READER FORTH CANADIAN EDITION

Edward J. Tarbuck

Frederick K. Lutgens

Cameron J. Tsujita Western University

Stephen R. Hicock Western University



Toronto

Editor-in-Chief: Michelle Sartor Acquisitions Editor: Cathleen Sullivan Marketing Manager: Marlene Olsavsky Program Manager: Darryl Kamo Project Manager: Kimberley Blakey Developmental Editor: Paul Donnelly Media Editor: Ben Zaporazan Media Producer: Daniel Szabo Production Services: Harleen Chopra®, Cenveo Publisher Services Permissions Project Manager: Marnie Lamb Photo Permissions Research: Zoe Milgram, QBS Learning TextPermissions Research: Haydee Hidalgo, Electronic Publishing Services, Inc. Art Director: ZenaDenchik Cover Designer: Alex Li Interior Designer: Nesbitt Graphics Cover Image: J. David Andrews/Masterfile

Credits and acknowledgments for material borrowed from other sources and reproduced, with permission, in this textbook appear on the appropriate page within the text.

Original edition published by Pearson Education, Inc., Upper Saddle River, New Jersey, USA. Copyright © 2013 Pearson Education, Inc. This edition is authorized for sale only in Canada.

If you purchased this book outside the United States or Canada, you should be aware that it has been imported without the approval of the publisher or the author.

Copyright © 2015 Pearson Canada Inc. All rights reserved. Manufactured in the United States of America. This publication is protected by copyright and permission should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission(s) to use material from this work, please submit a written request to Pearson Canada Inc., Permissions Department, 26 Prince Andrew Place, Don Mills, Ontario, M3C 2T8, or fax your request to 416-447-3126, or submit a request to Permissions Requests at **www.pearsoncanada.ca**.

 $10\ 9\ 8\ 7\ 6\ 5\ 4\ 3\ 2\ 1\ CKV$

Library and Archives Canada Cataloguing in Publication

Tarbuck, Edward J., author Earth : an introduction to physical geology / Edward J. Tarbuck, Frederick K. Lutgens, Dennis Tasa, Cameron J. Tsujita, Stephen R.

Hicock. — Fourth Canadian edition.

Revision of: Earth : an introduction to physical geology / Edward J. Tarbuck ... [et al.] 3rd Canadian ed.

551

Includes bibliographical references and index. ISBN 978-0-13-704776-5 (pbk.)

1. Physical geology-Textbooks. I. Title.

QE28.2.T37 2014

C2013-907524-0



BRIEF CONTENTS

PREFACE xiv

CHAPTER **1** AN INTRODUCTION TO GEOLOGY AND PLATE TECTONICS **1**

CHAPTER 2 MINERALS: THE BUILDING BLOCKS OF ROCKS 30

CHAPTER 3 IGNEOUS ROCKS 55

CHAPTER 4 VOLCANOES AND VOLCANIC PROCESSES 84

CHAPTER 5 WEATHERING AND SOIL 108

CHAPTER 6 SEDIMENTARY ROCKS 131

CHAPTER **7** METAMORPHISM AND METAMORPHIC ROCKS **162**

CHAPTER 8 GEOLOGIC TIME 183

CHAPTER 9 CRUSTAL DEFORMATION 204

CHAPTER 10 EARTHQUAKES AND EARTH'S INTERIOR 225

CHAPTER 11 THE OCEAN FLOOR 252 CHAPTER 12

PLATE TECTONICS: THE FRAMEWORK FOR MODERN GEOLOGY **270**

CHAPTER 13 MOUNTAIN BUILDING AND CONTINENTAL FRAMEWORKS 291

CHAPTER 14 MASS WASTING: THE WORK OF GRAVITY 310

CHAPTER 15 RUNNING WATER 329

CHAPTER 16 GROUNDWATER 359

CHAPTER 17 GLACIER AND GLACIATION 382

CHAPTER 18 DESERTS AND WINDS 410

CHAPTER 19 SHORELINES 427

CHAPTER 20 MINERAL AND ENERGY RESOURCES 445

GLOSSARY 489 INDEX 505

CONTENTS

PREFACE xiv

CHAPTER 1

AN INTRODUCTION TO GEOLOGY AND PLATE TECTONICS 1

The Science of Geology 2

BOX 1.1: Canadian Profile Sir William Logan: Canada's Premier Geologist **3**

Geology, People, and the Environment 4 Some Historical Notes about Geology 5

Geologic Time 7

Relative Dating and the Geologic Time Scale 7 The Magnitude of Geologic Time 9

Early Evolution of Earth 10 Origin of Planet Earth 10 Formation of Earth's Layered Structure 10

Plate Tectonics: A Geologic Paradigm 12 Continental Drift: An Idea Before Its Time 12

Planet of Shifting Plates 16 Plate Boundaries 17

Earth's Internal Structure 18

Layers Defined by Composition 19 Layers Defined by Physical Properties 19

Earth's Spheres 21 Hydrosphere 21

BOX 1.2: Understanding Earth Why Does Earth Have a Magnetic Field? 22

Atmosphere 23 Biosphere 24 Geosphere 24

The Face of Earth 24 Continents 24

Ocean Basins 24

Earth as a System 25 The Rock Cycle: Part of the Earth System 26

CHAPTER 2

MINERALS: THE BUILDING BLOCKS OF ROCKS 30

Minerals 31

The Composition of Minerals 32

Elements 32 Atomic Structure 34 Bonding 34

The Structure of Minerals 36

Physical Properties of Minerals 37

Crystal Habit (Shape) 37 Lustre 38 Colour 39 Streak 39 Hardness 40 Cleavage 40 Fracture 40 Specific Gravity 40 Other Properties of Minerals 40

Mineral Classes 41

BOX 2.1: Geology and Popular Media Kryptonite Discovered!...Sort Of **42**

The Silicates 43 Common Silicate Minerals 46 Important Nonsilicate Minerals 50

BOX 2.2: Understanding Earth Gemstones **52**

CHAPTER 3

IGNEOUS ROCKS 55

Magma: The Parent Material of Igneous Rock 56 Generating Magma from Solid Rock 57 The Nature of Magma 59 From Magma to Crystalline Rock 59

How Magmas Evolve 60

BOX 3.1: Canadian Profile Norman Bowen and His Reaction Series **61**



vi Contents

Bowen's Reaction Series and the Composition of Igneous Rocks 61 Partial Melting and Magma Formation 63

Igneous Compositions 65

Felsic versus Mafic Compositions 66 Other Compositional Groups 67 Silica Content as an Indicator of Composition 67

Igneous Textures 67

Factors Affecting Crystal Size 67

BOX 3.2: Understanding Earth Thin Sections and Rock Identification **69**

Types of Igneous Textures 70

Naming Igneous Rocks 72

Felsic (Granitic) Igneous Rocks 72 Intermediate (Andesitic) Igneous Rocks 74 Mafic (Basaltic) and Ultramafic Igneous Rocks 76 Pyroclastic Rocks 76

Intrusive Igneous Bodies 78

Nature of Plutons 78 Dykes 78 Sills 78 Laccoliths 80 Batholiths 81

CHAPTER 4

VOLCANOES AND VOLCANIC PROCESSES 84

The Nature of Volcanic Eruptions 86

Factors Affecting Viscosity 86

BOX 4.1: Geology and Popular MediaDante's Peak Versus Volcano: When Magma GotMacho 87

Importance of Dissolved Gases 88

Materials Extruded During an Eruption 88

Lava Flows 88 Gases 90 Pyroclastic Materials 91 Nuée Ardente: A Deadly Pyroclastic Flow 91 Lahars: Mudflows on Active and Inactive Volcanoes 92

Volcanic Structures and Eruptive

Styles 94

Anatomy of a Volcano 94 Shield Volcanoes 95 Cinder Cones 95 Composite Volcanoes 96 Calderas 101 Fissure Eruptions and Lava Plateaus 101 Lava Domes 102 Volcanic Pipes and Necks 102

Plate Tectonics and Volcanic Activity 104

CHAPTER 5

WEATHERING AND SOIL 108 Earth's External Processes 109

Weathering 109

Mechanical Weathering 110

Frost Wedging 110 Sheeting 111 Biologic Activity 111

Chemical Weathering 112

Dissolution 113 Oxidation 114

BOX 5.1: Earth as a System Acid Precipitation: A Human Impact on the Earth System **115**

Hydrolysis 116 Alterations Caused by Chemical Weathering 117

Rates of Weathering 117

Rock Characteristics 118 Climate 119 Differential Weathering 120

Soil 120

An Interface in the Earth System 120 What Is Soil? 120

Controls of Soil Formation 121

Parent Material 121 Time 122 Climate 122 Plants and Animals 122 Topography 122

The Soil Profile 122

Soil Types 124 The Canadian Soil Classification System 124 Ancient Soils: Paleosols 124

Soil Erosion 125

How Soil Is Eroded 125 Rates of Erosion 126 Controlling Soil Erosion 128

BOX 5.2: People and the Environment Return to the Dust Bowl? **128**

CHAPTER 6

- SEDIMENTARY ROCKS 131
- What Is a Sedimentary Rock? 132

Turning Sediment into Sedimentary Rock: Diagenesis and Lithification 132

Sedimentary Environments 133

Types of Sedimentary Environments 133 Sedimentary Facies 137

Types of Sedimentary Rocks 137

Detrital Sedimentary Rocks 138

Shale and Other Mudrocks138Sandstone140Conglomerate and Breccia142

Chemical Sedimentary Rocks 143

Limestone 143

BOX 6.1: Earth as a System The Carbon Cycle and Sedimentary Rocks 144

Dolostone 146 Chert 146 Evaporites 147

Coal: An Organic Sedimentary Rock 147 Classification of Sedimentary Rocks 148 Sedimentary Structures 150 Fossils: Evidence of Past Life 155

BOX 6.2: Canadian Profile The Burgess Shale: Yoho National Park, British Columbia **156**

CHAPTER 7

METAMORPHISM AND METAMORPHIC ROCKS 162

Metamorphism 163

Controlling Factors in Metamorphism 164 Composition of the Parent Rock 164 Heat as a Metamorphic Agent 164 Pressure as a Metamorphic Agent 164 Chemically Active Fluids 167 Metamorphic Grade and Index Minerals 167 Burial Metamorphism 169 Contact Metamorphism 169 Regional Metamorphism 0f Shale 173 Regional Metamorphism of Shale 173 Regional Metamorphism of Basalt 175 The Upper Limit of Regional Metamorphism 176 Regional Metamorphism and Nonfoliated Rocks 177 Subduction Zone Metamorphism 177

Metamorphic Facies and Plate Tectonics 177

BOX 7.1: Understanding Earth Impact Metamorphism **178**

Ancient Metamorphic Environments 180

CHAPTER 8

GEOLOGIC TIME 183 Geology Needs a Time Scale 184

Relative Dating: Key Principles 184

Geologic Time 184 Law of Superposition 185 Principle of Original Horizontality 185 Principle of Cross-Cutting Relations 185 Inclusions 186 Unconformities 186

Correlation of Rock Layers 189

Correlation by Physical Criteria 189 Fossils and Correlation 189



BOX 8.1: Understanding Earth Index Fossils and Ecology of Organisms 192

Dating with Radioactivity 193

Radioactivity 193 Half-Life 194 Radiometric Dating 195

BOX 8.2: Canadian Profile Dating Earth's Surface with Terrestrial Cosmogenic Nuclides **195**

Dating with Carbon-14 197

The Geologic Time Scale 197

Geologic Time 197 Structure of the Time Scale 197

BOX 8.3: Earth as a System Demise of the Dinosaurs **199**

Precambrian Time 201

Difficulties in Dating the Geologic Time Scale 201

CHAPTER 9

CRUSTAL DEFORMATION 204

Structural Geology: A Study of Earth's Architecture 205

Deformation 206 Force, Stress, and Strain 206 Types of Stress 206 How Rocks Deform 206

Mapping Geologic Structures 209

Strike and Dip 210

Folds 211

Types of Folds 211 Domes and Basins 213



Joints 215

Faults 217

Dip-Slip Faults 217

BOX 9.1: People and the Environment The San Andreas Fault System **218**

Strike-Slip Faults 221

CHAPTER 10

EARTHQUAKES AND EARTH'S INTERIOR 225

What Is an Earthquake? 227

Earthquakes and Faults 227 Elastic Rebound 228 Foreshocks and Aftershocks 228

Seismology 229

Locating the Source of an Earthquake 232 Earthquake Belts 232

Measuring the Size of Earthquakes 232

BOX 10.1: Canadian Profile Earthquakes in Canada 234

Intensity Scales 235 Magnitude Scales 237

Earthquake Destruction 238 Destruction from Seismic Vibrations 238 Tsunami 240

BOX 10.2: Understanding Earth 2011 Japan Tsunami **241**

BOX 10.3: People and the Environment Tsunami Warning System 242

Landslides and Ground Subsidence 242 Fire 243

Can Earthquakes Be Predicted? 243 Short-Range Predictions 243 Long-Range Forecasts 244

Probing Earth's Interior 245

BOX 10.4: Canadian Profile Lithoprobe: Probing the Depths of Canada **245**

The Nature of Seismic Waves 247 Seismic Waves and Earth's Structure 247

Discovering Earth's Major Boundaries 248

The Crust–Mantle Boundary (the Moho) 248 The Core–Mantle Boundary 248 Discovery of the Inner Core 249

CHAPTER 11

THE OCEAN FLOOR 252

Mapping the Ocean Floor 253

Continental Margins 254

Passive Continental Margins 255 Submarine Canyons and Turbidity Currents 256 Active Continental Margins 257

Features of the Deep-Ocean Basin 257

Deep-Ocean Trenches 257

BOX 11.1: Canadian Profile Grand Banks Earthquake and Turbidity Current **258**

BOX 11.2: Geology and Popular Media Many Days After Tomorrow . . . 259

Abyssal Plains 261 Seamounts 261

Coral Reefs and Atolls 262

Sea-Floor Sediments 263

Types of Sea-floor Sediments 263

Mid-Ocean Ridges 264 Sea-floor Spreading 265

BOX 11.3: Canadian ProfileDeep-Sea Hydrothermal Vents in Canada'sBackyard 266

Structure of the Oceanic Crust 267

CHAPTER 12

PLATE TECTONICS: THE FRAMEWORK FOR MODERN GEOLOGY 270

Continental Drift and Paleomagnetism 271 Paleomagnetism 271 Apparent Polar Wandering 271

A Scientific Revolution Begins 272 The Sea-floor Spreading Hypothesis 272 Geomagnetic Reversals 273

The Last Piece of the Puzzle 274

Plate Tectonics: The New Paradigm276Earth's Major Plates276

Divergent Plate Boundaries 276 Oceanic Ridges and Sea-floor Spreading 276

BOX 12.1: Understanding Earth The Breakup of a Supercontinent **277**

Continental Rifts 278

Convergent Plate Boundaries 280

Oceanic–Continental Convergence 281 Oceanic–Oceanic Convergence 282 Continental–Continental Convergence 282

Transform Fault Boundaries 283

BOX 12.2: Canadian Profile John Tuzo Wilson: Canada's Champion of Plate Tectonics **283**

Testing the Plate Tectonics Model 285

Plate Tectonics and Earthquakes285Evidence from Ocean Drilling285Hot Spots and Mantle Plumes286

Measuring Plate Motion 288

The Driving Mechanism288Mantle Drag289Ridge Sliding and Slab Pull289

CHAPTER 13

MOUNTAIN BUILDING AND CONTINENTAL FRAMEWORKS 291 Isostasy: Why Earth Isn't Smooth 292

- Mountains and Plate Tectonic Environments 293
- Mountains in Divergent Margin Settings 294
- Passive Margins: Precursors to Convergent Margins 295

Mountains in Convergent Margin Settings 295

Simple Subduction: Andean- and Aleutian-Type Mountain Building 295 Continental Collisions 298 Accreted Terranes 299

BOX 13.1: Canadian Profile Landscapes of the Canadian Rocky Mountains **300**



x Contents

Mountain Belts with Complex Histories 301 The Wilson Cycle 303 Convergence and the Obduction of Oceanic Crust 304 Isostatic Adjustment after Active Convergence 305

Broad Vertical Movements in Continents 305

Regions of Uplift 305 Regions of Subsidence 305

The Origin and Evolution of Continents307Early Evolution of Continents307Gradual Evolution of Continents307

CHAPTER 14

MASS WASTING: THE WORK OF GRAVITY 310

Mass Wasting and Landform Development 311

The Role of Mass Wasting 311 Slopes Change through Time 312

Controls and Triggers of Mass Wasting 312

The Role of Water312Oversteepened Slopes312Removal of Vegetation313

BOX 14.1:People and the EnvironmentTreacherousSlopes along the Sea-to-SkyHighway314

Earthquakes as Triggers 315 Liquefaction 316

Classification of Mass Wasting Processes 316

Type of Motion 316 Type of Material 317 Rate of Movement 317

Slump 319

Rock Slide 320

Debris Flow 321 Lahars 322



Earthflow 322

Slow Movements 323

Creep 323 Solifluction 323 Other Periglacial Features 323

BOX 14.2: Understanding Earth The Sensitive Permafrost Landscape **325**

CHAPTER 15

RUNNING WATER 329

Earth as a System: The Hydrologic Cycle 330 From Sheet Flow to Channel Flow 332

Basic Components of a Stream 332

Streamflow332Gradient and Channel Characteristics333Discharge and Changes Downstream334

Stream Erosion 334

Transport of Sediment by Streams 336

Dissolved Load 336 Suspended Load 336 Bed Load 336 Capacity and Competence 337

Deposition of Sediment by Streams 338

Channel Deposits 338 Floodplain Deposits 338

BOX 15.1: People and The Environment Red River Floods **339**

The Graded Stream Concept and Base Level 340

Stream Valleys 342

Narrow Valleys 342 Wide Valleys 344

Types of Stream Systems 344

Braided Streams 344 Meandering Streams 345 Anastomosed Streams 348

Alluvial Fans and Deltas 350 Alluvial Fans 350

Deltas 350

Drainage Patterns 352 Headward Erosion and Stream Piracy 353

Floods and Flood Control 354 Causes and Types of Floods 354

Flood Control 355

CHAPTER 16

GROUNDWATER 359 Importance of Underground Water 360 Distribution of Underground Water 360

The Water Table 361

Factors Influencing the Storage and Movement of Groundwater 363 Porosity 363

Permeability, Aquitards, and Aquifers 363

How Groundwater Moves 364

Springs 365

Hot Springs and Geysers 366

Wells 367

Artesian Wells 369

Environmental Problems 370

Mining Groundwater 370 Subsidence 371 Groundwater Contamination 371

BOX 16.1: Canadian Profile The Walkerton Tragedy: Geology Forms the Link **372**

The Geologic Work of Groundwater 375

Caverns 375

BOX 16.2: Geology and Popular Media Journey to the Centre of the Earth: When Jules Verne Met Geology **375**

Karst Topography 378

CHAPTER 17

GLACIER AND GLACIATION 382

Glaciers: A Part of Two Basic Cycles 383

BOX 17.1: Canadian Profile Glaciers and Canadian Diamonds **384**

Ice Sheets 385 Valley (Alpine) Glaciers 385 Other Types of Glaciers 386

Formation of Glacial Ice 387

Movement of a Glacier 388

Rates of Glacial Movement 388 Budget of a Glacier 389

Glacial Erosion 391

Landforms Created by Glacial

Erosion 392 Glaciated Valleys 393 Arêtes and Horns 395 Roches Moutonnées 396

Glacial Deposits 396

Landforms Made of Till 397

BOX 17.2: Canadian Profile Snowball Earth: Canadian Cryospheric Controversy **398**

Lateral and Medial Moraines 399 End and Ground Moraines 400 Drumlins 400

Landforms Made of Stratified Drift 402

Outwash Plains and Valley Trains 403 Ice-Contact Deposits 403

The Glacial Theory and the Ice Age 404

Other Effects of Ice-Age Glaciers 405

Causes of Ice Ages 406 Plate Tectonics 406 Variations in Earth's Orbit 407

CHAPTER 18

DESERTS AND WINDS 410

Distribution and Causes of Dry Lands 411

BOX 18.1: Understanding Earth What Is Meant by *Dry*? **412**

Subtropical Deserts and Steppes 412 Middle-Latitude Deserts 414 Polar Deserts 414

BOX 18.2:Canadian ProfileThe Okanagan Valley:A Canadian Desert415

Geologic Processes in Arid Climates 416

Weathering 416 The Role of Water 416

Transportation of Sediment by Wind 418 Bed Load 418 Suspended Load 419



Wind Erosion 419 Deflation, Blowouts, and Desert Pavement 419 Ventifacts and Yardangs 420

Wind Deposits 421

Sand Deposits 421 Types of Sand Dunes 422 Loess (Silt) Deposits 424

CHAPTER 19

SHORELINES 427

The Shoreline: A Dynamic Interface 428

Waves 428

Wave Characteristics 429 Circular Orbital Motion 429 Waves in the Surf Zone 430

Wave Erosion 430

Sand Movement on the Beach 430

Wave Refraction 431 Longshore Transport 433

Tides 433 Causes of Tides 433 Tidal Currents 434

Shoreline Features 435

Erosional Features 435 Depositional Features 436 Ancient Coastal Deposits 437 The Evolving Shore 439

Stabilizing the Shore 440

Hard Stabilization 440 Alternatives to Hard Stabilization 442

CHAPTER 20

MINERAL AND ENERGY RESOURCES 445 Renewable and Non-Renewable Resources 447

BOX 20.1: People and the Environment Resource Consumption and Sustainability: A Global Perspective **448**

Metallic Mineral Deposits and Geologic Processes 449

Magmatic Deposits 449 Hydrothermal Deposits 452 Hydrothermal Deposits Associated with Igneous Activity 453

BOX 20.2: People and the Environment Acid Mine Drainage (AMD) in Canada **454**

Sediment-Associated Hydrothermal Deposits 457 Sedimentary Deposits 459 Metamorphic Deposits 460 Weathering Deposits 462

Non-Metallic Mineral Resources 462

Aggregate and Stone 463 Industrial Minerals 463

Non-Renewable Energy Resources (Fossil Fuels) 467

Petroleum 467 Coal 469 Fossil Fuels in Canada 470 Environmental Effects of Fossil Fuel Use 471

BOX 20.3: Canadian Profile The Hard Oilers of Enniskillen Township and Canada's Petroleum Industry **473**

Unconventional Fossil Fuel Deposits 477

BOX 20.4: People and the Environment The Other Oil Crisis—The Deepwater Horizon Oil Disaster **479**

Nuclear Energy 481

Renewable Fuel Sources 483

Geothermal Energy 483 Organic-Based Sources 483 Hydroelectric Power 483 Solar Energy 484 Wind Energy 485 Tidal Power 485

Glossary 489 Index 505 Welcome to the fourth Canadian edition of *Earth:* An Introduction to Physical Geology. We are excited to be your personal guides on your journey into the fascinating world of geology. Some of you may have already glimpsed some of our tour stops—perhaps in a high school course, in a television documentary, on the news, or even first-hand. We hope the content of this textbook will strike a chord with you in terms of how it connects with these experiences, and that it will enhance your future encounters with geology, whether in pondering the source of graphite in your pencil, watching a volcanic eruption or earthquake on the news, or simply enjoying scenery on a vacation.

We became involved with this book for three reasons. First, we feel it is important for Canadian students to have a book that has direct relevance to them as citizens of Canada. Second, co-authoring a book provides us, as teachers, with an opportunity to reach students beyond the gates of our academic institution. And third, we love geology and feel privileged to share our enthusiasm for what we do as geologists.

As both authors and teachers, we are aware that while some students will have some background in geology, this will be a new experience for many of you. Thus, we have stood by our conviction to keep this an *introductory-level* textbook, and have done our best to keep the language simple and straightforward, to guide you through the concepts step by step, and to provide clear explanations of technical terms.

All of the changes we made to this book since the last edition were done with one focus—to improve its educational value for *you*, *the student*. We want you to feel that you got your money's worth in buying this book. While our editors, and many geology instructors

across Canada, offered valuable suggestions on revising this book, it was comments from students (that would be you!) that guided our overall approach. The main student suggestion was to shorten the book, making the text more "to the point" with more focus on fundamental concepts and less space taken up with details of non-essential issues. This fourth edition, shorter and more concise than its predecessors, is as much a product of your input as it is of our commitment to producing the best introductory geology text we can offer.

Another suggestion was to discuss geology in a way that is more relevant to students than what typically exists in textbooks, and preferably relating to popular culture. In response we offer special-interest boxes entitled Geology and Popular Media that focus on the portrayal of geology in Hollywood movies. We hope they will interest and entertain you without adding too much reading.

So here we go. Make sure to buckle up, as we will travel from the top of the atmosphere to Earth's core and from the highest mountains to the ocean floor. We will encounter processes operating from the subatomic level to those affecting our entire planet; and we will witness the development of Earth, from the time of its birth about 4.6 billion years ago to the present. We hope this trip will heighten your awareness about how we, as humans, fit into this complex system of rock, gases, water, life, and energy—how Earth provides resources we depend on, and how our use of these resources affects our planet. Above all, we hope you enjoy this journey of learning.

> Sincerely, your authors, Cam Tsujita and S. R. Hicock

PREFACE

Earth is a very small part of a vast universe. It is but one small planet orbiting a middle-aged, averagesized star (among billions of others), in one of an estimated 400 billion galaxies. But as the old saying goes, "good things come in small packages." In spite of being unremarkable in many ways, Earth stands out as being the only planet known to host complex life. Earth, the "Goldilocks planet" of our solar system, has just the right combination of conditions and ingredients necessary to support biologic activity: not too hot, not too cold; not too wet, not too dry; and so forth. The science of geology serves as the foundation for understanding how Earth formed, how it developed, how it works, and how we, as complex life forms, relate to the processes that have rendered Earth a unique, life-sustaining planet.

Media reports are constant reminders that our planet is highly dynamic, and since the publication of the third Canadian edition of *Earth* in 2012, the world has witnessed many examples of Earth's powerful forces. In 2013 alone, spectacular displays of volcanic activity were reported from Italy (Mt. Etna), Indonesia (Kelimutu), Kamchatka (Tolbachik), and Japan (Sakurajima).

Between 2012 and 2013, the world also witnessed the tragic devastation caused by natural disasters such as earthquakes in Iran (August 2012), Guatemala/ Mexico (December 2012), and Santa Cruz Islands in the South Pacific (February 2013); floods in India, Bangladesh, Nigeria, and Philippines (August 2012), and Australia (January 2013); and landslides in Colombia and Kenya (December 2012) and Philippines (March 2013). All of these events caught human populations off guard. In order to be better prepared for such events, we must gain an awareness of their underlying causes and their frequency of occurrence over long periods of time. Geology can aid in the understanding of where, why, and how natural disasters occur, and how we can lessen their impact on human populations through long-range planning.

Impacts of human activities on Earth's environment have also remained in the public eye since the last edition. Environmental issues and disasters related to our use of Earth's resources, such as global warming, climate change, and the frequency of extreme weather events, continue to intensify. Geology is important in this context because it yields clues to help us understand, prevent, and repair environmental problems. Just as an auto mechanic must have a good working knowledge of the interactions among the parts in a car in order to fix it, knowledge of our planet is critical to our well-being and is, indeed, vital to our survival. The primary function of this fourth Canadian edition is to serve as a meaningful, non-technical, up-to-date primer for college and university students taking their first course in geology. A main goal of *Earth* is to complement and reinforce the basic geologic principles and concepts learned in class.

DISTINGUISHING FEATURES Readability

The language of the book is straightforward and written so it can be understood by the layperson. Clear, readable discussions with a minimum of technical language are the rule. Frequent headings and subheadings help students follow discussions and identify the important ideas presented in each chapter. Large portions of the text were rewritten lineby-line or deleted in an effort to make the material more concise, more understandable, and more relevant to a Canadian audience.

Illustrations and Photographs

Geology is a highly visual science. Therefore, photographs and artwork are essential to an introductory book. *Earth* contains hundreds of photographs, of which many are new to this fourth edition. These have been carefully selected to aid understanding, add relevance and tangibility, and, where possible, infuse geologic concepts with a Canadian perspective. The illustrations in *Earth* are renowned for their quality. This edition features a selection of SmartFigures, which are described below, as well as some new or redesigned line art by Cam Tsujita that illustrate concepts more clearly and realistically than ever before.

Focus on Learning

When a chapter has been completed, three useful devices help students review: Chapter Summary, Review Questions, and a Glossary in MasteringGeology (www. masteringgeology.com) to clarify the spelling and meaning of common terms.

Special Interest Boxes

At appropriate places throughout the book, special interest boxes with icons appear relating to five themes: Earth as a System, People and the Environment, Canadian Profile, Understanding Earth, and Geology and Popular Media. These themes and boxes serve as threads that weave through the chapters and help tie them together while enhancing the main text material.

Maintaining a Focus on Basic Principles and Instructor Flexibility

The organization of chapters in this textbook is intended to be a compromise between the traditional approach of covering plate tectonics as a culmination of the understanding of geologic principles, and the more "systems-based" approach where plate tectonics is covered at the beginning of the text. This book's organization accommodates the study of minerals and rocks in the laboratory (which usually comes early in an introductory-level geology course), while exploring how each component fits into the basic idea of plate tectonics. By revisiting plate tectonics after covering the fundamentals (minerals, rocks, time, etc.), we believe that students will have a better appreciation of why plate tectonics is the central paradigm of modern geology.

The book begins with a rudimentary view of geology and a brief glimpse of plate tectonics as a general concept. We then turn to a discussion of Earth materials, from minerals to rocks. Next is the element of time—how time is classified, how Earth materials can be dated, and the sheer immensity of geologic time as revealed in the geologic record. From there, we examine how rocks are deformed and the dynamic nature of Earth's surface and interior as observed in earthquakes. We then examine the ocean floor and the mechanisms that move tectonic plates. Following that, we revisit plate tectonics in greater detail, when students are ready to appreciate how the "little pictures" fit into the "big picture."

Next the book turns its focus to Earth's surficial processes, including mass wasting, streams, groundwater, glaciation, wind, and waves and currents. Because these processes are gravity-driven (i.e., influenced by elevation and topography changes caused by plate tectonics), these topics are intentionally covered after plate tectonics.

Finally, we discuss mineral and energy resources from the viewpoints of resource use and value, and in the context of the environment. Because resource exploration is often viewed as the "bottom line" of geology, we felt it appropriate to cover that topic in the final chapter—from a uniquely Canadian perspective.

NEW TO THE FOURTH CANADIAN EDITION

Major changes to this edition are listed below.

New Concise Approach

• There is a greater focus on the fundamental principles of geology.

- The length of the book has been substantially reduced, enhancing readability and reducing paper use.
- Concise definitions and streamlined explanations have been increased to improve readability and comprehension.

New Examples and Explanations

- There are now more Canadian examples and better photographs to emphasize the relevance of concepts to Canadian students.
- Coverage of headlining events of geologic and environmental significance has been updated, including eruptions of Java's Mount Merapi and under Iceland's Eyjafjallajökull ice cap (Chapter 4), the devastating earthquake and tsunami in Japan (Chapter 10), new solar farms in Ontario, and the status of tidal turbines in the Bay of Fundy (Chapter 20)—all of which occurred since the third edition came out.

New and Improved Pedagogy

- SmartFigures—Art That Teaches: Inside every chapter are a number of SmartFigures. Just use your smartphone to scan the QR code next to such a figure, and the art comes alive! Prepared and narrated by Professor Callan Bentley, each three- to four-minute feature is a mini-lesson that examines and explains the concepts illustrated by the figure. It is truly art that teaches. For those without smartphones, SmartFigures are also available via www.masteringgeology.com and the eText.
- Also included are improved custom graphics by Cam Tsujita that help students visualize concepts described in the text.

Integration with Web-Based Activities and Animations

- MasteringGeology (www.masteringgeology. com) contains two sets of web-based activities and animations: GEODe: Earth; and Geoscience Animations to add a dynamic aspect to learning.
- **GEODe: Earth** is a dynamic program that reinforces key concepts with animations, tutorials, and interactive exercises.
- **Geoscience Animations** include over 60 animations to visualize key geologic processes.
- All GEODe: Earth activities and Geoscience Animations, organized by chapter, are listed on MasteringGeology.

THE TEACHING AND LEARNING PACKAGE

A comprehensive traditional and new supplements package accompanies the book and uses electronic media.

MasteringGeology

Each new copy of *Earth*, fourth Canadian edition, comes with a Student Access Code for MasteringGeology. MasteringGeology delivers engaging, dynamic learning opportunities—focused on course objectives and responsive to each student's progress—that are proven to help students absorb course material and understand difficult concepts.

- MasteringGeology provides a rich and flexible set of course materials to get instructors started quickly.
- MasteringGeology provides quick and easy access to information on student performance against learning outcomes. Instructors can quickly add their own learning outcomes to track student performance.
- The Mastering Geology gradebook and diagnostic tools capture the step-by-step work of every student, providing unique insight into class performance.
- Assignable items include the following:
 - SmartFigures bring key chapter illustrations to life! Found throughout the book, SmartFigures are sophisticated, annotated illustrations that are also narrated videos. The SmartFigure videos are accessible on mobile devices via scannable QuickResponse (QR) codes printed in the text and through the Study Area in MasteringGeology.
 - GigaPan® Activities take advantage of the GigaPan high-resolution panoramic picture technology developed by Carnegie Mellon University in conjunction with NASA. Photos and accompanying questions correlate with concepts in the student book.
 - Encounter Earth Activities provide interactive exploration of geology concepts using Google EarthTM. Students work through the activities in Google Earth and then test their knowledge by answering the assessment questions, which include hints and specific wronganswer feedback.
 - Animation Activities illuminate the most difficult-to-understand topics in geology. The animation activities include audio narration, a text

transcript, and assignable multiple-choice questions with specific wrong-answer feedback.

- **GeoTutor Activities** consist of sophisticated, high-impact visuals that ask students to demonstrate their knowledge by synthesizing and analyzing core concepts using higher-order thinking skills.
- Concept Check questions, Give It Some Thought questions, Reading questions, and Test Bank questions are also included.
- MasteringGeology includes a Study Area for students to access all of their study resources. The Study Area includes geoscience animations, GEODe activities, *In the News* RSS feeds, Self-Study Quizzes, Weblinks, Glossary, Flashcards, and an optional Pearson eText.

See www.masteringgeology.com

CourseSmart

CourseSmart goes beyond traditional expectations providing instant, online access to the textbooks and course materials you need at a lower cost for students. And even as students save money, you can save time and hassle with a digital eTextbook that allows you to search for the most relevant content at the very moment you need it. Whether it's evaluating textbooks or creating lecture notes to help students with difficult concepts, CourseSmart can make life a little easier. See how when you visit www. coursesmart.com/instructors.

Pearson eText

Pearson eText gives students access to the text whenever and wherever they have access to the internet. eText pages look exactly like the printed text, offering powerful new functionality for students and instructors. Users can create notes, highlight text in different colours, create bookmarks, zoom, click hyperlinked words and phrases to view definitions, and view in single-page or two-page view. Pearson eText allows for quick navigation to key parts of the eText using a table of contents and provides full-text search. The eText may also offer links to associated media files, enabling users to access videos, animations, or other activities as they read the text.

INSTRUCTOR'S RESOURCES

The authors and publisher have been pleased to work with a number of talented people who produced an excellent supplements package, which can be downloaded from the Pearson Canada catalogue.

Instructor's Manual

The Instructor's Manual has been designed to help seasoned and new professors alike, offering in each chapter an introduction to the chapter, outline, learning objectives/focus on concepts, and answers to review questions and suggested quiz questions.

Test Bank

This extensive test bank contains multiple-choice, true/false, and short-answer questions, a selection of which you can link to actual figures and photos from the text. This is available as a Word File and as a TestGen [®] computerized test generator.

PowerPoint® Presentations

These presentations average 40 slides per chapter, consisting of customizable lecture outlines with supporting art.

Image Library

All the photos, art, and tables from the text, in order, loaded into PowerPoint slides.

The Geoscience Animation Library

This library includes animations that illuminate many difficult-to-visualize topics of physical geology. Created through a unique collaboration among five of Pearson's leading geoscience authors, these animations represent a significant leap forward in lecture presentation aids.

Pearson Custom Library

For enrolments of at least 25 students, you can create your own textbook by choosing the chapters that best suit your own course needs. To begin building your custom text, visit www.pearsoncustomlibrary. com. You may also work with a dedicated Pearson Custom editor to create your ideal text—publishing your own original content or mixing and matching Pearson content. Contact your local Pearson Representative to get started.

peerScholar

Firmly grounded in published research, peerScholar is a powerful online pedagogical tool that helps develop your students' critical and creative thinking skills. peerScholar facilitates this through the process of creation, evaluation, and reflection. Working in stages, students begin by submitting a written assignment. peerScholar then circulates their work for others to review, a process that can be anonymous or not depending on your preference. Students receive peer feedback and evaluations immediately, reinforcing their learning and driving the development of higher-order thinking skills. Students can then re-submit revised work, again depending on your preference. Contact your Pearson Representative to learn more about peerScholar and the research behind it.

Technology Specialists

Pearson's technology specialists work with faculty and campus course designers to ensure that Pearson technology products, assessment tools, and online course materials are tailored to meet your specific needs. This highly qualified team is dedicated to helping schools take full advantage of a wide range of educational resources, by assisting in the integration of a variety of instructional materials and media formats. Your local Pearson Education sales representative can provide you with more details on this service program.

ACKNOWLEDGEMENTS

Revising a textbook is a mammoth task that demands input from many talented individuals. It is largely due to the consistently superior work of the publishing team at Pearson Canada that we enthusiastically accepted the challenge of co-authoring this fourth Canadian edition of *Earth*.

We are indebted to many friends and colleagues who generously contributed material and reviews to various editions of *Earth*; such enthusiasm for this project is a testament to the dedication of Canadian geologists in promoting geo-literacy in this country. Above all, we tip our hats to our students, whose insightful questions and comments ultimately improve how we teach.

Many colleagues unselfishly contributed material for the Canadian Profile boxes. Thanks are extended especially to Claudia Cochrane, Matt Devereux, David Eaton, John Gosse, Brian Hart, Richard Léveillé, Mike Powell, Rob Schincariol, Gordon Southam, Vic Tyrer, Gordon Winder, and Grant Young.

Several colleagues and other individuals were also very generous in providing photographs for all Canadian editions of *Earth*, and in many cases allowed us to use multiple images from their personal collections. We thank all who donated their images for the greater cause of enhancing the tangibility of concepts discussed in this book. Special thanks go to those colleagues who prepared in-depth reviews for the fourth Canadian edition of *Earth*. Their critical comments and thoughtful input helped guide our work and strengthen the text, even in the smallest details. We wish to thank the following reviewers:

Mary-Helen Armour, York University Mary Lou Bevier, University of British Columbia Luke Copland, University of Ottawa Jaroslav Dostal, Saint Mary's University Cliff Shaw, University of New Brunswick Attila M. Zsaki, Concordia University

We would also like to acknowledge the publishing team at Pearson Canada. Many thanks are due to Cathleen Sullivan, acquisitions editor, who brought us on board; and Paul Donnelly, our developmental editor, who patiently coordinated this project. We also thank the production team, led by Kimberly Blakey; copyeditor Sally Glover; proofreader Colleen Ste. Marie; permissions researcher Marnie Lamb; and technical reviewer Philip Giles for their outstanding work. The professionalism and high standard for detail that you have all demonstrated during the production of this book is deeply appreciated. Thanks also to editorial director Gary Bennett for having steadfast faith in us and the value of this product.

Cam extends his heartfelt thanks to his father (James Tsujita), mother (Lilly Tsujita), sister (Kimberly Kaszas), and brother-in-law (George Kaszas), who have provided unwavering support throughout his academic career. Special thanks to Cam's wife, Erica Tsujita, and his three sons, Jeremy, Casey, and Warner, who persevered through his long work hours during the preparation of this textbook. Cam also thanks all the students who inspired the work in this textbook.

Steve gives heartfelt thanks to his wife, Fran, for her patience and understanding when work on the textbook meant spending evenings and weekends away from home.

Cam Tsujita and Steve Hicock