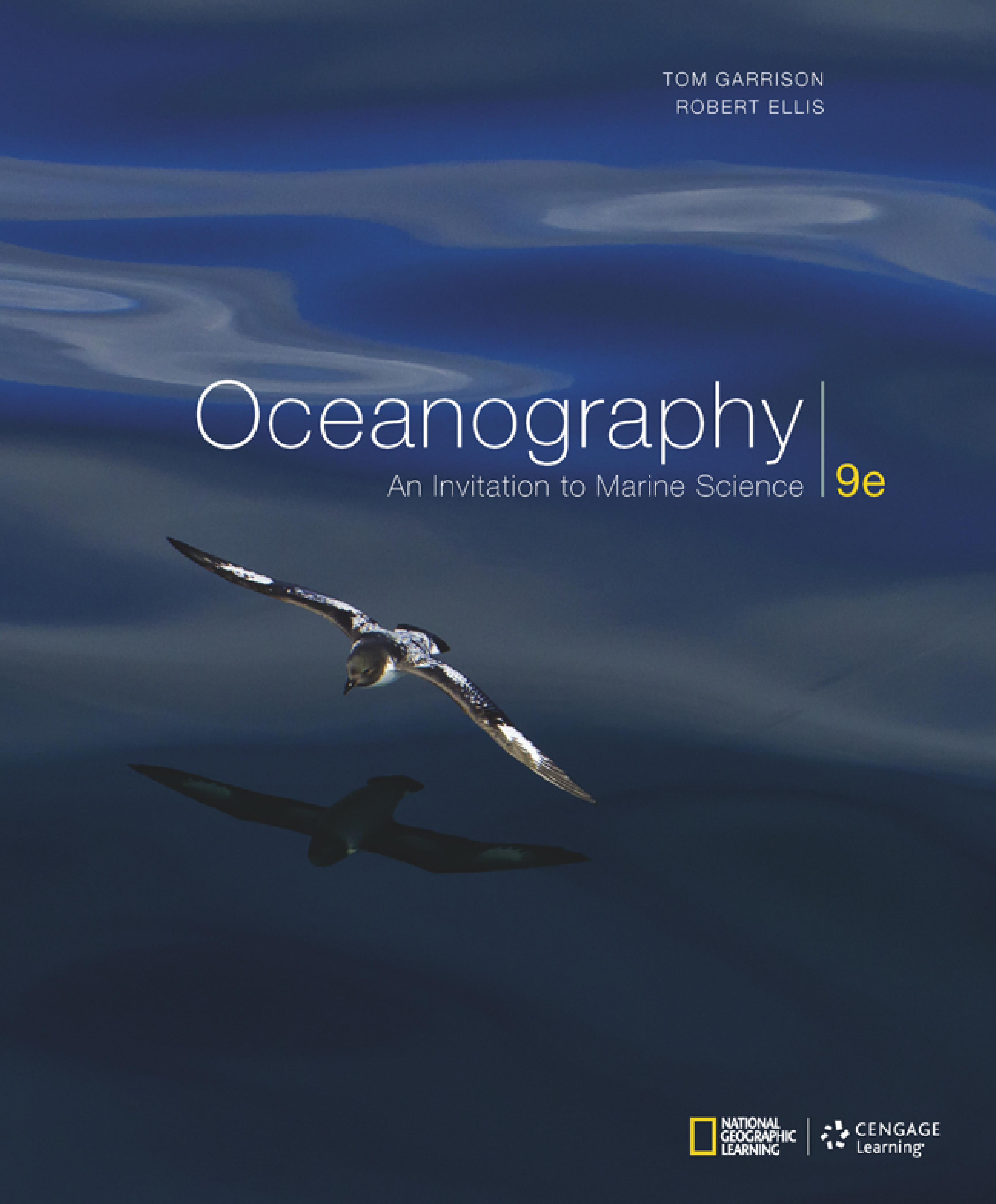


TOM GARRISON
ROBERT ELLIS

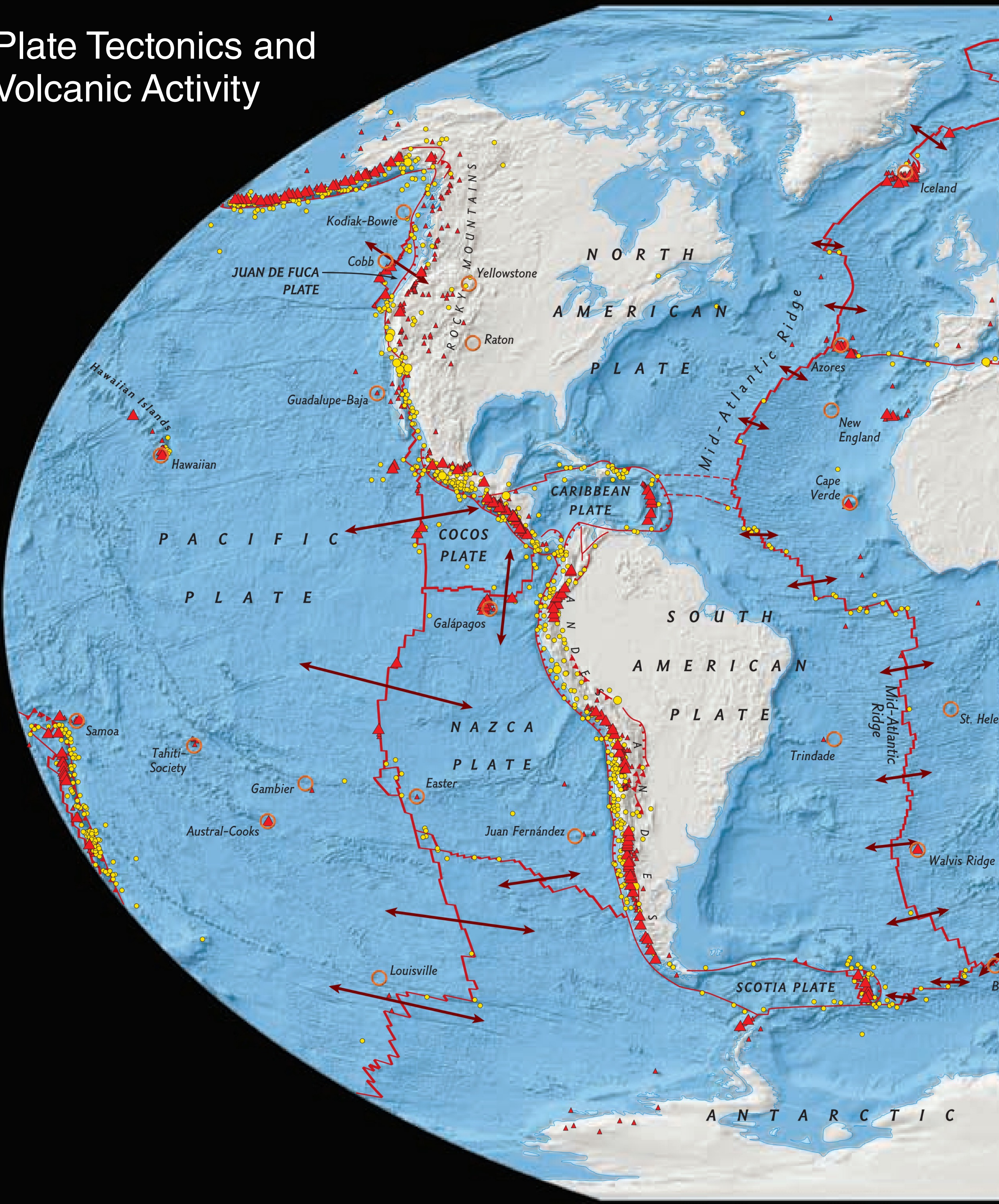
Oceanography

An Invitation to Marine Science

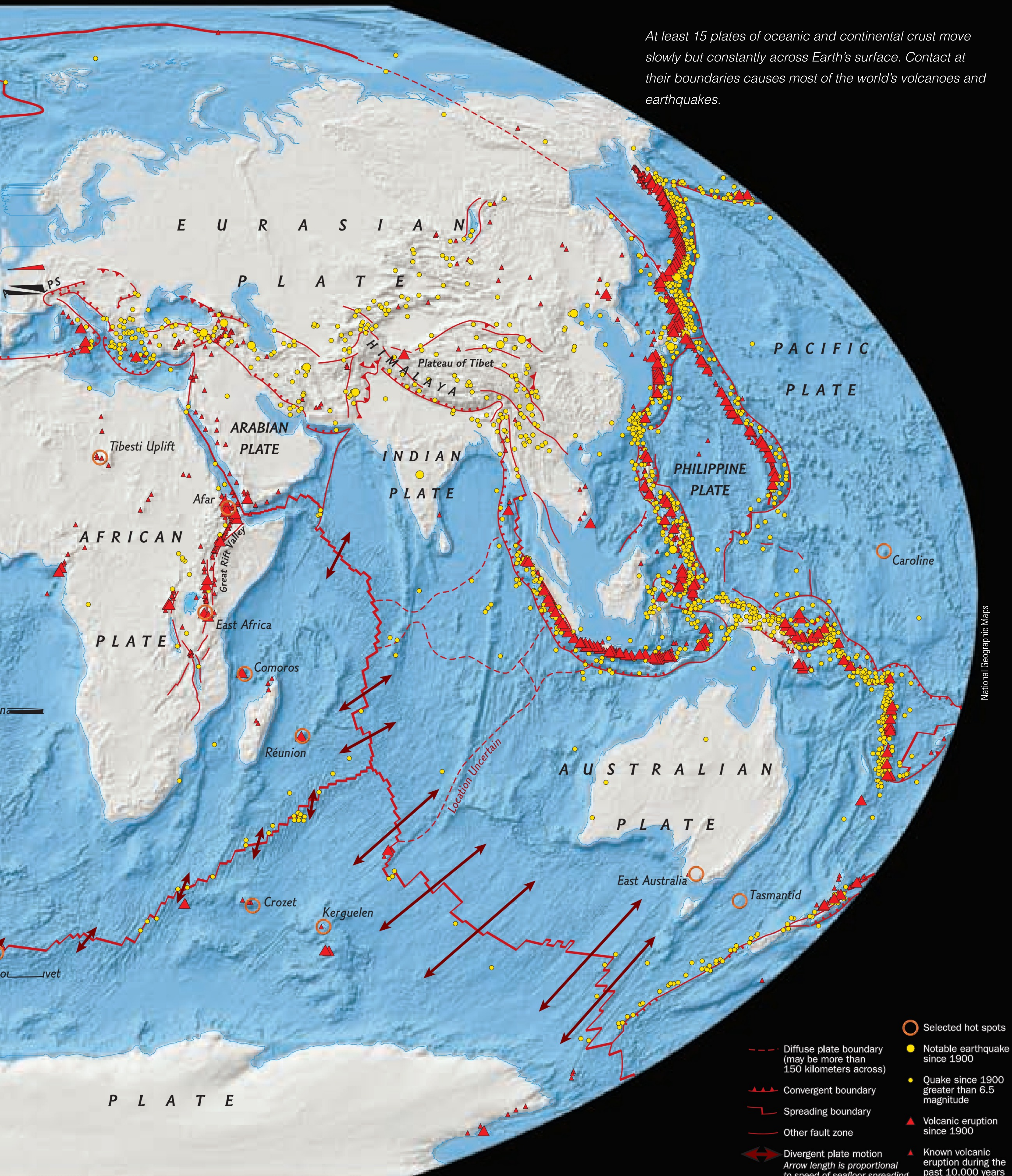
9e

NATIONAL GEOGRAPHIC LEARNING | CENGAGE Learning

Plate Tectonics and Volcanic Activity



At least 15 plates of oceanic and continental crust move slowly but constantly across Earth's surface. Contact at their boundaries causes most of the world's volcanoes and earthquakes.



Oceanography

An Invitation to Marine Science

9e

RALPH LEE HOPKINS/National Geographic Creative

Oceanography

An Invitation to Marine Science 9e

Tom Garrison
Orange Coast College
University of Southern California

Robert Ellis
Orange Coast College

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***Oceanography: An Invitation to Marine Science*, Ninth Edition**
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To our families and our students,
our hope for the future.

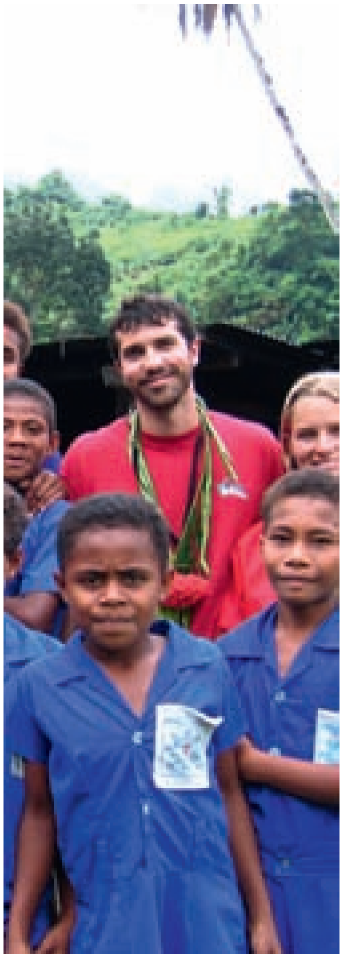
About the Authors

Hank Schellengerhaut, Orange Coast College PR department

Tom Garrison (Ph.D., University of Southern California) is emeritus professor of Marine Science at Orange Coast College (OCC) in Costa Mesa, California, one of the largest undergraduate marine science departments in the United States. Dr. Garrison also holds an adjunct professorship at the University of Southern California. He has been named the country's Outstanding Marine Educator by the National Marine Technology Society, is a founding member of COSEE, writes a regular column for the journal *Oceanography*, and has written for *National Geographic* magazine. He was a winner of the prestigious Salgo-Noren Foundation Award for Excellence in College Teaching. Dr. Garrison was an Emmy Award team participant as writer and science advisor for the PBS syndicated *Oceanus* television series and writer and science advisor for *The Endless Voyage*, a set of television programs in oceanography completed in 2003. His widely used textbooks in oceanography and marine science are the college market's best sellers. In 2009, the faculty of OCC selected Dr. Garrison as the institution's first Distinguished Professor, and in 2010, he was honored by the Association of Community College Trustees as the outstanding community college professor in western North America.

His interest in the ocean dates from his earliest memories. As he grew up with a U.S. Navy admiral as a dad, the subject was hard to avoid! He had the good fortune to meet great teachers who supported and encouraged this interest. Years as a midshipman and commissioned naval officer continued the marine emphasis; graduate school and 42+ years of teaching have allowed him to pass his oceanic enthusiasm to more than 65,000 students. Although he retired from full-time professoring in 2011, he continues to bother OCC staff and students on a regular basis.

Dr. Garrison travels extensively and most recently served as a guest lecturer at the University of Hong Kong, the University of Tasmania (Australia), and the National University of Singapore. He has been married to an astonishingly patient lady for more than 47 years, has a daughter who teaches in a local public school, a diligent son-in-law, two astonishingly cute granddaughters and a fresh new grandson, and a son who, along with his fashionista wife, works in international trade. He and his family live in and around Newport Beach, California, USA.



Robert Ellis

Robert Ellis (M.E.S.M., University of California, Santa Barbara) has been teaching marine, earth, and environmental science courses in both the classroom and in the field since 2000. He currently serves as Assistant Professor in the Marine Science Department at Orange Coast College in southern California. When not on campus, Robert often helps to develop and teach international field courses in marine science and management in various parts of the Caribbean, Central America, and the South Pacific. His graduate work focused on Marine Resource Management at UC Santa Barbara, and he has participated in and managed research projects and educational programs in many parts of the world. He hopes to have the good fortune to continue to travel and explore the world with his wife, Katie, and son, Kalen.

Top photo: Brian J. Skerry/National Geographic Creative

Brief Contents

Philip Hart/Stocktrek Images/Getty Images

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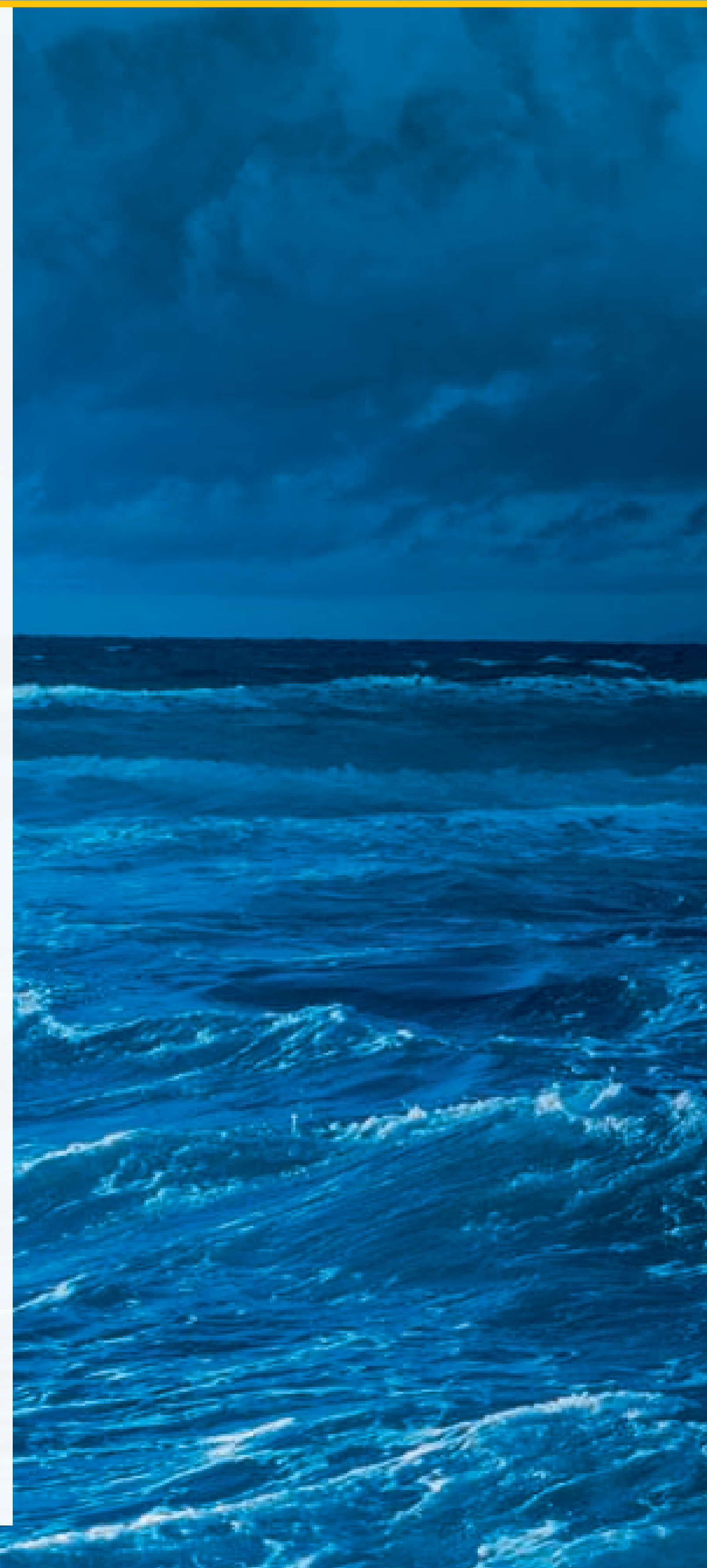
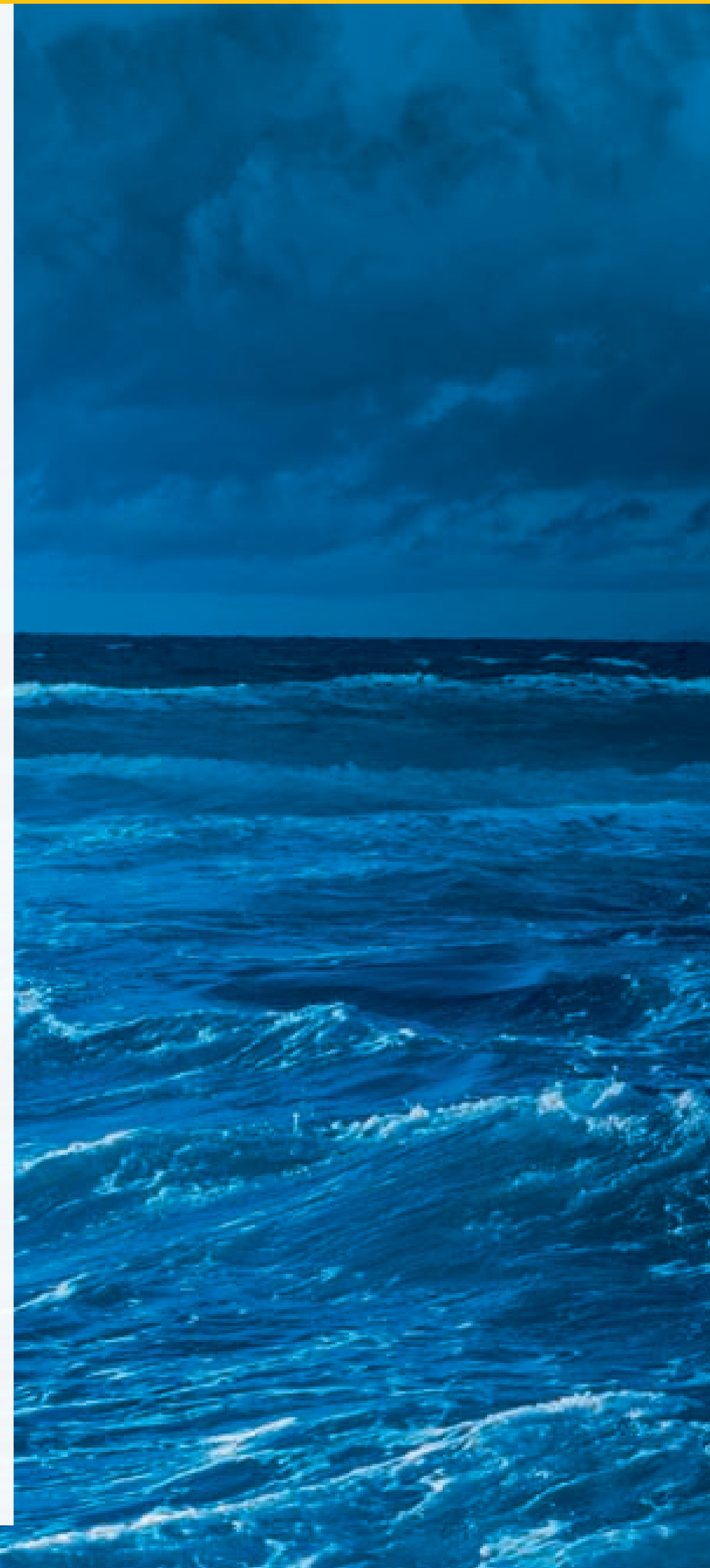
4 Ocean Basins 102





Preface

This book was written to provide an *interesting*, clear, current, and reasonably comprehensive overview of the ocean sciences. It was designed for students who are curious about Earth's largest feature, but who may have little formal background in science.

Students bring a natural enthusiasm to their study of this subject, an enthusiasm that will be greatly enhanced by our partnership with the National Geographic Society. Access to more than 125 years of archival resources makes this National Geographic Learning text uniquely appealing. Even the most indifferent reader will perk up when presented with stories of encounters with huge waves, photos of giant squid, tales of exploration under the best and worst of circumstances, evidence that vast chunks of Earth's surface move slowly, news of Earth's past battering by asteroids, micrographs of glistening diatoms, and data showing the growing economic importance of seafood and marine materials. If pure spectacle is required to generate an initial interest in the study of science, oceanography wins hands down!

In the end, however, it is subtlety that triumphs. Studying the ocean re-instills in us the sense of wonder we all felt as children when we first encountered the natural world. There is much to tell. The story of the ocean is a story of change and chance—its history is written in the rocks, the water, and the genes of the millions of organisms that have evolved here.

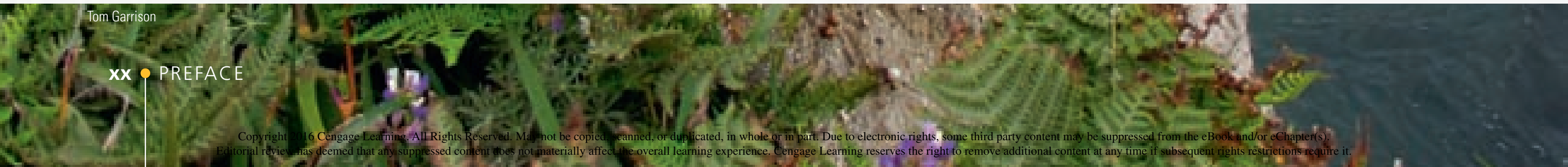
The Ninth Edition

Our aim in writing this book was to produce a text that would enhance students' natural enthusiasm for the ocean. Our students have been involved in this book from the very beginning—indeed, it was their request for a readable, engaging, and thorough text that initiated the project a long time ago. Through the many years we have been writing textbooks, our enthusiasm for oceanic knowledge has increased (if that is possible), forcing our patient reviewers and editors to weed out an excessive number of exclamation points. But enthusiasm does shine through. One student reading the final manuscript of an earlier edition commented, "At last, a textbook that does not read like stereo instructions." Good!

This new edition builds on its predecessors. National Geographic resources have been instrumental in the book's focus on the *processes* of science and exploration. Decades of original art, charts and maps, explorers' diaries, data compilations, artifact collections, and historic photographs have been winnowed and included when appropriate. The experience has been exhilarating. Indeed, the National Geographic staff in Washington, D.C., has been *very* patient in tolerating authors whose every other word seemed to be "Wow!"

As before, a great many students have participated alongside professional marine scientists in the writing and reviewing process. In response to their recommendations, as well as those of instructors who have adopted the book and the many specialists and reviewers who contributed suggestions for strengthening the earlier editions, we have:

- **Modified every chapter to reflect current thought and recent research**. New discoveries concerning the establishment of Earth's age, the evolution of its atmosphere, the details of subduction, the sources of ocean water, the maintenance and measurement of salinity, and thermohaline circulation have been incorporated in the text. Recent developments in remote sensing are discussed. Material on the origin, evolution, and extent of life have been updated, as have recent developments in our understanding of oceanic food webs. Recent events are covered: IPCC data on global climate change, the 2010 Gulf of Mexico oil spill, the 2011 earthquake and tsunami in northern Japan, invasive species, coastal development in Dubai, and the ongoing collapse of fisheries.
- **Modified the illustration program** to incorporate National Geographic Society assets. The maps, charts, paintings, and photographs drawn from more than 125 years of Society archives have greatly enhanced the visual program for increased clarity and accuracy.
- **Emphasized the process of science throughout.** The first chapter's discussion of the nature of science has been expanded, and underlying assumptions and limitations are discussed throughout the book. Additional "How Do We Know?" boxes expand on this theme by describing how oceanographers know what they know about the ocean.
- **Added "Insights from an Explorer."** These text boxes highlight the experiences of National Geographic Explorers, men and women whose research has been supported by the National Geographic Society. They are among the top scientists in their respective fields, and their discoveries have significantly expanded our understanding of the ocean sciences.
- **Added new features to encourage active learning and develop critical thinking skills.** Selected figures are accompanied by "Thinking Beyond the Figure." These queries at the ends of the captions guide the readers to investigations of topics related to what they are learning in the chapter. Global Geo-Watch activities have been added to the end-of-chapter material. Each chapter ends with two sets of review questions. The first, "Thinking Critically," invites students to recall specific information covered in the chapter; the second, "Thinking Analytically," challenges students to apply what they have learned to novel situations.
- **Added relevant quotes** in highlighted windows from sources within each chapter and from famous individuals. The popu-


Tom Garrison

lar "Questions from Students" feature has been retained and expanded—these brief discussions address topics of immediate or controversial interest immediately after a chapter.

- **Developed Oceanography MindTap.** MindTap is well beyond an eBook, a homework solution or digital supplement, a resource center Web site, a course delivery platform, or a Learning Management System. MindTap is a new personal learning experience that combines all the digital assets—readings, multimedia, activities, and assessments—into a singular learning path to improve student outcomes.

Tom Garrison

Running on the beach, watching waves. If you're 2, could anything be more fun?

Ocean Literacy and the Plan of the Book

Ocean literacy is the awareness and understanding of fundamental concepts about the history, functioning, contents, and utilization of the ocean. An ocean-literate person recognizes the influence of the ocean on his or her daily life, can communicate about the ocean in a meaningful way, and is able to make informed and responsible decisions regarding the ocean and its resources. **This book has been designed with ocean literacy guidelines firmly in mind**.

The book's plan is straightforward: Because all matter on Earth except hydrogen and some helium was generated in stars, our story of the ocean starts with stars. Have oceans evolved elsewhere? The history of marine science follows (with additional historical information sprinkled through later chapters). The theories of Earth structure and plate tectonics are presented next, as a base on which to build the explanation of bottom features that follows. A survey of ocean physics and chemistry prepares us for discussions of atmospheric circulation, classical physical oceanography, and coastal processes. Our look at marine biology begins with an overview of the problems and benefits of living in seawater, continues with a discussion of the production and consumption of food, and ends with taxonomic and ecological surveys of marine organisms. The last chapters treat marine resources and environmental concerns.

This icon appears when our discussion turns toward the topic of global climate change. Oceanography is central to an understanding of this interesting and controversial set of ideas, so those areas have been expanded, emphasized, and clearly marked in this edition.

Tom Garrison

A discerning shopper in a Hong Kong wet market selects the freshest seafood for her family's dinner.

As always in our books, *connections between disciplines* are emphasized throughout. Marine science draws on several fields of study, integrating the work of specialists into a unified whole. For example, a geologist studying the composition of marine sediments on the deep seabed must be aware of the biology and life histories of the organisms in the water above, the chemistry that affects the shells and skeletons of the creatures as they fall to the ocean floor, the physics of particle settling and water density and ocean currents, and the age and underlying geology of the study area. This book is organized to make those connections from the first.

Organization and Pedagogy

A broad view of marine science is presented in 18 chapters, each freestanding (or nearly so) to allow instructors to assign chapters in any order they find appropriate. Each chapter begins with a list of the **five or six most important concepts** to be covered. An engaging chapter opener photo and caption whets the appetite for the material to come.

The chapters are written in an **engaging style**. Terms are defined and principles developed in a straightforward manner. Some of the more complex ideas are initially outlined in broad brushstrokes, and then the same concepts are discussed again in greater depth after the reader has a clear view of the overall situation (a "spiral approach"). When appropriate to their meanings, the derivations of words are shown. **Measurements** are given in both metric (S.I.) and U.S. systems. At the request of a great many students, the units are written out (that is, we write *kilometer* rather than *km*) to avoid ambiguity and for ease of reading.

The photos, charts, graphs, and paintings in the **extensive illustration program** have been chosen for their utility, clarity, and beauty. **Heads and subheads** are usually written as complete sentences for clarity, with the main heads sequentially numbered. A set of **Concept Checks** concludes each chapter's major sections. The answers are provided in the book's dedicated Web site.

Also concluding each chapter is a **Questions from Students** section. These questions are ones that students have asked us over the years. This material is an important extension of the chapters and occasionally contains key words and illustrations. Each chapter ends with an array of study materials for students, beginning with **Chapter in Perspective**, a narrative review of the chapter just concluded. Important **terms and concepts to remember** are listed next; these are also defined in an extensive **glossary** in the back of the book. **Study Questions** are also included in each chapter.

Appendixes explain measurements and conversions, geological time, absolute and relative dating, latitude and longitude, chart projections, taxonomy, and the Law of the Sea. For students interested in joining us in our life's work, the second to last appendix discusses **jobs in marine science**.

The book has been thoroughly **student tested**. You need not feel intimidated by the concepts—this material has been mastered by students just like you. Read slowly and go step by step through any parts that give you trouble. Your predecessors have found the ideas presented here to be useful, inspiring, and applicable to their lives. Best of all, they have found the subject to be *interesting*!

Suggestions for Using This Book

1. **Begin with a preview.** Scout the territory ahead—note the photo and caption that begin each chapter; flip through the assigned pages, reading only the headings and subheadings; look at the figures and read any captions that catch your attention.
2. **Keep a pen and paper handy.** Jot down a few questions—any questions—that this quick glance stimulates. *Why* is the deep ocean cold if the inside of Earth is so hot? *What* makes storm conditions like those seen in the eastern United States in 2014? *Where* did sea salt come from? *Will* climate change actually be a problem? *Does* anybody still hunt whales? *How* do we know how old Earth is? Writing questions will help you focus when you start studying.
3. **Now read in small but concentrated doses.** Each chapter is written in a sequence and tells a story. The logical progression of ideas is going somewhere. Find and follow the organization of the chapter. Stop to read the "Brief Review" sections. Flip back and forth to review and preview.
4. **Strive to be actively engaged!** Write marginal notes, underline occasional passages (underlining whole sections is seldom useful), write more questions, draw on the diagrams, check off subjects as you master them, make flashcards while you read (if you find them helpful), *use your book*!
5. **Monitor your understanding.** If you start at the beginning of the chapter, you will have little trouble understanding the concepts as they unfold. But if you find yourself at the bottom of the page having only scanned (rather than understood) the material, stop there and start that part again. Look ahead to see where we're going. Remember, students just like you have been here before, and we have listened to their comments to make the material as clear as we can. This book was written for you.
6. **Enjoy the journey.** Your instructor and teaching assistants would be glad to share their understanding and appreciation of marine science with you—you have only to ask. Students, instructors, and authors all work together

toward a common goal: an appreciation of the beauty and interrelationships a growing understanding of the ocean can provide.


Tom Garrison

Identification of intertidal organisms is a pleasant summer morning challenge.

Instructor Resources

Instructor Companion Site

Everything you need for your course in one place! This collection of book-specific lecture and class tools is available online via www.cengage.com/login. Access and download PowerPoint presentations, images, instructor's manual, videos, and more.

Cognero Test Bank

Cengage Learning Testing Powered by Cognero is a flexible, online system that allows you to:

- author, edit, and manage test-bank content from multiple Cengage Learning solutions
- create multiple test versions in an instant
- deliver tests from your Learning Management System, your classroom, or wherever you want

Global Geoscience Watch

Updated several times a day, the Global Geoscience Watch is an ideal one-stop site for classroom discussion and research projects for all things geoscience! Broken into the four key course areas (Geography, Geology, Meteorology, and Oceanography), this site makes it easy for you to get to the most relevant content available for your course. You and your students will have access to the latest information from trusted academic sources, news outlets, and magazines. You will also receive access to statistics, primary sources, case studies, podcasts, and much more!


Robert Ellis

A group of students learns navigational techniques before setting sail.

Student Resources

Oceanography MindTap

MindTap is well beyond an eBook, a homework solution or digital supplement, a resource center Web site, a course delivery platform, or a Learning Management System. MindTap is a new personal learning experience that combines all the digital assets—readings, multimedia, activities, and assessments—into a singular learning path to improve learning outcomes.

Acknowledgments

Many years ago, Jack Carey, the grand master of college textbook publishing, willed the first edition of this book into being. His suggestions have been combined with those of more than 1,400 undergraduate students and 190 reviewers to contribute to our continuously growing understanding of marine science. Donald Lovejoy, Stanley Ulanski, Richard Yuretich, Ronald Johnson, John Mylroie, and Steve Lund at the senior author's alma mater, the University of Southern California, deserve special recognition for many years of patient direction. For this edition, we have especially depended on the expert advice of Allen J. Costa, Tidewater Community College–Norfolk Campus; Brent Lewis, Coastal Carolina University; Carrie E. Schweitzer, Kent State University at Stark; Charles Greene, Cornell University; Len Pietrafesa, North Carolina State University & Coastal Carolina University; Ryan P. Mulligan, East Carolina University; Stephanie Schwabe, University of Kentucky; Heather Miller, Grand Valley State University; Randall J. Adsit, East Los Angeles College; Calvin Prothro, Onondaga Community College; Michelle Hardee, Asnuntuck Community College; Mike Valentine, University of Puget Sound; David Gillikin, Union College; Joe Staton, University of South Carolina–Beaufort; Michele Hoffman, Columbia College; Joseph Gorga, Diablo Valley College–San Ramon.

Our long-suffering departmental colleagues Dennis Kelly, Karen Baker, Mary Blasius, Erik Bender, Robert Profeta, and Steven Hatosy again should be awarded medals for putting up with the two of us, answering hundreds of our questions, and being so forbearing through the book's lengthy gestation period. Thanks also to our dean, Robert Mendoza, and our college president, Dennis Harkins, for supporting this project and encouraging our faculty to teach, conduct research, and be involved in community service. Our past and present department teaching assistants deserve praise as well, especially Timothy Heuer, Peter Hernandez, Kevin-Dan Williams, Spencer Wonder, Lili Clark, Belen Cairo, Briana Trevino, Bristol Coon, David Krueger, and Velvet Park.

Yet another round of gold medals should go to our families for being patient (well, *relatively* patient) during those years of days and nights when we were holed up in our respective dark reference-littered caves, throwing chicken bones out the door and listening to *really* loud Telemann and Bach recordings, again working late on The Book. Thank you Marsha, Jeanne, Greg, Grace, Sarah, John, Dinara, Alem, Katie, and Kalen for your love and understanding. The many friends and colleagues that we have bounced ideas off deserve special recognition, including Jenell Schwab, Mary Arbogast, Joana Tavares-Reager, Chris Krajacic, Sarah Sikich, and Andy Balendy.

The people who provided pictures and drawings have worked miracles to obtain the remarkable images in these pages. To mention just a few: Gerald Können allowed us to use his extraordinary image of a broken rainbow to illustrate seawater's index of refraction; Gerald Kuhn sent classics taken by his late SIO colleague Francis Shepard; Vincent Courtillot of the University of Paris contributed the remarkable photo of the Aden Rift; Catherine Devine at Cornell provided time-lapse graphics of tsunami propagation; Robert Headland of the Scott Polar Research Institute in Cambridge searched out prints of polar subjects; Charles Hollister at Woods Hole kindly provided seafloor photos from his important books; Andreas Rechnitzer and Don Walsh recalled their exciting days with *Trieste;* and Bruce Hall, Pat Mason, Ron Romanoski, Ted Delaca, William Cochlan, Christopher Ralling, Mark McMahon, John Shelton, Alistair Black, Howard Spero, Eric Bender, Ken-ichi Inoue, and Norman Cole contributed beautiful slides. Seran Gibbard provided the highest-resolution images yet made of the surface of Titan, and Michael Malin forwarded truly beautiful images of erosion on Mars. Herbert Kawainui Kane again allowed us to reprint his magnificent paintings of Hawai'ian subjects. Deborah Day and Cindy Clark at Scripps Institution, Jutta Voss-Diestelkamp at the Alfred Wegener Institut in Bremerhaven, and David Taylor at the Centre for Maritime Research in Greenwich dug through their archives one more time. Don Dixon, William Hartmann, Ron Miller, and William Kaufmann provided paintings, Dan Burton sent photos, and Andrew Goodwillie printed customized charts. Bryndís Brandsdóttir of the Science Institute, University of Iceland, patiently showed me the jaw-slackening Thingvillir rift. Wim van Egmond contributed striking photomicrographs of diatoms, forams, and copepods. Kim Fulton-Bennett of MBARI found extraordinarily beautiful photos of delicate midwater animals. Peter Ramsay at Marine Geosolutions, Ltd., of South Africa, sent state-of-the-art side-scan sonar images. Michael Boss kindly contributed his images of Admiral Zheng He's astonishing *beochuan.* Bill Haxby at Lamont provided truly beautiful seabed scans. Karen Riedel helped with DSDP core images. James Ingle offered a desk and breathing room at Stanford whenever

it was needed. NOAA, JOI, NASA, USGS, the Smithsonian Institution, the Royal Geographical Society, the U.S. Navy, and the U.S. Coast Guard came through time and again, as did private organizations like Alcoa Aluminum, Cunard, Shell Oil, The Maersk Line, Grumman Aviation, Breitling-SA, CNN, Associated Press, MobileEdge, and the *Los Angeles Times.* The Woods Hole team was also generous—especially Robin Hurst, Jack Cook, Larry Madin, and Ruth Curry. Thanks also to WHOI researchers Philip Richardson, William Schmitz, Susumu Honjo, Doug Webb, James Broda, Albert Bradley, John Waterbury, and Kathy Patterson, who all provided photographs, diagrams, and advice. Individuals with special expertise have also been willing to share: Hank Brandli processed satellite digital images of storms, Peter Sloss at the National Geophysical Data Center helped me sort through computer-generated seabed images, Steven Grand of the University of Texas provided a descending deep-slab image, Hans-Peter Bunge of Princeton patiently explained mantle-core dynamics, Michael Gentry again mined the archives of the Johnson Space Center for Earth images, Jurrie van der Woulde at JPL and Gene Feldman at NASA helped with images of oceans here and elsewhere, John Maxtone-Graham of New York's Seaport Museum found me a rogue wave picture, Ed Ricketts, Jr., contributed a portrait of his father, and professor Lynton Land of the University of Texas sent a rare photo of a turbidity current. Michael Latz at Scripps Institution taught me about bioluminescence. Thomas Maher, retired vice-provost and friend, led the senior author and his son on a personal inspection of the Gulf Stream and other fluid wonders. Dr. Wyss Yim of Hong Kong University offered suggestions and references (as well as unending hospitality and dim sum), and Dr. Shouye Yang of Tongji University in Shanghai graciously explained his research and shared plans for China's expansion into the field of oceanography. Tommi Lahtonen sent images of a Norwegian maelstrom. Kim Fulton-Bennett of MBARI shared some astonishing photos of midwater organisms. Neil Holbrook at Australia's University of Tasmania taught us about Sydney's Hawkesbury sandstone and bagpipes simultaneously. Dave Sandwell at Scripps shared his astonishing satellite-generated imagery of the seabed. Rick Grigg at the University of Hawai'i encouraged us to tackle some tricky bits of wave physics. Dr. Wilhelm Weinrebe of GEOMAR in Kiel, Germany, arranged for the use of bathymetric images of unprecedented resolution and clarity. Ulrke Schulte-Rahde at L-3Com sent images of the latest side-scan sonar installations. Dr. Steve Hatosy at UCI provided training in marine microbiology. Ruth Curry at WHOI added to the senior author's understanding of ocean circulation. The staff of The Viking Ship Museum and The *Fram*


Tom Garrison

Father, son, ocean—learning marine science is a joy at any age.


Tom Garrison

Despite a severe California drought, these supratidal plants are sustained by heavy morning fogs.

Tom Garrison

A tourist photographs the steerboard of a restored Viking longship.

Museum in Oslo were kind in allowing access to their magnificent ships. Liping Zhou made encouraging contributions from Peking University, Beijing. Adam Spitzer at Nanyang Technical University and Pavel Tkalich and Soo Chin Liew at the National University of Singapore were gracious and patient hosts. Gray Williams provided an occasional home base (and welcome cold beer) at Hong Kong University's magnificently sited Swire Institute of Marine Science. Without their inestimable goodwill, a project like this would not be possible.

The National Geographic team was understanding of our needs and deadlines. Erin West deserves a medal for her work with the Society's Explorers and Grantees mentioned in the text. The photo and image archive staff, led by Bill Bonner, opened the magic door and allowed these overwhelmed writer-oceanographers unfettered access. Maureen Flynn and James McClelland of the National Geographic Maps provided updates to many of the spectacular National Geographic maps and graphics in the text.

The Cengage/Brooks-Cole team performed the customary miracles. The charge was led by Jake Warde, whose patience, understanding, and panic-proof demeanor was a constant model and inspiration. The text was polished by the late Mary Arbogast, a good friend and the best text editor in the Orion arm of the galaxy (and who will be *greatly* missed), and Marcie McGuire, the copy editor who saved us from many errors. Carley Bergey worked tirelessly to assist in photo research and permissions, and Dan Fitzgerald and Carol Samet were in charge of production. Stefanie Chase developed the content for Oceanography MindTap. The amazing Yolanda Cossio and our always-upbeat editor, Aileen Berg, kept us all running in the same direction. What skill!

Our unending thanks to all.

A Goal and a Gift

The goal of all this effort: *To allow you to gain an oceanic perspective.* "Perspective" means being able to view things in terms of their relative importance or relationship to one another. An oceanic perspective lets you see this misnamed planet in a new light and helps you plan for its future. You will see that water, continents, seafloors, sunlight, storms, seaweeds, and society are connected in subtle and beautiful ways.

The ocean's greatest gift to humanity is intellectual—the constant challenge its restless mass presents. Let yourself be swept into this book and the class it accompanies. Give yourself time to ponder: "Meditation and water are wedded forever," wrote Herman Melville in *Moby Dick*. Take pleasure in the natural world. Ask questions of your instructors and TAs, read some of the references, and try your hand at the questions at the ends of the chapters.

Though you will find discouraging news in the last chapters, be optimistic. Take pleasure in the natural world. Please write to us when you find errors or if you have comments. Above all, *enjoy yourself*. Learning something new is a permanent pleasure!

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Foreword

by Dr. Enric Sala

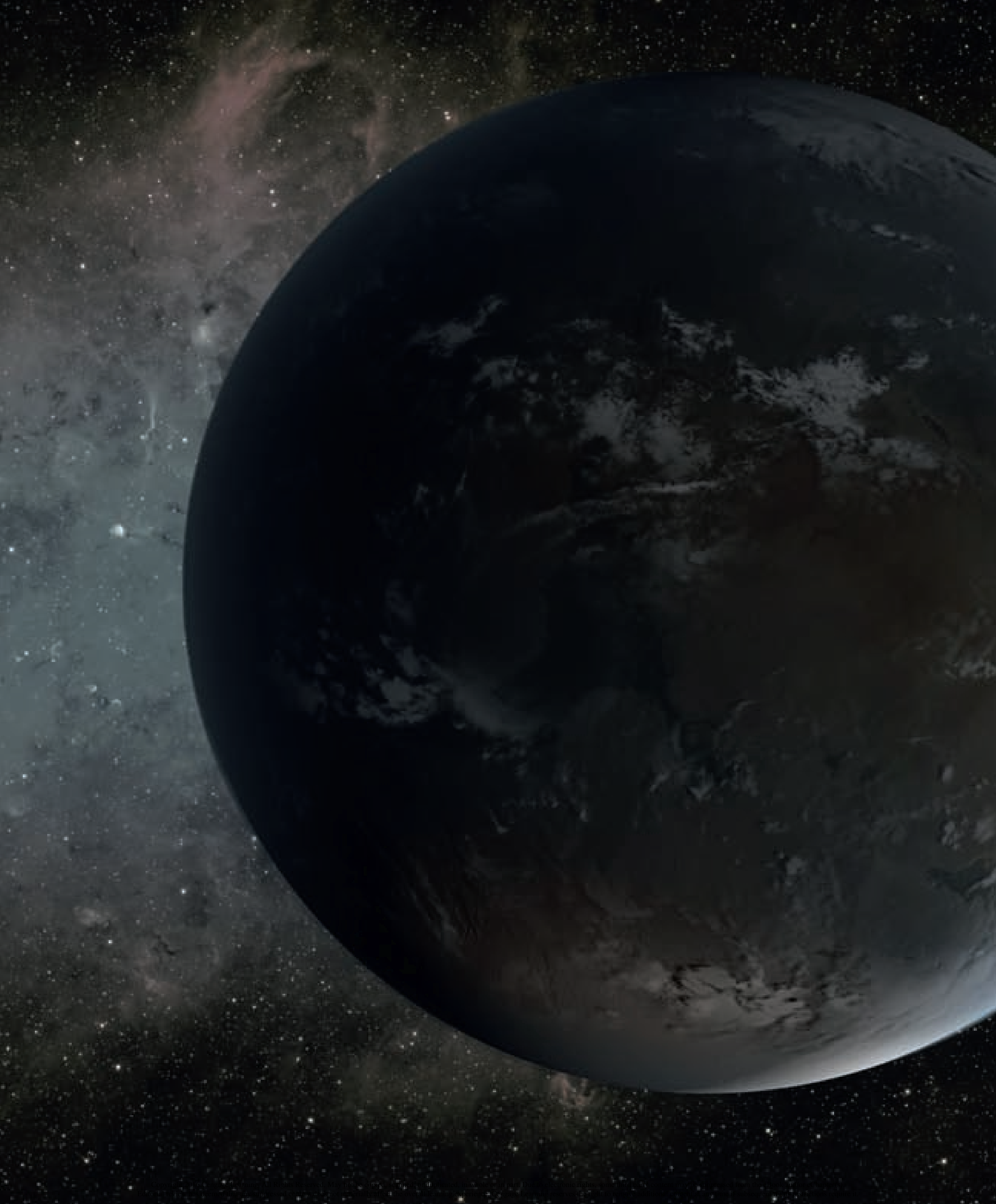
Rebecca Hale/National Geographic Creative

Dr. Enric Sala
Marine Ecologist
National Geographic Explorer-in-Residence

Imagine that an alien were visiting Earth for the first time to explore its landscape and inhabitants. It would have a 72% chance to "land" the spaceship on the ocean, because this is how much of our planet is ocean. But if the alien asked us about this largest feature of our planet, there would be huge gaps in our description. We have more detailed maps of the surface of the moon than of the bottom of the ocean, and we have explored in detail less than 5% of the ocean. Unfortunately, the technology that allows humans to descend into the deep only became available long after we had begun to degrade the ocean. Our understanding of ocean life is a by-product of studying degraded ecosystems, like trying to understand how a car functions by studying a car wreck in a junkyard.

Despite these shortcomings, we have learned enough about the ocean to know that it regulates our climate, is vital for the water cycle that creates the rain that waters our forests and fields, produces more than half of the oxygen we breathe, absorbs more than a quarter of the carbon dioxide we put in the atmosphere, gives us almost 100 million metric tonnes of seafood every year, and provides jobs and livelihoods for hundreds of millions of people worldwide. Despite everything the ocean gives us for free, we seem determined to degrade marine life, by taking out of the ocean what we like (seafood) and throwing in what we don't want (pollution, carbon dioxide, excess heat). These insults reduce the capacity of the ocean to provide all these goods and services that are essential to our well-being.

To find solutions to these problems, we need to start by reviewing what we know about the ocean. And I cannot think of a better way than through Tom Garrison's *Oceanography*. Professor Garrison does a terrific job showing why there is so much water in the ocean, why it is salty, why there are ocean currents, and how currents influence the climate. Most importantly, this book frames oceanography in the context of global change and shows clearly how to distinguish between natural changes and human impacts. If I gave that alien explorer an instruction manual for the ocean to take to his planet, I would give him this book.



1 The Origin of the Ocean

KEY CONCEPTS

Science is a systematic process of asking questions about the observable world by gathering and then studying information. DER/NOAA

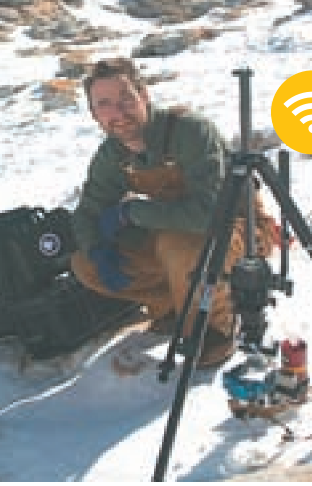
The universe's observable mass consists mostly of hydrogen atoms. The heavy elements we see around us were constructed in stars. Rogelio Bernal Andreo/NASA Images

Earth is density stratified—that is, as Earth formed, gravity pulled the heaviest materials (iron, nickel) to its center as lighter minerals rose to the surface. Earth's first solid surface formed about 4.6 billion years ago. © Cengage Learning

Life probably originated in the ocean shortly after it formed. © Cengage Learning

Water, even liquid water, appears to be present in other places in our solar system. Tom Garrison

An artist imagines an Earth-like planet orbiting a distant star. Water worlds may not be rare in the universe, but we know of only one: the beautiful blue sphere we call home.
NASA/Ames/JPL-Caltech



Kevin Hand/National Geographic

Media Connection
Start off this chapter by listening to a podcast featuring National Geographic Explorer Kevin Hand as he discusses Europa and what he hopes to find on Jupiter's fourth largest moon. Visit www.cengagebrain.com to access MindTap, a complete digital course that includes this podcast and other resources.

1.1 Earth Is an Ocean World

Think of oceanography as the story of the ocean. In this first chapter, the main character—the world ocean—is introduced in broad brushstrokes. We begin our investigation of the ocean with an overview of the process of science and then look at the long and often surprising story of how the ocean came to be.

Imagine, for a moment, that you had never seen this place—this ocean world—this poorly named Earth. As worlds go, you would surely find this one singularly beautiful and exceptionally rare. But the sun warming its surface is not rare—there are billions of similar stars in our home galaxy. The atoms that compose Earth are not rare—every kind of atom known here is found in endless quantity in the nearby universe. The water that makes our home planet shine a gleaming blue from a distance is not rare—there is much more water on our neighboring planets. The fact of the seasons, the free-flowing atmosphere, the daily sunrise and sunset, the rocky ground, the changes with the passage of time—none is rare.

What *is* extraordinary is a happy combination of circumstances. Our planet's orbit is roughly circular around a stable star. Earth is large enough to hold an atmosphere, but not so large that its gravity would overwhelm. Its neighborhood is tranquil—supernovae have not seared its surface with radiation. Our planet generates enough warmth to recycle its interior and generate the raw materials of atmosphere and ocean but is not so hot that lava fills vast lowlands or roasts complex molecules. Best of all, our distance from the sun allows Earth's abundant surface water to exist in the liquid state. Ours is an ocean world **(Figure 1.1 and Table 1.1)**.

The **ocean**[1] may be defined as the vast body of saline water that occupies the depressions of Earth's surface. More than 97% of the water on or near Earth's surface is contained in the ocean;

[1]When an important new term is introduced and defined, it is printed in boldface type. These terms are listed at the end of the chapter and defined in the Glossary.

Table 1.1 Some Statistics for the World Ocean

- Total area: 331,441,932 square kilometers (127,970,445 square miles)
- Total volume: 1,303,155,354 cubic kilometers (312,643,596 cubic miles)
- Total mass: 1.41 billion billion metric tons (1.55 billion billion tons)
- Average depth: 3,682 meters (12,081 feet)
- Greatest depth: 10,994 meters (36,070 feet)
- Mean ocean crust thickness: 6.5 kilometers (4.04 miles)
- Average temperature: 3.9°Celsius (39.0°Fahrenheit)
- Average salinity: 34,482 grams per kilogram (0.56 ounces per pound); 3.4%
- Average elevation of land: 840 meters (2,772 feet)
- Age: 4.5 billion years
- Future: Uncertain

© Cengage Learning

NASA Earth Observatory

Figure 1.1 Dominating Earth's surface is a single great ocean of liquid water. This ocean moderates temperature and dramatically influences weather. The dry land on which nearly all of human history has unfolded is hardly visible from space, for nearly three quarters of the planet is covered by water. In this 2011 photograph from NASA's *Aqua* satellite, North America's wrinkled western edge is seen beneath a thin veil of atmosphere. Strong easterly winds blow dust into the vast Pacific. *Oceanus* would surely be a better name for our watery home.

about 2.5% is held in land ice, groundwater, and all the freshwater lakes and rivers. If all Earth's surface water were gathered into a sphere, its diameter would measure only 1,380 kilometers (860 miles) **(Figure 1.2)**.

Traditionally, we have divided the ocean into artificial compartments called *oceans* and *seas*, using the boundaries of continents and imaginary lines such as the equator. In fact, the ocean has few dependable natural divisions, only one great mass of water. The Pacific and Atlantic oceans, the Mediterranean and Baltic seas, so named for our convenience, are in reality only temporary features of a single **world ocean**. In this book we refer to the ocean *as a single entity*, with subtly different characteristics at different locations but with very few natural partitions. Such a view emphasizes the interdependence of ocean and land, life and water, atmospheric and oceanic circulation, and natural and human-made environments.

On a *human* scale, the ocean is impressively large—it covers 331 million square kilometers (128 million square miles) of Earth's surface.[2] The average depth of the ocean is about 3,682 meters (12,081 feet); the volume of seawater is 1.3 billion cubic kilometers (312 million cubic miles); the average temperature a cool 3.9°C (39°F). Its mass is a staggering 1.41 billion *billion* metric tons. If Earth's contours were leveled to a smooth ball, the ocean would cover it to a depth of 2,686 meters (8,810 feet). The average land elevation is only 840 meters (2,772 feet), but the average ocean depth is 4½ times as great! The ocean borders most of Earth's largest cities—nearly half of the planet's 7 billion human inhabitants live within 240 kilometers (150 miles) of a coastline.

On a *planetary* scale, however, the ocean is insignificant. Its average depth is a tiny fraction of Earth's radius—the blue ink representing the ocean on an 8-inch paper globe is proportionally thicker. The ocean accounts for only slightly more than 0.02% of Earth's mass, or 0.13% of its volume. Much more water is trapped within Earth's hot interior than exists in its ocean and atmosphere.

The ocean has few dependable natural divisions, only one great mass of water. The Pacific and Atlantic oceans, the Mediterranean and Baltic seas, so named for our convenience, are in reality only temporary features of a single world ocean.

[2]Throughout this book, SI (metric) measurements precede American measurements. For a quick review of SI units and their abbreviations, please see Appendix 1.

CONCEPT CHECK

Before going on to the next section, check your understanding of some of the important ideas presented so far:

Why did we write that there is *one* world ocean? What about the Pacific and Atlantic oceans, the "Seven Seas"?

Which is greater: the average depth of the ocean or the average height of the continents above sea level?

Is most of Earth's water in the ocean?

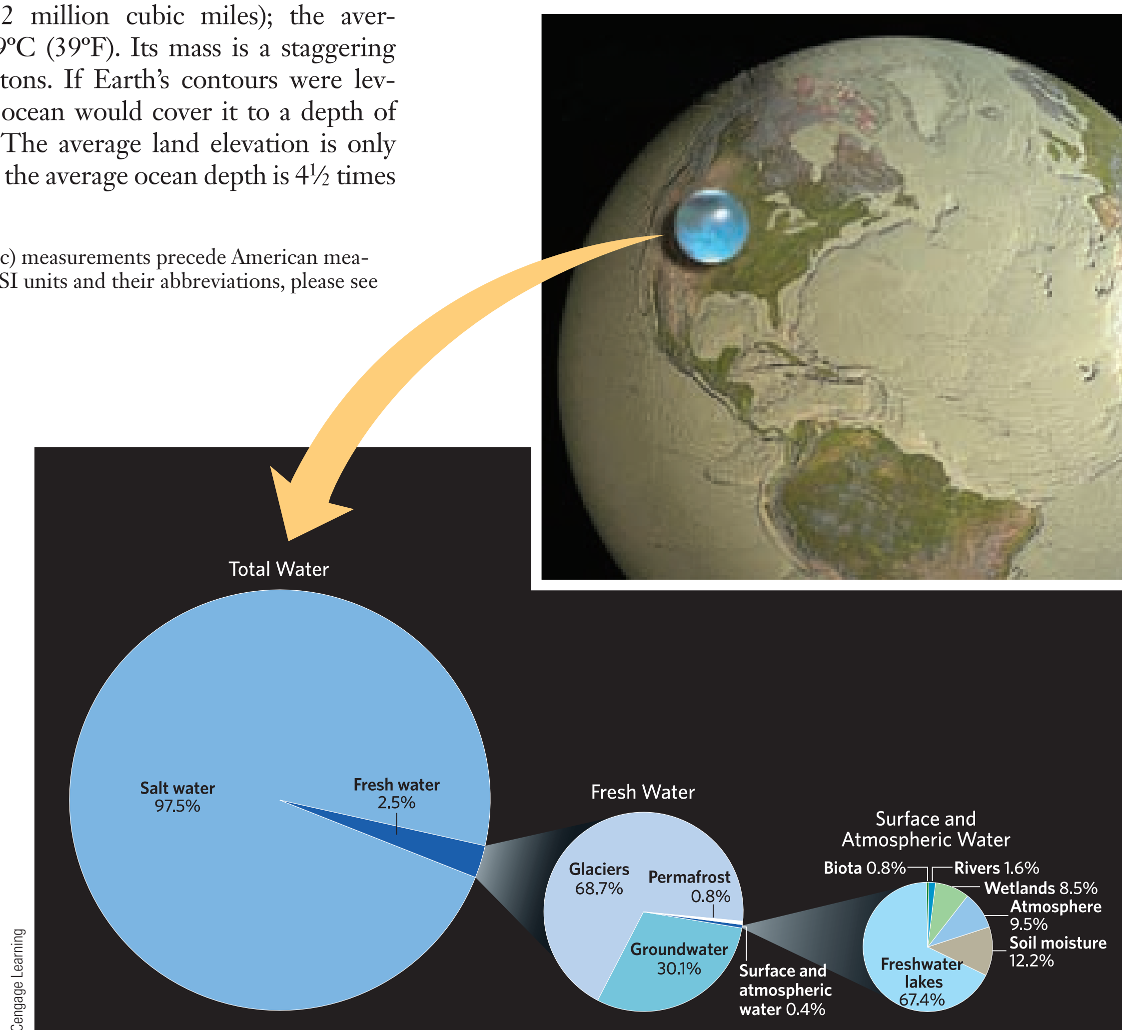


Figure 1.2 The relative amount of water in various locations on or near Earth's surface. More than 97% of the water lies in the ocean. If all water at Earth's surface were gathered into a sphere, its diameter would measure only 1,380 kilometers (860 miles).

THINKING BEYOND THE FIGURE

Given the predominance of water at Earth's surface, why do you think there is any dry land at all?

a. Kevin Hand (JPL/Caltech), Jack Cook (Woods Hole Oceanographic Institution), Howard Perlman (USGS)/NASA Images

1.2 Marine Scientists Use the Logic of Science to Study the Ocean

Marine science (or **oceanography**) is the process of discovering unifying principles in data obtained from the ocean, its associated life-forms, and its bordering lands. Marine science draws on several disciplines, integrating the fields of geology, physics, biology, chemistry, and engineering as they apply to the ocean and its surroundings. Nearly all marine scientists specialize in one area of research, but they also must be familiar with related specialties and appreciate the linkages between them.

- *Marine geologists* focus on questions such as the composition of inner Earth, the mobility of the crust, the characteristics of seafloor sediments, and the history of Earth's ocean, continents, and climate. Some of their work touches on areas of intense scientific and public concern, including earthquake prediction and the distribution of valuable resources.
- *Physical oceanographers* study and observe wave dynamics, currents, and ocean–atmosphere interaction.
- *Chemical oceanographers* study the ocean's dissolved solids and gases and their relationships to the geology and biology of the ocean as a whole.
- *Climate specialists* investigate the ocean's role in Earth's changing climate. Their predictions of long-term climate trends are becoming increasingly important as pollutants change Earth's atmosphere.
- *Marine biologists* work with the nature and distribution of marine organisms, the impact of oceanic and atmospheric pollutants on the organisms, the isolation of disease-fighting drugs from marine species, and the yields of fisheries.
- *Marine engineers* design and build oil platforms, ships, harbors, and other structures that enable us to use the ocean wisely.

Other marine specialists study the techniques of weather forecasting, ways to increase the safety of navigation, methods to generate electricity, and much more. **Figure 1.3** shows marine scientists in action.[3]

Marine scientists today are asking some critical questions about the origin of the ocean, the age of its basins, and the nature of the life-forms it has nurtured. We are fortunate to live at a time when scientific study may be able to answer some of those questions. **Science** is a systematic *process* of asking questions about the observable world by gathering and then studying information (data), but the information by itself is not science. Science *interprets* raw information by constructing a general explanation with which the information is compatible.

Scientists start with a question—a desire to understand something they have observed or measured. They then form a tentative explanation for the observation or measurement. This explanation is often called a working **hypothesis**, a speculation about the natural world that can be tested and verified or disproved by further observations and controlled experiments. (An **experiment** is a test that simplifies observation in nature or in the laboratory by manipulating or controlling the conditions under which the observations are made.) Hypotheses consistently supported by observation, experiment, or historical exploration often evolve to become a **theory**, a statement that explains the observations.

Comprehensive constructs, known as **laws**, can also summarize experimental observations. Laws are principles explaining events in nature that have been observed to occur with unvarying uniformity under the same conditions. A law usually takes the form of a concise mathematical or verbal expression; a theory provides an *explanation* for the observations. *One is not "more true" than the other–both a law and a theory can be statements of facts.*

Theories and laws in science do not arise fully formed or all at once. Scientific thought progresses as a continuous chain of questioning, testing, and matching theories to observations. A theory is strengthened if new facts support it. If not, the theory is modified or a new explanation is sought (science is thus "self-correcting"). The power of science lies in its ability to operate *in reverse;* that is, in the use of a theory or law to predict and anticipate new facts to be observed.

This procedure, often called the **scientific method**, is an orderly process by which theories are verified or rejected. The scientific method rests upon the assumption that nature "plays fair"—that the rules governing natural phenomena do not change capriciously as our powers of questioning and observing improve. We believe that the answers to our questions about nature are *ultimately knowable.*

There is no one scientific method. Some researchers observe, describe, and report on some subject and leave it to others to hypothesize. Scientists don't have one single method in common—the general method they employ is a critical attitude about being *shown* rather than being *told*, and taking a logical approach to problem solving. The process is circular and collaborative—new theories and laws always suggest new questions. See **Figure 1.4**.

You've heard of the scientific method before but may have thought that scientific thinking was beyond your interest or ability. Nothing could be further from the truth—you use scientific logic many times a day. Consider your line of thinking if, later today, you try to start your car but are met only with silence. Your first thoughts (after the frustration subsided) would likely be these:

1. So! The car won't start!
2. *Why* won't the car start? (That second thought—*why*—is a very powerful bit of Western philosophy. Its implication: The car won't start for a *reason*, and that reason is *knowable.*)

You immediately begin to conduct a set of mental experiments:

3. You know that cars need electricity to start. You turn on the lights. They work. Electricity is present. The problem is not a lack of electricity.
4. Cars need air to combine with fuel in the engine. Is air present? You take a breath. Air? Yes. The problem is not lack of air.
5. Cars need fuel. Is there fuel? You turn on the ignition. The fuel gauge registers three-fourths full. (You also notice a fuel receipt in your pocket from yesterday.) Yes, there's fuel.
6. Cars need all of these things to be present *simultaneously* in order to start. You open the hood to look for loose wires or hoses interrupting flow. *AHA*! A wire is loose.

[3]Would you like to join us? Appendix 8 discusses careers in the marine sciences.

Robert Ellis

a A student research team attempts to identify a humpback whale by comparing its unique fluke pattern to previously cataloged individuals.

Courtesy Ingrid Burke and Stephen Hatosy

b Quiet, thoughtful study comes before an experiment is begun and after the data are obtained. A student works with a flashlight on a lab report during a power outage at the University of California's Moorea Research Station in the South Pacific.

Philippe Crassous/Science Source

c Sometimes marine scientists come up with an unanticipated surprise. Fortunately this marine worm is very, very small.

Figure 1.3 Doing marine science is sometimes anxious, sometimes routine, and always interesting.

7. You put the wire back into place.
8. The car starts! Science wins! The question "why" is answered!

Or you could pursue an alternative line of thinking: You could decide that the spirits of car starting have somehow turned against you. Once you lose their confidence, your power over cars is greatly diminished, and you will almost certainly never be able to drive again. Maybe if you shake your keys over the hood of the car, the spirits will look favorably on you and the car might start, but you can't possibly fix anything yourself—these things are out of your hands. Your relationship with cars is over. (This line of reasoning is not very productive!)

Although clearly powerful in its implications and applications, nothing is ever shown to be *irrevocably* true by the scientific method. Still, the mechanism of science has provided durable, valuable conclusions that have withstood the test of time and immeasurably improved our lives. It is the best tool we have for exploring the natural world. Note that *science is neither a democratic process nor a popularity contest.* As we can sense from the current acrimonious debates over global climate change or even evolution, conclusions about the natural world that we reach by scientific process may not always be comfortable, easily understood, or immediately embraced. But if those conclusions consistently match observations, they may be considered true.

This textbook shows some of the results of the scientific process as they have been applied to the world ocean. It presents facts, interpretations of facts, examples, stories, and some of the crucial discoveries that have led to our present understanding of the ocean and the world on which it formed. As the results of science change, so will the ideas and interpretations presented in books like this one. As you read the chapters to come, you will see examples of scientific thought in boxes labelled: "How Do We Know. . .?"

a In this oversimplistic view, a logical series of steps represents the *procedure* of science. A progression of rational assumptions backed by data (information) leads to a solution to a specific problem. In fact, there is no single way of applying scientific logic applicable to all situations.

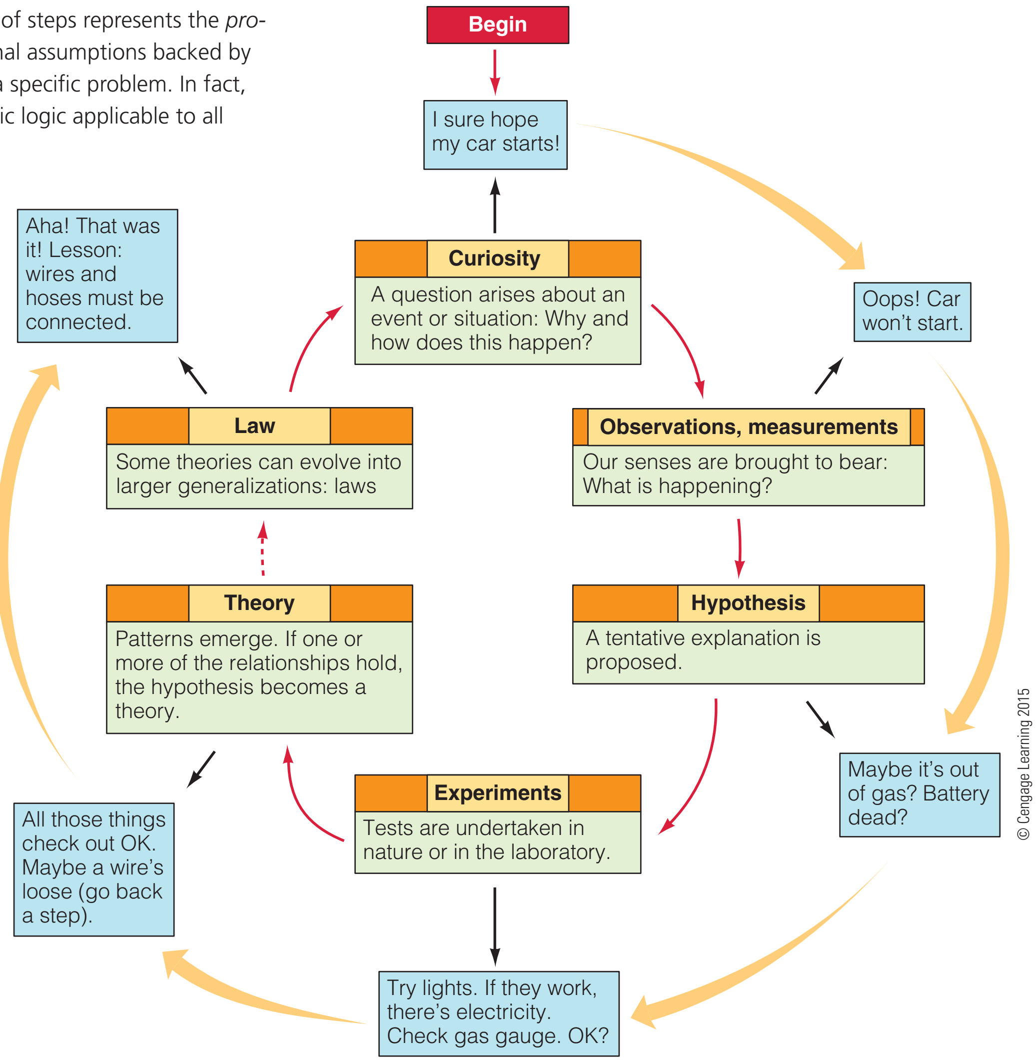


Figure 1.4 There is no single "scientific method."

THINKING BEYOND THE FIGURE

What's wrong with this statement: "I've been going to the same barber for 25 years, and I'm going bald. She must be using something on my scalp that makes me lose my hair."

CONCEPT CHECK

Before going on to the next section, check your understanding of some of the important ideas presented so far:

Can the scientific method be applied to speculations about the natural world that are not subject to test or observation?

What is the nature of "truth" in science? Can anything be proven *absolutely* true?

What if, at the moment you shake the keys, the wires under the hood are jostled by a breeze and fall back into place? What if the car starts when you try it again? Can you see how superstition might arise?

1.3 Stars Form Seas

To understand the ocean, we need to understand how it formed and evolved through time. Since the world ocean is the largest feature of Earth's surface, it should not be surprising that we believe the origin of the ocean is linked to Earth's origin. The origin of Earth is linked to that of the solar system and the galaxies.

Theories may change as our knowledge and powers of observation change.

The formation of Earth and ocean is a long and wonderful story—one we've only recently begun to know. As you continue reading this chapter, you may be startled to discover that most of the atoms that make up Earth, its ocean, and its inhabitants were formed within stars billions of years ago. Stars spend their lives changing hydrogen and helium to heavier elements. As they die, some stars eject these elements into space during cataclysmic explosions. The sun and the planets, including Earth, condensed from a cloud of dust and gas enriched by the recycled remnants of exploded stars.

Our ocean did not come directly from that cloud, however. Most of the ocean formed later, as water vapor trapped in Earth's outer layers escaped to the surface through volcanic activity during the planet's youth. The vapor cooled and condensed to form an ocean. Comets may have delivered additional water to the new planet's surface. Life originated in the ocean soon after, developing and flourishing in the nurturing ocean for more than 3 billion years before venturing onto the unwelcoming continents.

Tom Garrison

b The underlying method of science describes an attitude. Scientists like to be shown why an idea is correct, rather than being told. All science is a work in progress, never completed. The external world, not internal conviction, must be the testing ground for scientific beliefs. Here, marine scientists are planning an experiment to better understand how small intertidal snails withstand the high temperatures of their tropical environment. They have a hypothesis and will design experimental steps to resolve it.

Stars Formed Early in the History of the Universe

The universe apparently had a beginning. The **big bang**, as that event is modestly named, occurred about 13.7 billion years ago. All of the mass and energy of the universe is thought to have been concentrated at a geometric point at the beginning of space and time, the moment when the expansion of the universe began. We don't know what initiated the expansion, but it continues today and will probably continue for billions of years, perhaps forever.

The very early universe was unimaginably hot, but as it expanded, it cooled. About a million years after the big bang, temperatures fell enough to permit the formation of atoms from the energy and particles that had predominated up to that time. Most of these atoms were hydrogen, then as now the most abundant form of matter in the universe. About a billion years after the big bang, this matter began to congeal into the first galaxies and stars.

Stars and Planets Are Contained within Galaxies

A **galaxy** is a huge, rotating aggregation of stars, dust, gas, and other debris held together by gravity. Our galaxy **(Figure 1.5)** is named the **Milky Way galaxy** (from the Greek *galaktos*, which means "milk").[4]

[4]Because they can be useful, as well as interesting, the derivations of words are sometimes included in the text.

ESO/Science Source

Figure 1.5 A brilliant laser points toward the center of our Milky Way galaxy. (The beam is used to monitor conditions in Earth's upper atmosphere to provide a clearer image of the distant stars.) Analysis of these images suggests our home galaxy contains between 100 and 400 billion stars and is about 120,000 light-years in diameter. Our solar system lies about 27,000 light-years from the galactic center in a concentration of dust and gas called the Orion-Cygnus Arm. (A light-year is the distance light travels in one year: about 9.5 trillion kilometers or 6 trillion miles.) Our solar system orbits the galactic center at a speed of about 220 kilometers (138 miles) per second. This galaxy is one of the 54 galaxies comprising what astronomers have called the "local group."

THINKING BEYOND THE FIGURE
Think for a moment: What does the term "local group" suggest?

Figure 1.6 A filament of hot gas erupts from the face of our sun in September of 2012. Like all normal stars, the sun is powered by nuclear fusion—the welding together of small atoms to make larger ones. These violent reactions generate the heat, light, matter, and radiation that pour from stars into space. The entire Earth could easily fit beneath this filament's fiery arc. NASA Images

The **stars** that make up a galaxy are massive spheres of incandescent gases. They are usually intermingled with diffuse clouds of gas and debris. In spiral galaxies like the Milky Way, the stars are arrayed in curved arms radiating from the galactic center. Our part of the Milky Way is populated with many stars, but distances within a galaxy are so huge that the star nearest the sun is about 42 trillion kilometers (26 trillion miles) away. Astronomers tell us there are perhaps 100 billion galaxies in the universe and 100 billion stars in each galaxy. Imagine more stars in the Milky Way than grains of sand on a beach!

Our sun is a typical star **(Figure 1.6)**. The sun and its family of planets, called the **solar system**, are located about three fourths of the way out from the galaxy's center, in a spiral arm. We orbit the galaxy's brilliant core, taking about 230 million years to make one orbit—even though we are moving at about 280 kilometers per second (half a million miles an hour). Earth has made about 20 circuits of the galaxy since the ocean formed.

Every chemical element heavier than hydrogen—most of the atoms that make up the planets, the ocean, and living things—was manufactured by the stars.

Stars Make Heavy Elements from Lighter Ones

As we will see, most of the Earth's substance and that of its ocean was formed by stars. Stars form in **nebulae**, large, diffuse clouds of dust and gas within galaxies. With the aid of telescopes and infrared-sensing satellites, astronomers have observed such clouds in our own and other galaxies. They have seen stars in different stages of development and have inferred a sequence in which these stages occur. The **condensation theory**, a theory based on this inference, explains how stars and planets are believed to form.

The life of a star begins when a diffuse area of a spinning nebula begins to shrink and heat up under the influence of its own weak gravity. Gradually, the cloudlike sphere flattens and condenses at the center into a knot of gases called a *protostar* (*protos*, "first"). The original diameter of the protostar may be many times the diameter of our solar system, but gravitational energy causes it to contract, and the compression raises its internal temperature. When the

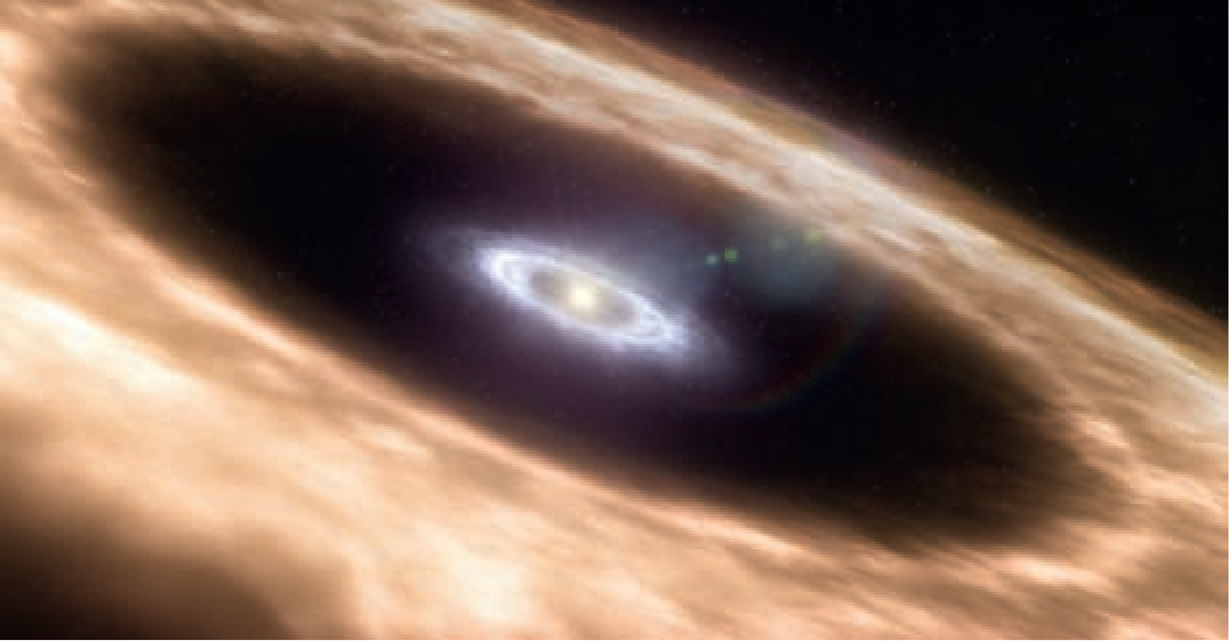


Figure 1.7 An artist depicts the origin of our sun and its family of planets about 5 billion years ago. Near our star, the dust and gas has clumped together to form planetary embryos. Farther away in the distant cold, a halo of comets and debris is coalescing.

protostar reaches a temperature of about 10 million degrees Celsius (18 million degrees Fahrenheit), nuclear fusion begins. That is, hydrogen atoms begin to fuse to form helium, a process that liberates even more energy. This rapid release of energy, which marks the transition from *protostar* to *star*, stops the young star's shrinkage. (The process is shown in the top half of **Figure 1.7**.)

After fusion reactions begin, the star becomes stable—neither shrinking nor expanding, and burning its hydrogen fuel at a steady rate. Over a long and productive life, the star converts a large percentage of its hydrogen to atoms as heavy as carbon or oxygen.

This stable phase does not last forever, though. The life history and death of a star depend on its initial mass. When a medium-mass star (like our sun) begins to consume carbon and oxygen atoms, its energy output slowly rises and its body swells to a stage aptly named *red giant* by astronomers. The dying giant slowly pulsates, incinerating its planets and throwing off concentric shells of light gas enriched with these heavy elements. But most of the harvest of carbon and oxygen is forever trapped in the cooling ember at the star's heart.

Stars much more massive than the sun have shorter but more interesting lives. They, too, fuse hydrogen to form atoms as heavy as carbon and oxygen, but being larger and hotter, their internal nuclear reactions consume hydrogen at a much faster rate. In addition, higher core temperatures permit the formation of atoms—up to the mass of iron.

The dying phase of a massive star's life begins when its core—depleted of hydrogen—collapses in on itself. This rapid compression causes the star's internal temperature to soar. When the infalling material can no longer be compressed, the energy of the inward fall is converted to a cataclysmic expansion called a **supernova** (*nova*, "new" [star]). The explosive release of energy in a supernova is so sudden that the star is blown to bits, and its shattered mass accelerates outward at nearly the speed of light. The explosion lasts only about 30 seconds, but in that short time the nuclear forces holding apart individual atomic nuclei are overcome, and atoms heavier than iron are formed. The gold in your rings, the mercury in a thermometer, and the uranium in nuclear power plants were all created during such a brief and stupendous flash. The atoms produced by a star through millions of years of orderly fusion *and* the heavy atoms generated in a few moments of unimaginable chaos are sprayed into space **(Figure 1.8)**. Every chemical element heavier than hydrogen—most of the atoms that make up the planets, the ocean, and living creatures—was manufactured by the stars.

Solar Systems Form by Accretion

Earth and its ocean formed as an indirect result of a supernova explosion. The thin cloud, or **solar nebula**, from which our sun and its planets formed was probably struck by the shock wave and some of the matter of an expanding supernova remnant. Indeed, the turbulence of the encounter may have caused the condensation of our solar system to begin. The solar nebula was affected in two important ways: First, the shock wave caused the condensing mass to spin; second, the nebula absorbed some of the heavy atoms from the passing supernova remnant. In other words, a massive star had to live its life (constructing elements in the process) and then undergo explosive disintegration in order to seed heavy elements back into the nebular nursery of dust and gas from which our solar system arose. The planets are made mostly of matter assembled in a star (or stars) that disappeared billions of years ago. We ourselves are also made of that stardust. Our bones and brains are composed of ancient atoms constructed by stellar fusion long before the solar system existed.

By about 5 billion years ago, the solar nebula was a rotating, disk-shaped mass of about 75% hydrogen, 23% helium, and 2% other material (including heavier elements, gases, dust, and ice). Like a spinning skater bringing in her arms, the nebula spun faster as it condensed. Material concentrated near its center became the protosun. Much of the outer material eventually became **planets**, the smaller bodies that orbit a star and do not shine by their own light.