of the LSU Residential Colleges Program. Previously, he was assistant professor of geography at Kent State University (KSU) and regional climatologist at the Southern Regional Climate Center. His teaching and research interests are in physical geography, particularly synoptic and applied meteorology/climatology, atmospheric circulation variability, and hydroclimatology. He has taught Physical Geography, Climatology, Meteorology, World Climates, Methods in Synoptic Climatology, Applied Meteorology, Analysis of Spatial Data, Water Resources Geography, and others. Major themes in his teaching include the systems approach to physical geography, collaboration among students from different disciplines in producing group research projects, and development of applied problem-solving skills. He has been an active supporter of undergraduate education initiatives, including living-learning communities, LSU's Communication across the Curriculum program, improved teaching assessment methods, and outreach activities—especially those that promote geography. He has published more than 45 refereed research articles, mostly on topics related to synoptic or applied climatology, and over 20 loosely refereed manuscripts, encyclopedia articles, proceedings papers, and technical reports. He has also coauthored *Climatology*, a widely used textbook, and *Louisiana Weather and Climate*.

JULIA K. JOHNSON



Julia K. Johnson is currently a full-time faculty member in the School of Earth and Space Exploration at Arizona State University. Her M.S. and Ph.D. research involved structural geology and geoscience education research. She teaches introductory geoscience to more than 1,500 students per year, both online and in person, and supervises the associated in-person and online labs. She also coordinates the introductory geoscience teaching efforts of the School of Earth and Space Exploration, helping other instructors incorporate active learning and inquiry into large lecture classes. Julia coordinated an innovative project focused on redesigning introductory geology classes so that they incorporated more online content and asynchronous learning. This project was very successful in improving student performance, mostly due to the widespread implementation of concept sketches and partly due to Julia's approach of decoupling multiple-choice questions and concept-sketch questions during exams and other assessments. Julia is recognized as one of the best science teachers at ASU and has received student-nominated teaching awards and very high teaching evaluations in spite of her challenging classes. Her efforts have dramatically increased enrollments. She coauthored the widely used *Exploring Geology*, *Exploring Earth Science*, and publications on geology and science-education research, including an article in the *Journal of Geoscience Education* on concept sketches. She is the lead author of *Observing and Interpreting Geology*, an innovative laboratory manual in which all learning is built around a virtual world. She also developed a number of websites used by students around the world, including the *Visualizing Topography* and *Biosphere 3D* websites.

PETER R. WAYLEN



Peter Waylen is Professor of Geography and associate dean in the college of Liberal Arts and Sciences at the University of Florida. He holds a B.Sc. in geography from the London School of Economics, England, and a Ph.D. from McMaster University, Canada. He has also served as assistant professor at the University of Saskatchewan, visiting associate professor at the University of Waterloo, Canada, Hartley Visiting Research Fellow at the University of Southampton, England, and visiting scholar in the Department of Engineering Hydrology, University

College Galway, Ireland. His teaching and research interests are in the fields of hydrology and climatology, particularly the temporal and spatial variability of risks of such hazards as floods, droughts, freezes, and heat waves, and the way in which these vary in the long run, driven by global-scale phenomena like ENSO. He has worked throughout Anglo- and Latin America, and several parts of Africa. He teaches Introductory Physical Geography, Principles of Geographic Hydrology, and Models in Hydrology, and is a former University of Florida Teacher of the Year. His research is principally interdisciplinary and collaborative with colleagues and students. It has been supported variously by the Natural Research Council of Canada, NSF, NOAA, NASA, and the Inter-American Institute for Global Change Research. Results appear in over 100 geography, hydrology, and climatology refereed outlets and book chapters.

MARK A. FRANCEK



Mark Francek is a geography professor at Central Michigan University (CMU). He earned his doctorate in geography from the University of Wisconsin-Milwaukee, his master's in geography from the University of South Carolina, and his bachelor's degree in geography and psychology from the State University

College at Geneseo, New York. He has teaching and research interests in earth science education, physical geography, and soil science. Mark has pedaled three times across America and teaches biking geography field classes in and around the Great Lakes region and the Appalachian Mountains. He has authored and coauthored more than 30 scholarly papers, funded in part by the NSF and the State of Michigan, and has presented his research at national and state conferences. At CMU, Francek has served as acting director of the Environmental Studies Program, director of the Science and Technology Residential College, and now interim chair of the Geography Department. He has received state and national teaching awards, including the CMU Teaching Excellence Award, the Carnegie Foundation for the Advancement of Teaching Michigan Professor of the Year, the Presidents Council State Universities of Michigan Distinguished Professor of the Year, the National Council for Geographic Education Distinguished Teaching Award, and Michigan Science Teachers Association College Teacher of the Year. His "Earth Science Sites of the Week" Listserv, which highlights the best earth-science websites and animations, reaches thousands of K-16 educators from around the world.

Illustrators and Artists

CYNTHIA SHAW

Cynthia Shaw holds a B.A. in zoology from the University of Hawaii–Manoa as well as a master's in education from Washington State University, where she researched the use of guided illustration as a teaching and learning tool in the science classroom. Now focusing on earth science, mapping, and coral reef ecology, she writes and illustrates for textbooks and museums, and develops ancillary educational materials through her business, Aurelia Press. Her kids' novel, *Groupers Moon*, is used in many U.S. and Caribbean science classrooms and is making a real impact on shaping kids' attitudes toward fisheries conservation. Currently landlocked in Richland, Washington, Cynthia escapes whenever possible to travel, hike, and dive the reefs to field-sketch and do reference photography for her projects.

CHUCK CARTER

Chuck Carter has worked in the artistic end of the science and entertainment industries for more than 30 years. He helped create the popular computer game *Myst* in 1992. Chuck worked on more than two dozen video games as an artist, art director, computer graphics supervisor, and group manager. He has a decades-long relationship with *National Geographic* as an illustrator and helping launch National Geographic Online. Carter worked as a digital matte painter for science fiction shows like *Babylon 5*, *Crusade*, and *Mortal Kombat*, as well as art and animation for motion rides like Disney's Mission to Mars and Paramount's Star Trek: the Experience. His illustration clients include *Wired* magazine, *Scientific American*, and numerous book publishers. He is co-founder of Eagle Games Inc.

SUSIE GILLATT

Susie Gillatt grew up in Tucson, Arizona, where she received a bachelor of arts degree from the University of Arizona. She has worked as a photographer and in different capacities in the field of video production. She is president of Terra Chroma, Inc., a multimedia studio. Initially specializing in the production of educational videos, she now focuses on scientific illustration and photo preparation for academic books and journals. Many of the photographs in this book were contributed by Susie from her travels to experience different landscapes, ecosystems, and cultures around the world. For her own art, she especially enjoys combining photography with digital painting and exploring the world of natural patterns. Her award-winning art has been displayed in galleries in Arizona, Colorado, and Texas.

exploring physical
geography

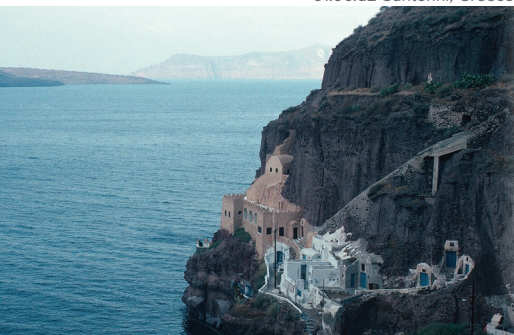
The Nature of Physical Geography

THE EARTH HAS A WEALTH of intriguing features, from dramatic mountains to intricate coastlines and deep ocean trenches, from lush, beautiful valleys to huge areas of sparsely vegetated sand dunes. Above the surface is an active, ever-changing atmosphere with clouds, storms, and variable winds. Occupying all these environments is life. In this chapter and book, we examine the main concepts of physical geography, along with the tools and methods that physical geographers use to study the landscapes, oceans, climate, weather, and ecology of Earth.

The large globe spanning these two pages is a computer-generated representation of Earth, using data collected by several satellites. On land, brown colors depict areas of rock, sand, and soil, whereas green areas have a more dense covering of trees, bushes, grasses, and other vegetation. Oceans and lakes are colored blue, with greenish blue showing places where the water is shallow or where it contains mud derived from the land. Superimposed on Earth's surface are light-colored clouds observed by a different satellite, one designed to observe weather systems.

What are all the things you can observe from this portrait of our planet? What questions arise from your observations?

01.00.a2 Santorini, Greece



Natural hazards, including volcanic eruptions and earthquakes, are a major concern in many parts of the world. In the Greek Island of Santorini (◄), people live on the remains of a large volcano that was mostly destroyed in a huge eruption 3,600 years ago, an eruption that probably gave rise to the story of Atlantis.

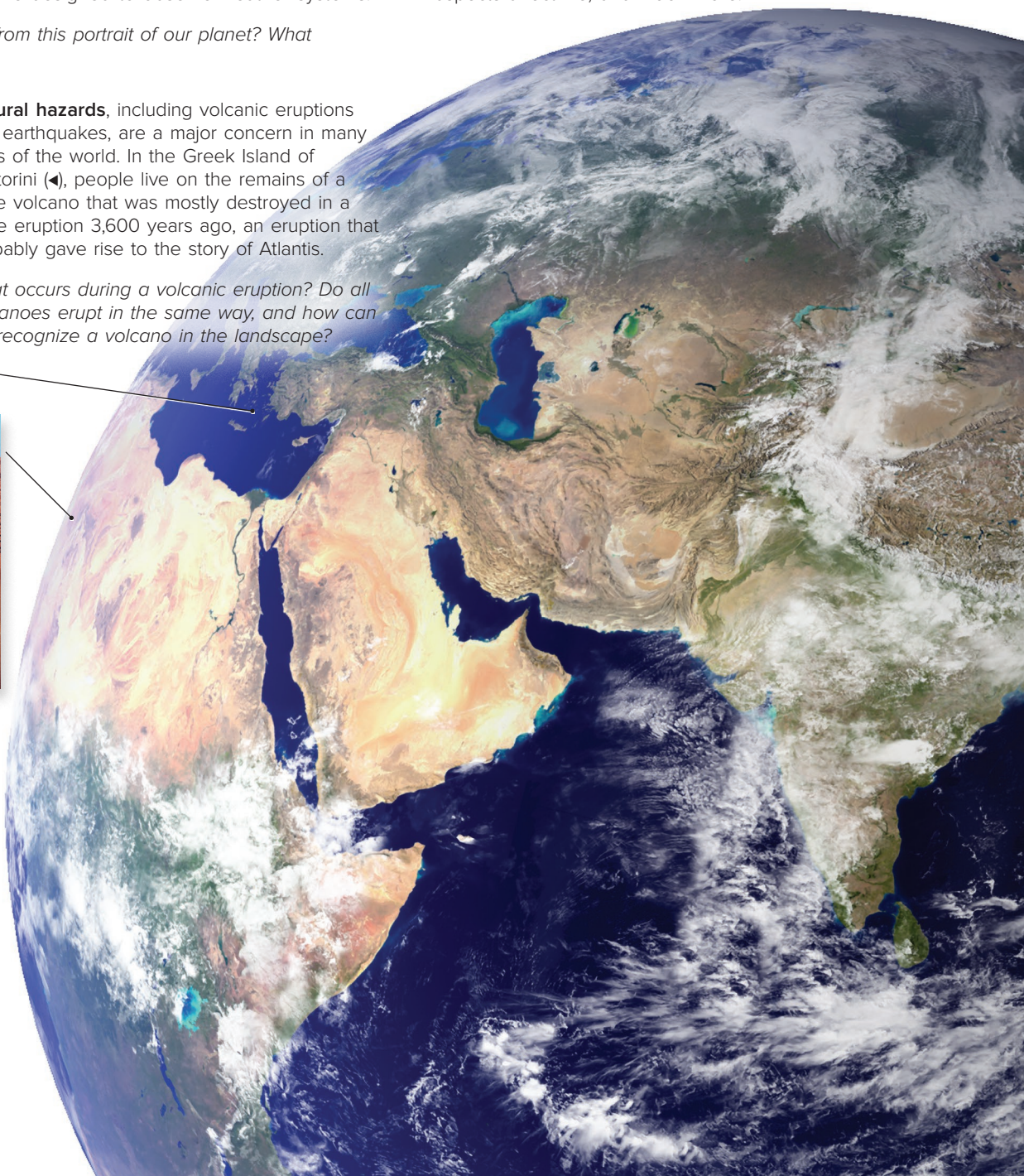
What occurs during a volcanic eruption? Do all volcanoes erupt in the same way, and how can we recognize a volcano in the landscape?

01.00.a3 Morocco



The Sahara Desert, on the opposite side of the Mediterranean Sea from Greece, has a very different climate. Here is a very dry environment, resulting in huge areas covered by sand dunes (▲) with sparse vegetation.

What do the features of the landscape—the landforms—tell us about the surface processes that are forming and affecting the scenery? What causes different regions to have different climates, some that are hot and dry, and others that are cold and wet? Is the climate of the Sahara somehow related to the relative lack of clouds over this area, as shown on the globe?



Most questions that arise from observing this globe are within the domain of *physical geography*. Physical geography deals with the landforms and processes on Earth's surface, the character and processes in oceans and other bodies of water, atmospheric processes that cause weather and climate, and how these various aspects affect life, and much more.



TOPICS IN THIS CHAPTER

1.1	What Is Physical Geography?	4	1.10	How Do We Use Maps and Photographs?	22
1.2	How Do We Investigate Geographic Questions?	6	1.11	How Do We Use Global Positioning Systems and Remote Sensing?	24
1.3	How Do Natural Systems Operate?	8	1.12	How Do We Use GIS to Explore Spatial Issues?	26
1.4	What Are Some Important Earth Cycles?	10	1.13	What Is the Role of Time in Geography?	28
1.5	How Do Earth's Four Spheres Interact?	12	1.14	CONNECTIONS: How Did Geographers Help in the 2010 Gulf of Mexico Oil-Spill Cleanup?	30
1.6	How Do We Depict Earth's Surface?	14	1.15	INVESTIGATION: What Might Happen If This Location Is Deforested?	32
1.7	What Do Latitude and Longitude Indicate?	16			
1.8	What Are Some Other Coordinate Systems?	18			
1.9	How Do Map Projections Influence the Portrayal of Spatial Data?	20			

01.00.a4 Tibet



Water is the most important resource on the planet, and Earth's temperatures allow water to occur in three states of matter—solid, liquid, and vapor. Examine this photograph (▲) and identify all the ways in which water is expressed on the surface and in the atmosphere. Is some water likely present but not visible? Geographers are concerned with where resources are, what causes a resource to be where it is, and how to reconcile the inevitable economic, environmental, and cultural trade-offs involved in using a resource.

How does water occur in the atmosphere, how is its presence expressed, and what is its role in severe weather? How does water occur and move on Earth's surface, and what landforms result from running water?

01.00.a5 Indonesia



Oceans cover about 70% of Earth's surface. Ocean temperatures, currents, and salinity all play a major role in global weather, climate, and the livability of places, even for those far from the coast. The oceans and nearby lands (▲) represent important habitats for plants and animals, which can be greatly impacted by human activities.

How do satellites help us measure the temperature, salinity, and motion of the oceans, and how do changes in any of these factors affect plants and animals that live in or near the sea?

01.00.a1

The Ancient and Modern Discipline of Geography

Geographers seek to understand the Earth. They do this by formulating important and testable questions about the Earth, employing principles from both the natural and social sciences. Geographers use these principles to portray features of the Earth using maps and technologically intensive tools and techniques that are distinctly geographical. Geographers synthesize the diverse information revealed by these tools to investigate the interface between the natural and human environments. The study of the spatial distribution of natural features and processes occurring near Earth's surface, especially as they affect and are affected by humans, is physical geography.

The ancient discipline of geography is especially relevant in our modern world, partly because of the increasing recognition that many problems confronting society involve complex interactions between natural and human dimensions. Such problems include the spatial distribution and depletion of natural resources; contamination of air, water, and soils; susceptibility of areas to landslides, flooding, and other natural disasters; formation of and damage caused by hurricanes, tornadoes, and other severe weather; the current and future challenges of global environmental change; and the environmental implications of globalization. The topics and questions introduced on these pages provide a small sample of the aspects investigated by physical geographers and are discussed more fully in the rest of the book. We hope you enjoy the journey learning about the fascinating planet we call home.

What Is Physical Geography?

PHYSICAL GEOGRAPHY IS THE STUDY of spatial distributions of phenomena across the landscape, processes that created and changed those distributions, and implications for those distributions on people. Geography is both a natural and a social science. Geographers think broadly, emphasizing interconnections and complex issues, solving complicated problems such as resource management, environmental impact assessment, spread of disease, and urban planning. Although many such occupations do not have the title of *geographer*, they require a geographic perspective. Let's have a closer look at what the geographic perspective entails.

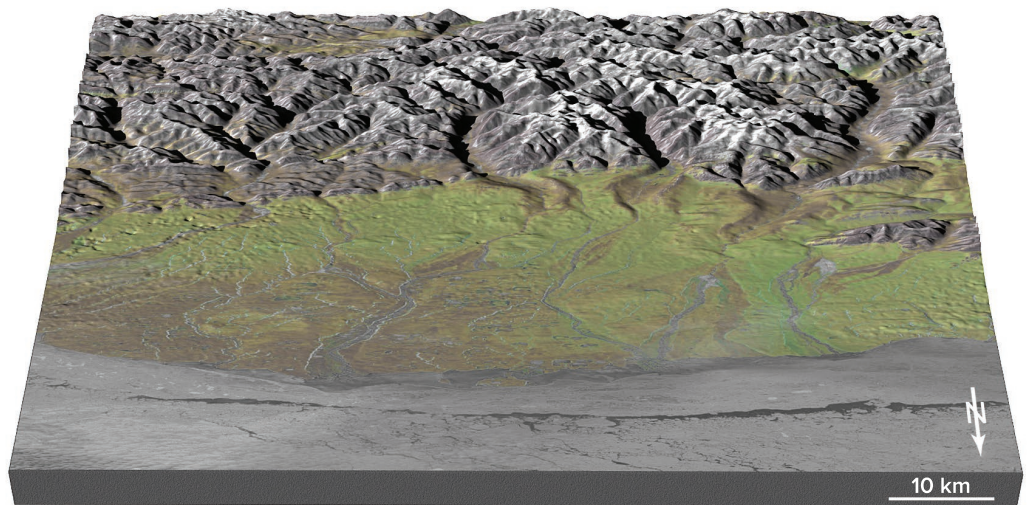
A What Approach Do Geographers Use to Investigate Important Issues?

Geographers approach problems from different perspectives than other natural and social scientists. Specifically, geographers think *spatially*, meaning they emphasize the setting, such as location, in addressing problems, and *holistically*, integrating ideas from a wide variety of the natural and social sciences. In many ways, it is not *what* is studied that makes it geography, but instead *how* it is studied. The decision of whether to drill for oil in Alaska's Arctic National Wildlife Refuge (ANWR) is a complicated issue that can be best understood using the geographic approach.

1. This figure (►) shows a three-dimensional perspective of the central part of ANWR, looking south with the ice-covered Arctic Ocean in the foreground. ANWR is well known for its abundant caribou and other Arctic animals. Before reading on, examine this scene and think about all the information you would need if you wanted to understand how drilling for oil and gas might impact the caribou.

2. To understand this issue, you might ask a series of questions. Where do the caribou live? Since they migrate seasonally, where are they at different times of the year? What do they eat, where are these foods most abundant, and what factors control these abundances? Where is water available, and how much rain and snow do different parts of the region receive? Is the precipitation consistent from year to year? When is the mating season, and where do the mothers raise their young?

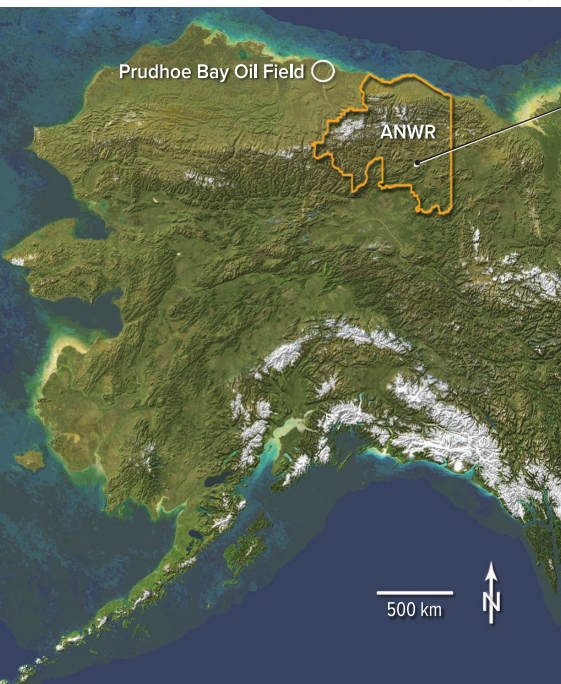
3. You could also ask questions about the subsurface oil reserves. Where is the oil located, and what types of facilities will be required to extract and transport the oil? How much land will be disturbed by such activities, and how will this affect the caribou?



01.01.a1

4. The issues of ANWR nicely illustrate why we would use a geographic approach. Most of the questions we asked here have a *spatial component*, as indicated by the word "where," and could be best answered with some type of map. The questions also have an explicit or implicit societal component, such as how development could affect the traditional way of life of the native people of the region.

01.01.a2



5. The *spatial perspective* allows us to compare the locations of the physical, environmental, economic, political, and cultural attributes of the issue. ANWR (◄) is the large area outlined in orange. Its size is deceptive since Alaska is huge (by far the largest state in the U.S.). For comparison, ANWR is only slightly smaller than the state of South Carolina.

6. Directly to the west of ANWR is the Prudhoe Bay oil field, the largest oil field in North America. Not all of ANWR is likely to contain oil and natural gas, and an assessment of the oil resources by the U.S. Geological Survey (USGS) identified the most favorable area as being near the coast. To consider the question about oil drilling, we would want to know where this favorable area is, how much land will be disturbed by drilling and associated activities, when these disturbances will occur, and how these compare with the location of caribou at different times of the year, especially where they feed, mate, and deliver their young.

01.01.a3 ANWR, AK



7. The *holistic perspective* allows us to examine the interplay between the environment and the aesthetic, economic, political, and cultural attributes of the problem. Most of ANWR is a beautiful wilderness area (▲), as well as being home to caribou, native people, and various plants and animals.

B How Does Geography Influence Our Lives?

Observe this photograph, which shows a number of different features, including clouds, snowy mountains, slopes, and a grassy field with horses and cows (the small, dark spots). For each feature you recognize, think about what is there, what its distribution is, and what processes might be occurring. Then, think about how these factors influence the life of the animals and how they would influence you if this were your home.

01.01.b1 Henry Mtns., UT



1. The snow-covered mountains, partially covered with clouds, indicate the presence of water, an essential ingredient for life. The mountains have a major influence on water in this scene. Melted snow flows downhill toward the lowlands, to the horses and cows. The elevation and shape of the land influence the spatial distribution and type of precipitation (rain, snow, and hail) and the pattern of streams that develop to drain water off the land.

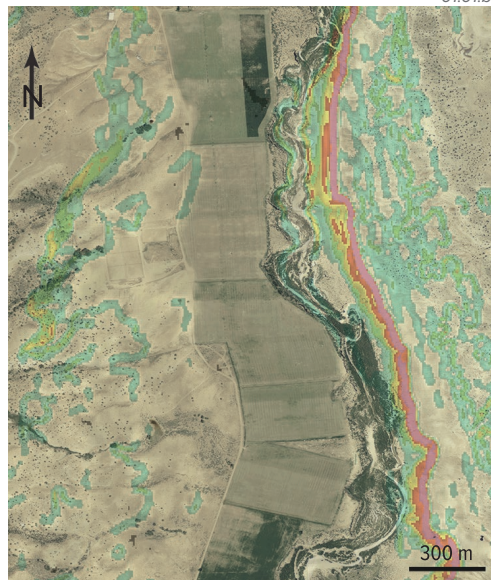
2. The horses and cows roam on a flat, grassy pasture, avoiding slopes that are steep or barren of vegetation. The steepness of slopes reflects the strength of the rocks and soils, and the flat pasture resulted from loose sand and other materials that were laid down during flooding along a desert stream. The distribution of vegetation is controlled by steepness of slopes, types of soils and other material, water content of the soil, air temperatures, and many other factors, all of which are part of physical geography. The combined effect of such factors in turn affect, and are affected by, the human settlements in the area to make every place, including this one, distinctive and unique.

01.01.b2



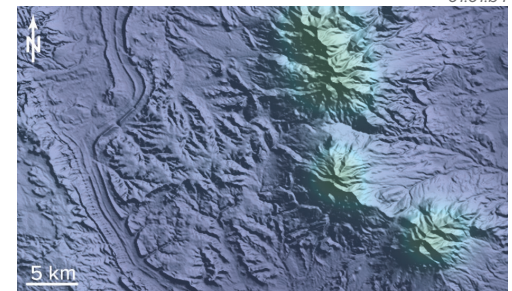
3. A better view of the spatial distribution of the green pasture is provided by this aerial photograph (a photograph taken from the air, like from a plane or drone). This view of the pasture and adjacent areas reveals the shape of the pasture, and we could measure its length, width, and area. Such measurements would help us decide how many horses and cows the land could support.

01.01.b3



4. Geographers calculate various measures of the landscape, like the steepness of slopes, and then overlay this information on the original map or image. In the figure above, red shading shows the steepest slopes, along and below the pinkish cliff. Yellow and green indicate less steep slopes, and relatively flat areas are unshaded. Such a map would help us decide which areas could be new pastures.

01.01.b4



5. This image shows the shape of the land across the region, including the mountains (the pasture is on the left part of the map). Colors indicate the average amount of precipitation, with green showing the highest amounts. The mountains, on average, receive the most rain and snow.

Before You Leave This Page

- Describe the geographic approach.
- List some examples of information used by physical geographers and how these types of information could influence our lives.

How Do We Investigate Geographic Questions?

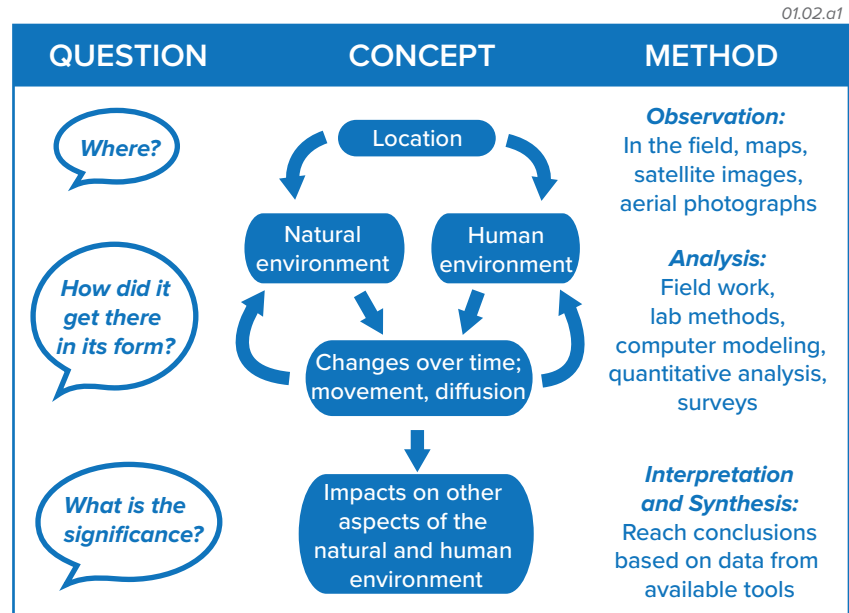
PHYSICAL GEOGRAPHERS STUDY DIVERSE PROBLEMS, ranging from weather systems and climate change to ocean currents and landscape evolution. The types of data required to investigate each of these problems are equally diverse, but most geographers try to approach the problem in a similar, objective way, guided by spatial information and relying on various geographic tools. Geography utilizes approaches from the natural and social sciences, blending them together in a geographic approach. Like other scientists, geographers pose questions about natural phenomena and their implications, propose a possible explanation (hypothesis) that can be tested, make predictions from this hypothesis, and collect data needed to critically evaluate whether the hypothesis passes the tests.

A How Do Geographers Approach Problems?

Geographers ask questions like the following:

- Where is it?
- Why is it where it is?
- How did it get where it is?
- Why does it matter where it is?
- How does “where it is” influence where other things are and why they are there?

The conceptual basis of these questions lies in the notion that the *location* of something affects, and is a product of, other features or processes in both the natural and human environment, and of interactions between the natural and human environments. Natural and human phenomena are constantly changing and constantly impacting other features in new ways, influencing aspects like site selection and risk of natural hazards. To address such complex issues, we use a variety of tools and methods, such as maps, computer-simulation models, aerial photographs, satellite imagery, statistical methods, and historical records. The figure to the right illustrates some aspects to consider.



B What Is the Difference Between Qualitative and Quantitative Data?

Geographers approach problems in many ways, asking questions about Earth processes and collecting data that help answer these questions. Some questions can be answered with qualitative data, but others require quantitative data, which are numeric and are typically visualized and analyzed using data tables, calculations, equations, and graphs.

01.02.b1 Augustine Island, AK



When Augustine volcano in Alaska erupts, we can make various types of observations and measurements. Some observations are *qualitative*, like descriptions, and others are measurements that are *quantitative*. Both types of data are essential for documenting natural phenomena.

01.02.b2 Augustine Island, AK



Qualitative data include descriptive words, labels, sketches, or other images. We can describe this picture of Augustine volcano with phrases like “contains large, angular fragments,” “releases steam,” or “the slopes seem steep and unstable.” Such phrases can convey important information about the site.

01.02.b3 Augustine Island, AK



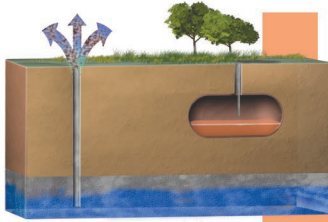
Quantitative data involve numbers that represent measurements. Most result from scientific instruments, such as this thermal camera that records temperatures on the volcano, or with measuring devices like a compass. We could also collect quantitative measurements about gases released into the air.

C How Do We Test Alternative Explanations?

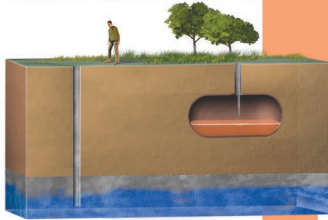
Science proceeds as scientists explore the unknown—making observations and then systematically investigating questions that arise from observations that are puzzling or unexpected. Often, we try to develop several possible explanations and then devise ways to test each one. The normal steps in this *scientific method* are illustrated below, using an investigation of groundwater contaminated by gasoline.

Steps in the Investigation

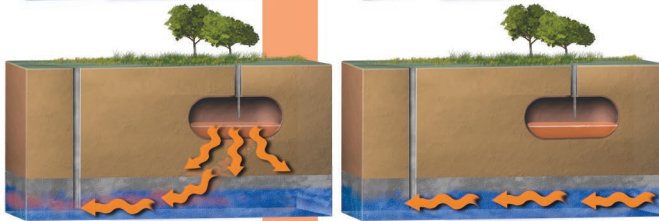
Observations



Questions Derived from Observations



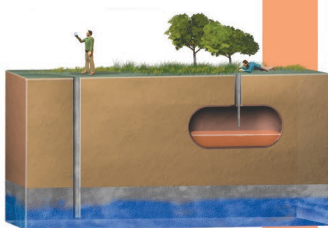
Proposed Explanations and Predictions from Each Explanation



4. One explanation is that the buried tank is the source of contamination.

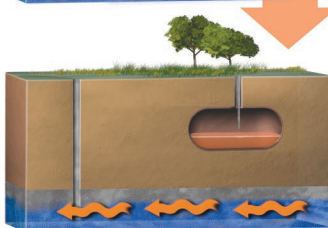
5. Another explanation is that the buried tank is not the source of the contamination. Instead, the source is somewhere else, and contamination flowed into the area.

Results of Investigation



7. To study this problem, an early step is to compile all the necessary data. This might include maps showing the location of water wells, the direction of groundwater flow, and locations of gas stations and other possible sources of gasoline. In our case, investigation discovered no holes in the tank or any gasoline in the soil around the tank. Records show that the tank held leaded gasoline, but gasoline in the groundwater is unleaded. We compare the results of any investigation with the predictions to determine which possible explanation is most consistent with the new data.

Conclusions



8. Data collected during the investigation support the conclusion that the buried tank is not the source of contamination. Any explanation that is inconsistent with data is probably incorrect, so we pursue other explanations. In this example, a nearby underground pipeline may be the source of the gasoline. We can devise ways to evaluate this new hypothesis by investigating the pipeline. We also can revisit the previously rejected hypothesis if we discover a new way in which it might explain the data.

9. The goal is to collect data, assemble information, and draw conclusions without letting our personal bias interfere with carrying out good science. We want to reach the explanation that best explains all the data. Few things are ever “proved” in science, some can be “disproved,” but generally we are left to weigh the pros and cons of several still-viable explanations. We choose the one that, based on the data, is most likely to be correct.

01.02.ct

Before You Leave This Page

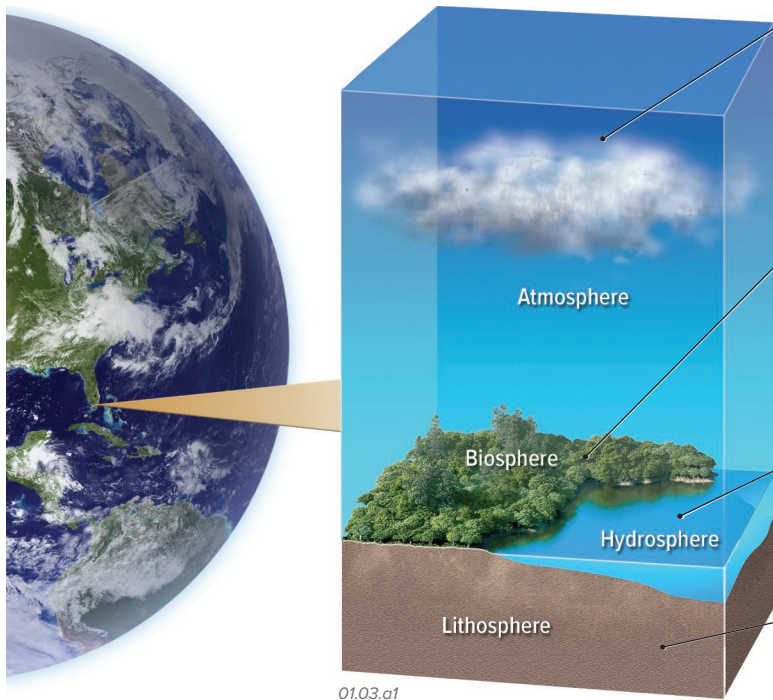
- ✓ Summarize some of the aspects commonly considered using a geographic approach.
- ✓ Explain the difference between qualitative and quantitative data, providing examples.
- ✓ Explain the logical scientific steps taken to critically evaluate a possible explanation.

How Do Natural Systems Operate?

EARTH HAS A NUMBER OF SYSTEMS in which matter and energy are moved or transformed. These involve processes of the solid Earth, water in all its forms, the structure and motion of the atmosphere, and how these three domains (Earth, water, and air) influence life. Such systems are *dynamic*, responding to any changes in conditions, whether those changes arise internally *within* the system or are imposed externally from *outside* the system.

A What Are the Four Spheres of Earth?

Earth consists of four overlapping spheres—the atmosphere, biosphere, hydrosphere, and lithosphere—each of which interacts with the other three spheres. The atmosphere is mostly gas, but includes liquids (e.g., water drops) and solids (e.g., ice and dust). The hydrosphere represents Earth’s water, and the lithosphere is the solid Earth. The biosphere includes all the places where there is life—in the atmosphere, on and beneath the land, and on and within the oceans.



01.03.a1

1. The *atmosphere* is a mix of mostly nitrogen and oxygen gas that surrounds Earth’s surface, gradually diminishing in concentration out to a distance of approximately 100 kilometers, the approximate edge of outer space. In addition to gas, the atmosphere includes clouds, precipitation, and particles such as dust and volcanic ash. The atmosphere is approximately 78% nitrogen, 21% oxygen, less than 1% argon, and smaller amounts of carbon dioxide and other gases. It has a variable amount of water vapor, averaging less than 4%.
2. The *biosphere* includes all types of life, including humans, and all of the places it can exist on, above, and below Earth’s surface. In addition to the abundant life on Earth’s surface, the biosphere extends about 10 kilometers up into the atmosphere, to the bottom of the deepest oceans, and downward into the cracks and tiny spaces in the subsurface. In addition to visible plants and animals, Earth has a large population of diverse microorganisms.
3. The *hydrosphere* is water in oceans, glaciers, lakes, streams, wetlands, groundwater, moisture in soil, and clouds. Over 96% of water on Earth is salt water in the oceans, and most fresh water is in ice caps, glaciers, and groundwater, not in lakes and rivers.
4. The *lithosphere* refers generally to the solid upper part of the Earth, including Earth’s crust. Water, air, and life extend down into the lithosphere, so the boundary between the solid Earth and other spheres is not distinct, and the four spheres overlap.

B What Are Open and Closed Systems?

Many aspects of Earth can be thought of as a system—a collection of matter, energy, and processes that are somehow related and interconnected. For example, an air-conditioning system consists of some mechanical apparatus to cool the air, ducts to carry the cool air from one place to another, a fan to move the air, and a power source. There are two main types of systems: *open systems* and *closed systems*.



01.03.b1 Noxubee NWR, MS

1. An *open system* allows matter and energy to move into and out of the system. A tree (◀) is an open system, taking in water and soil-derived nutrients, extracting carbon dioxide from the air to make the carbon-rich wood and leaves, sometimes shedding those leaves during the winter as shown here, and expelling oxygen as a by-product of photosynthesis, fueled by externally derived energy from the Sun.
2. A *closed system* does not exchange matter, or perhaps even energy, with its surroundings. The Earth as a whole (▶) is fundamentally a closed system with regard to matter, except for the escape of some light gases into space and the arrival of occasional meteorites. It is an open system for energy, which is gained via sunlight and can be lost to space.



01.03.b2

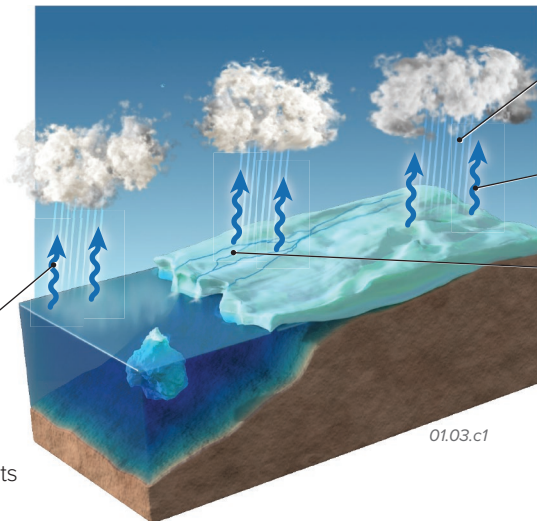
C How Do Earth Systems Operate?

Systems consist of matter and energy, and they respond to internally or externally caused changes in matter and energy, as a tree responds to a decrease in rain (matter) or colder temperatures during the winter (energy). Systems can respond to such changes in various ways, either reinforcing the change or counteracting the change.

System Inputs and Responses

1. One of Earth's critical systems involves the interactions between ice, surface water, and atmospheric water. This complex system, greatly simplified here (►), remains one of the main challenges for computer models attempting to analyze the causes and possible consequences of climate change.

2. Liquid water on the surface *evaporates* (represented by the upward-directed blue arrows), becoming water vapor in the atmosphere. If there is enough water vapor, small airborne droplets of water accumulate, forming the low-level clouds illustrated here.



3. Under the right conditions, the water freezes, becoming snowflakes or hail, which can fall to the ground. Over the centuries, if snow accumulates faster than it melts, the snow becomes thick and compressed into ice, as in *glaciers*, which are huge, flowing fields of ice.

4. The water molecules in snow and ice can return directly to the atmosphere via several processes.

5. If temperatures are warm enough, snow and ice can melt, releasing liquid water that can accumulate in streams and flow into the ocean or other bodies of surface water. Alternatively, the meltwater can evaporate back into the atmosphere. Melting also occurs when icebergs break off from the glacier.

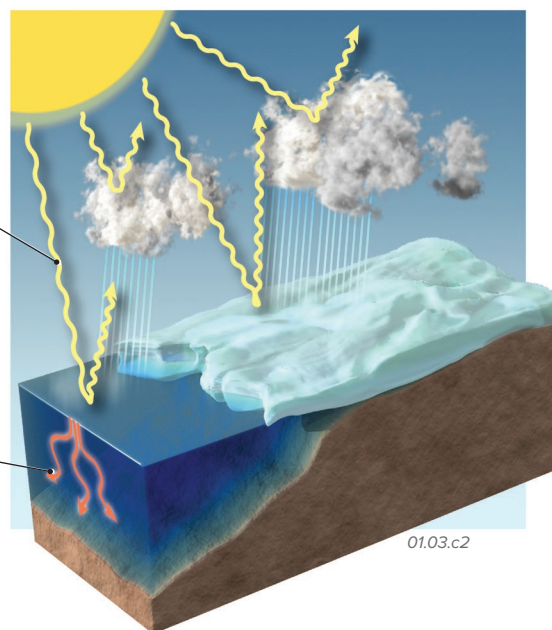
6. The movement of matter and energy carried in the various forms of water is an example of a *dynamic system*—a system in which matter, energy, or both, are constantly changing their position, amounts, or form.

Feedbacks

7. The system can respond to changes in various ways, which can either reinforce the effect, causing the overall changes to be amplified (increased in effect), or partially or completely counteract the effect, causing changes to be dampened (decreased in effect). Such reinforcements or inhibitors are called *feedbacks*.

8. In our example, sunlight shines on the ice and water. The ice is relatively smooth and light-colored, reflecting much of the Sun's energy upward, into the atmosphere or into space. In contrast, the water is darker and absorbs more of the Sun's energy, which warms the water.

9. If the amount of solar energy reaching the surface, or trapped near the surface, increases, for whatever reason, this may cause more melting of the ice. As the front of the ice melts back, it exposes more dark water, which absorbs more heat and causes even more warming of the region. In this way, an initial change (warming) triggers a response that causes even more of that change (more warming). Such a reinforcing result is called a *positive feedback*.



10. The warming of the water results in more evaporation, moving water from the surface to the atmosphere, which in turn may result in more clouds. Low-level clouds are highly reflective, so as cloud cover increases they intercept more sunlight, leading to less warming. This type of response does not reinforce the change but instead dampens it and diminishes its overall effect. This dampening and resultant counteraction is called a *negative feedback*.

11. As this overly simplified example illustrates, a change in a system can be reinforced by positive feedbacks or stifled by negative ones. Both types of feedbacks are likely and often occur at the same time, each nudging the system toward opposite behaviors (e.g., overall warming or overall cooling). Feedbacks can leave the system largely unchanged, or the combined impact of positive and negative feedbacks can lead to a stable but gradually changing state, a condition called *dynamic equilibrium*.

Before You Leave This Page

- ✓ Describe Earth's four spheres.
- ✓ Explain what is meant by open and closed systems.
- ✓ Sketch and explain examples of positive and negative feedbacks.