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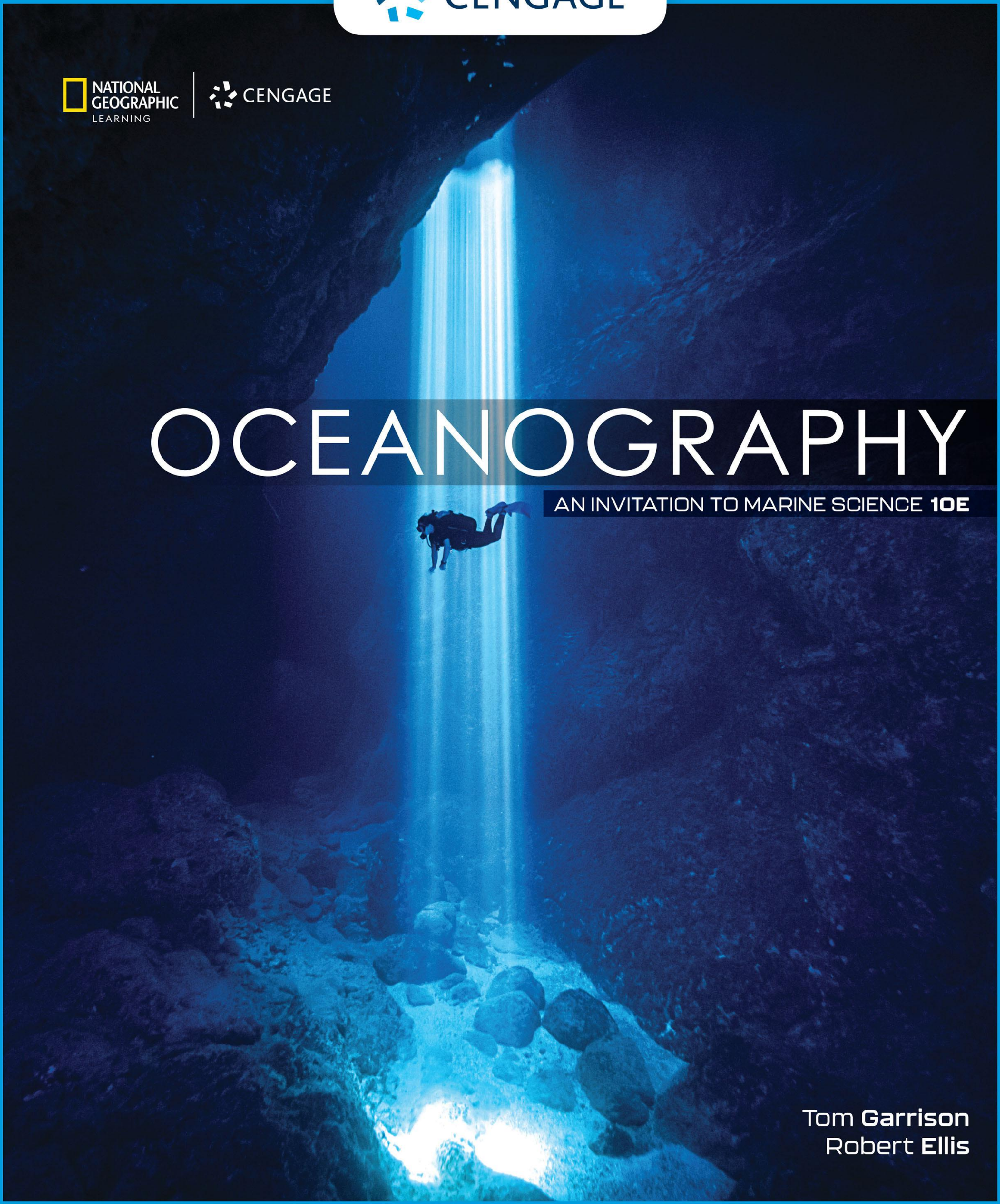
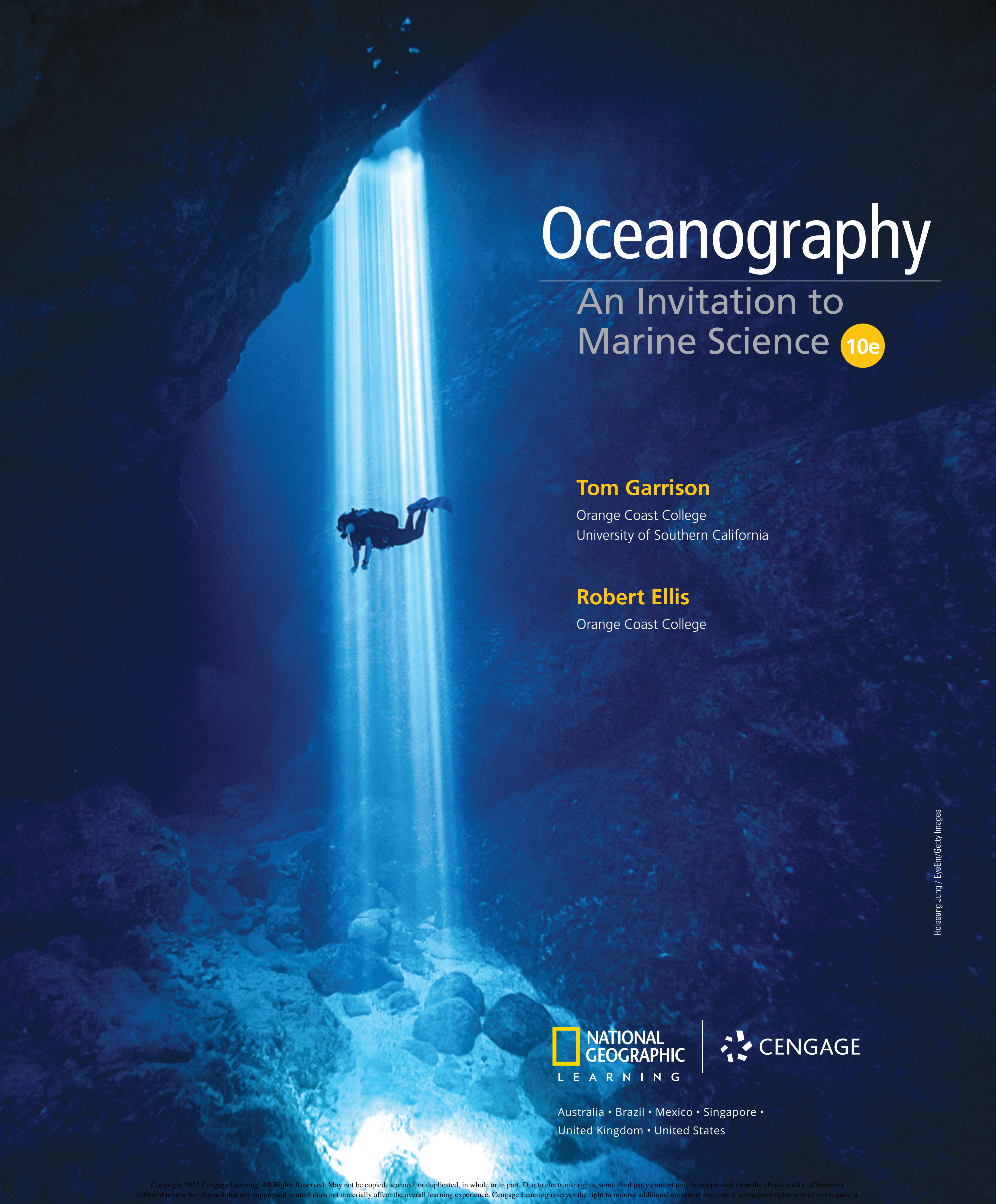
AN INVITATION TO MARINE SCIENCE 10E



Tom Garrison
Robert Ellis



Oceanography

An Invitation to Marine Science 10e

Tom Garrison
Orange Coast College
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Robert Ellis
Orange Coast College

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

About the Authors

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Tom Garrison (PhD, University of Southern California) was an inspiring professor of marine science for more than 47 years at Orange Coast College (OCC) in Costa Mesa, California, one of the largest undergraduate marine science departments in the United States. Dr. Garrison also held an adjunct professorship at the University of Southern California. He was named the country's Outstanding Marine Educator by the National Marine Technology Society, was a founding member of COSEE, wrote a regular column for the journal *Oceanography*, and enjoyed writing for *National Geographic* magazine. He was a winner of the prestigious Salgo-Noren Foundation Award for Excellence in College Teaching, and in 1992, 1993, and 1997, he was a recipient of the University of Texas NISOD award in recognition of his outstanding contributions in teaching and learning. In 1997, students and faculty at Orange Coast College elected him Faculty Member of the Year. He served as a grants judge for the National Science Foundation in Washington, D.C. Dr. Garrison was an Emmy Award team participant as writer and science adviser for the PBS syndicated *Oceanus* television series, and was writer and science adviser 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 allowed him to pass his oceanic enthusiasm to more than 65,000 students in his career. He retired from full-time professoring in 2011; however, he bothered OCC staff and students on a regular basis right up until his final days.

Dr. Garrison traveled extensively and served as a guest lecturer at the University of Hong Kong, the University of Tasmania (Australia), and the National University of Singapore.

He was married to an astonishingly patient lady for nearly 50 years, and had a daughter who teaches in a local public school, a diligent son-in-law, three astonishingly cute granddaughters and a grandson, and a son who, along with his fashionista wife, works in international trade. He and his family lived in and around Newport Beach, California. To most, he was known as Dr. Garrison, the inspiring and enthusiastic professor of marine science, but to a select few he was known as Papa and will forever be remembered as a loving friend, grandpa, dad, and husband.

Katie 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 associate professor in the Marine Science Department at Orange Coast College (OCC) in Southern California and as assistant director of the OCC Public Aquarium. When not on campus, Professor Ellis often helps 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 has two wonderful kids, Kalen and Abigail, with his wife, Katie.

Brief Contents

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Contents

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Background photo: BlueOrange Studio

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 130 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 Tenth 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.** Each chapter has been thoroughly revised to reflect the latest findings in the field, and many areas of the text have been expanded based on current events and the recommendations of other instructors. It is our sincere hope that the resulting work accurately reflects the present state of our fast-moving field of science.
- **Emphasized the interdisciplinary nature of marine science.** In addition to our historical strong emphasis on the interdisciplinary nature of marine sciences throughout the text, the new edition includes an Interdisciplinary Connections feature in every chapter. These features are designed to profile specific issues that make it easy for students to appreciate how concepts from many scientific fields are essential to understanding some of the most important topics in oceanography.
- **Added new Learning Objective to guide students through each chapter.** The new chapter Learning Objectives have guided the revision to produce a more complete educational resource that focuses on the key concepts that are most important for students to understand.
- **Modified the illustration program to make the textbook more visually appealing to better engage students.** We have incorporated a number of new National Geographic Society assets to greatly enhance the visual program for increased clarity and accuracy. Many additional figures have been added or revised to help students better understand the concepts.
- **Emphasized the process of science throughout.** The "How Do We Know?" boxes have been retained to provide insight on *how* oceanographers have determined some of the key information described in the book. Additional information has been added throughout the chapters to expand on this theme.
- **Added new voices to the "Insights from an Explorer" features.** 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. Some of the explorers have been retained from the previous edition and a new generation of diverse National Geographic Explorers are included to offer their insights related to current core concepts contained in the text.

- **Expanded features to encourage active learning and develop critical thinking skills.** A greater number of "Thinking Beyond the Figure" questions have been added to get students thinking about other aspects of key graphs, tables, and photos. They are designed to help reinforce connections between chapters and look at visual evidence through different contexts. New "Concept Check" questions have been added to many of the sections to help students retain some of the main points of what they read. Each chapter also 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 additional information to address common student questions.** The popular "Questions from Students" feature has been retained and expanded—these brief discussions address topics of immediate or controversial interest immediately after a chapter. Relevant quotes are highlighted from sources within each chapter or from famous individuals to draw student attention to them.
- **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.

©Robert Ellis

A group of students learns navigational techniques before setting sail.

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

©Gregory Matthew Allen

Learning about the ocean involves close contact and often great fun.

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 address 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.

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 set of **Learning Objectives** that inform students of the key things that they should be able to do after reading the chapter. An engaging chapter opener photo and caption helps to generate interest in 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 each sequentially numbered to keep concepts organized. A set of **Concept Checks** concludes each chapter's major sections. The answers are provided in the MindTap Reader.

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**.

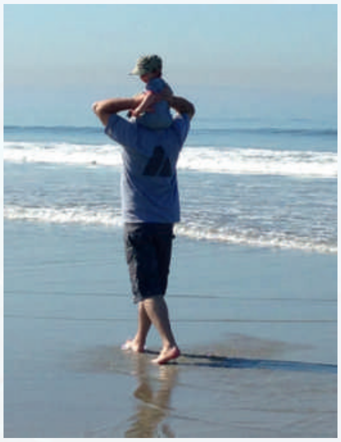
The book has been thoroughly **student tested**. You need not feel intimidated by the concepts—this material has been mastered by students just like you. Read slowly and go step by step through any parts that give you trouble. Your predecessors have found the ideas presented here to be useful, inspiring, 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? *Who* still hunts 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 flash cards 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

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

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.


©Robert Ellis

A marine science student finds a peaceful place to study on a crisp morning in British Columbia.

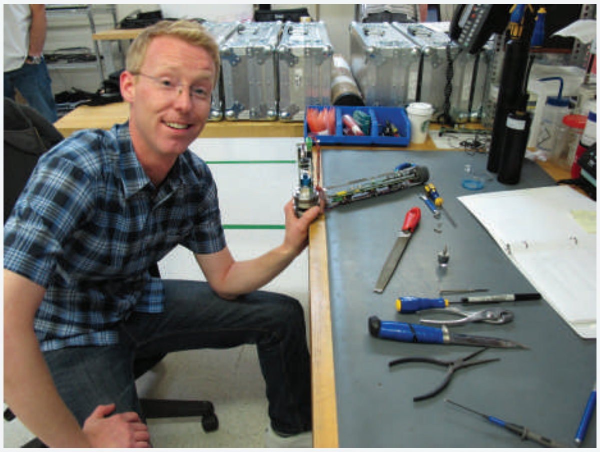
Cognero Test Bank

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

Oceanography MindTap

MindTap for Garrison/Ellis's *Oceanography: An Invitation to Marine Science*, 10th Edition, is the digital learning solution that powers students from memorization to mastery. It gives you complete control of your course—to provide engaging content, to challenge every individual and to build their confidence. Empower students to accelerate their progress with MindTap.


©Tom Garrison

A marine technician assembles a sensor. Most oceanographic data are collected by remote sensors like this one.

MindTap for Oceanography is designed to ensure class preparedness through concept check activities; increase conceptual understanding through high-quality visualizations, including animations and videos; and improve critical-thinking skills through homework activities that solidify concepts at an appropriately rigorous level.

Student Resources

Oceanography MindTap

MindTap for Garrison/Ellis's *Oceanography: An Invitation to Marine Science*, 10th Edition, helps students learn on their terms. MindTap allows students instant access in their pocket. Students can take advantage of the Cengage Mobile App to learn on their terms. They can read or listen to textbooks and study with the aid of instructor notifications, flashcards and practice quizzes.

Students can track their own scores and stay motivated toward their goals. Whether they have more work to do or are ahead of the curve, they'll know where they need to focus their efforts.

Students can also create custom flashcards, highlight key sections in their textbook they want to remember, complete homework assigned by their instructor, and watch videos and animations to help strengthen their understanding of lecture and reading material.

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.

Our long-suffering departmental colleagues Karen Baker, Rip Profeta, Mary Blasius, Lindsey Williamson, Don Johnston, Lisa Snyder, Umi Prince, Dennis Kelly, and our division coordinator, JP Nguyen 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, Tara Giblin, and our college president, Angelica Suarez, 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 and student aquarium managers deserve a great deal of praise for helping us develop new education materials and maintain a positive leaning environment for our students, especially Mersades Hineman, Maddie Enriquez, Katie Iavelli, Connor Mahan, Zack Burnett, Taylor Minke, Matt Coleman, Zane Calendine, Bethany Yates, Magali Martinez, Zeke Firth, Laura Minor, Anthony Lebron, Nyssa Guidengen, Nicole Freed, and Angela Willhite.

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, Alia, Katie, Kalen, and Abigail for your love and understanding. The many friends and colleagues that we have bounced ideas off deserve special recognition, including Karen Baker, Mary Blasius, Lindsey Williamson, Scott Mitchell, Rip Profeta, Erik Bender, Jerome Fang, Chris Berg, Kelli Elliott, Jan Goerrissen, Nick Contopoulos, Angelo Esposito, Mike Vanry, Mark Boryta, Matthew Kohlmyer, Joana Tavares-Reager, J.T. Reager, Richard Ray, Sarah Sikich, Chris Krajacic, and Andy Balendy.

Without their inestimable goodwill, a project like this would not be possible.

The National Geographic team was understanding of our needs and deadlines. Avi Mednick coordinated with National Geographic's map team to research new maps, secure approvals, and corresponded with National Geographic explorers to review their features. Hayley Chwazik-Gee provided additional research and guidance for finding new photos in the National Geographic image collection and led the collaboration. 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 Learning team performed the customary miracles. The charge was led by Sean Campbell, who helped polish the chapters and manage the many aspects of producing the book. Paula Bonilla, our copy editor, saved us from many errors and helped to shape the book into its final form. Ann Hoffman, Kelli Besse, and Nisha Bhanu Beegum worked tirelessly to assist us in photo research and permissions, and Manoj Kumar was in charge of production. Special thanks to our learning designer, Sara Huber, and Mark Hopkinson, who kept the digital world in line for the book's Web site. Our product manager, Vicky True, the marketing manager,

Tom Garrison

A tourist photographs the steerboard of a restored Viking longship. ***Steerboard*** **became** ***starboard*****, the right side of a vessel.**

©Deborah Ellis

Kayaking in the crystal-clear waters of the tropics can provide relaxation for the entire family.

Tom Garrison

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

©Zak Noyle/A-Frame

Trash in the surf in Java, southern Indonesia. Residents dump their waste in rivers that lead to the sea.

Shannon Hawkins, and our cover designer, Chris Doughman all deserve special recognition for their hard work and amazing attention to detail.

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 Image Collection

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 tons 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.

In Loving Memory of Dr. Tom S. Garrison

From a daughter to her dad—From a student to her teacher

Tom Garrison

On February 24, 2016, Dr. Garrison, my dad, passed away after a long battle with lymphoma.

To quote my dad's idyllic professor, Earl Pullius, USC, "A teacher is many things… a guide, a model, a modernizer, a searcher, a student, a counselor and a friend. A teacher is a creator, a doer of routine, a storyteller, and a builder of community. A teacher is a way of being." My dad was the embodiment of this quote. He realized the impact he had on his students; not just in teaching the subject of marine science, but in setting students on the right course by exemplifying the different roles of a teacher, just as Dr. Pullius emphasized.

My dad saw the potential in us all. He called us all "Masters of the Universe." He made all of us want to be better and he made us want to continue growing and pushing forward for the rest of our lives. He celebrated so many victories with *me* and always guided *me* forward when *I* needed it the most, as he did with all his students. As a teacher, my dad was a master at sucking you in to the material through the magic, the mystery, and the astonishing power of his stories and then guiding you on a path that would lead you to exactly where you needed to be. It was then that he would stop and watch you walk ahead, confidently, into your future

My dad always told me that the most important goal of anyone's life is to be happy. He defined happiness as a state of peace, satisfaction, and friendship. He said it comes from having the education to see the connections between things, the stability to have meaningful relationships and raise a family, the ability to get and hold a job, and the desire to make a difference in the world. He always said that Thomas Jefferson was amazingly insightful in basing his vision for a new country on the pursuit of happiness. Not a guarantee, mind you, but the assurance of freedom to pursue whatever you wanted. He also reminded me that there would be hard times and I would need to weather the storms of my own doubts. He encouraged me, as he did with all his students, and he was always confident in our abilities to succeed.

He explained to me that teaching is the immortal profession because you have the ability to inspire students long after you're gone. My dad still lives on in me, as I hope he will in all of you. His personality shines through in his textbooks. Growing up, I have fond memories of him sitting at his desk at all hours of the night, listening to classical music and writing. His hope was to pass on his joy, his love of learning, and his knowledge of the ocean to the world. He was a distinguished professor, a world renowned author, an endearing husband, and a beloved father and friend. He made a difference! I hope he will continue to inspire you to achieve your fullest potential. He told me regularly, "There is much good in this world, go and add to it." This was his motto. Along with *citius*, *altius*, *fortius*—faster, higher, stronger. He dedicated his life to his family, his friends, and his students. He wants all of us to know that *we* are his hope for the future. He wants us to find what makes us truly happy and then race, unwaveringly, toward it. Do as Tennyson suggests in his Ulysses: *To strive, to seek, to find, and not to yield.*

Tom Garrison

1 The Origin of the Ocean

LEARNING OBJECTIVES

1.1 Explain why we consider there to be only one world ocean.

1.2 Describe how the ocean affects life on this planet.

1.3 Identify the various academic disciplines related to oceanography.

1.4 Explain why stars are important to the ocean's composition and characteristics.

1.5 Describe the characteristics of our planet that make it suitable to house and maintain a liquid water ocean.

1.6 Identify the sources of Earth's water and how they are thought to have formed our ocean.

1.7 Explain how the moon likely formed and how it affects Earth.

1.8 Describe the features of the ocean that made it a good environment to have nurtured early life.

1.9 Compare and contrast Earth's ocean to oceans on other planets and moons.

Nearby stars shine over the ocean as the sun begins to rise in Los Cabos, Mexico. Earth, its ocean, and all of its inhabitants were formed by unimaginable energies across enormous spans of time. Our story begins here, with the stars. Kenneth_Wilson/Getty Images

1.1 Earth Is an Ocean World

This is a book about the dominant surface feature of a poorly named planet. "Earth" seems a strange name for our home world, 71% of which is covered by an ocean of water.

Think of oceanography as the story of the ocean. In this first chapter, the main character—the world ocean—is introduced with broad brushstrokes. We begin our investigation of the ocean with an overview of the scientific process 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 ocean world. 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 that Earth has seasons, a free-flowing atmosphere, a daily sunrise and sunset, a rocky ground, and that its characteristics change with the passage of time—none of these are 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 **(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; 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 1.1)**.

Traditionally, we have divided the ocean into artificial compartments called *oceans* and *seas*, using the boundaries of continents and relative position on the planet. 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 and 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 **(Figure 1.2)**.

> 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.**

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 (2,756 feet), but the average ocean depth is 4½ times greater! The ocean borders most of Earth's largest cities—nearly half of the planet's 7-plus 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.

Regardless of the scale in which it is viewed, the ocean's influence on the planet is undeniable. Weather patterns and regional microclimates are significantly affected by the ocean, as is the longer-term global climate. The ocean provides a variety of resources ranging from food and water to energy, construction materials, and life-saving pharmaceuticals. It supports a significant proportion of the biodiversity on the planet and has played a large role in human history and culture through both limiting and promoting trade and providing a means for transportation. The ocean gives us a sense of awe, offers inspiration, and provides many types of recreational opportunities for people all over the world.

[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.

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

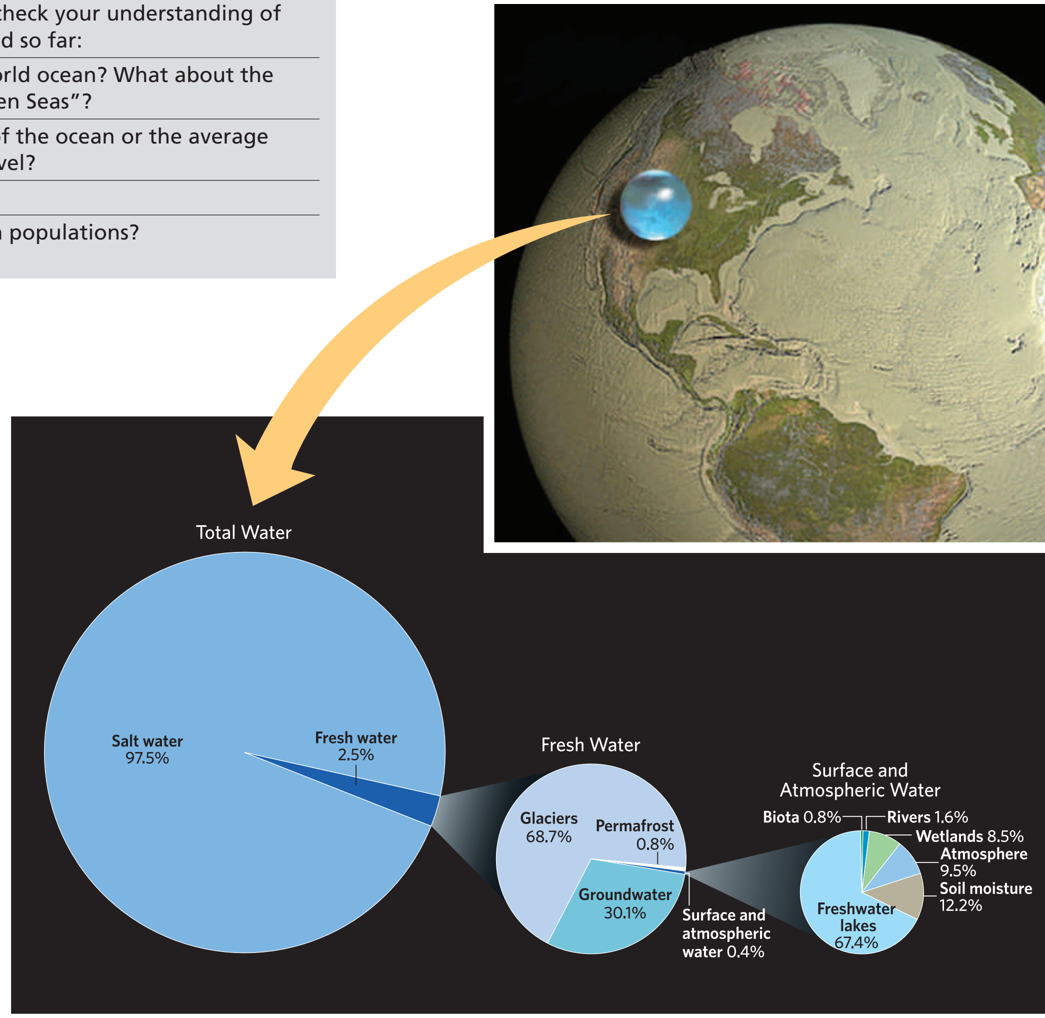
Table 1.1 Some Statistics for the World Ocean

- 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°C (39.0°F)
- 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

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's *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?
- How does the ocean influence human populations?



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

Figure 1.1 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?

Simon Dannhauer/Shutterstock.com

Figure 1.2 The ocean influences, and is influenced by, many of the other features on planet Earth. This Costa Rican beach is clearly shaped by a combination of elements including land, ocean, weather, wave energy, living organisms, and nonliving structures.

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

Oceanography (or **marine science**) is the scientific study of the ocean, its associated life-forms, and its bordering lands. Marine science draws on many disciplines, integrating the fields of geology, physics, biology, chemistry, astronomy, atmospheric science, anthropology, ecology, computer science, math, 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 disciplines 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.

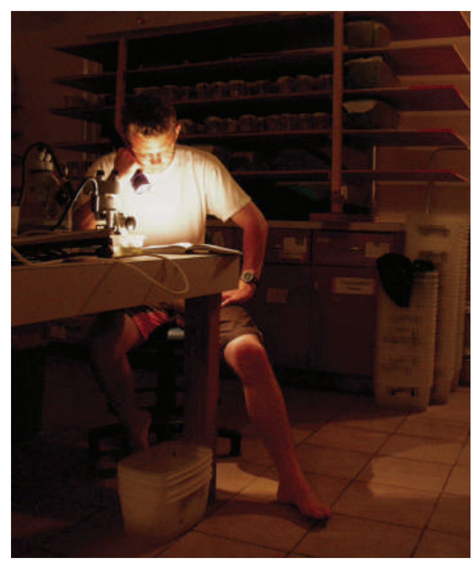
Other marine specialists study the techniques of weather forecasting, ways to increase the safety of navigation, methods to generate electricity, and much more. **Figure 1.3** shows marine scientists in action.[3]

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

[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 patterns to previously catalogued individuals.



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.

NOAA / National Marine Sanctuaries (Image: FGBNMS/Hickerson)

c This researcher is photographing sections of a reef to help monitor changes over time.

Figure 1.3 Doing marine science is sometimes anxiety-provoking, sometimes routine, and always interesting.

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.

Laws are principles explaining events in nature that have been observed to occur with unvarying uniformity under the same conditions. A law summarizes experimental observations in 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 way to conduct science. Some researchers observe, describe, and report on a subject and leave it to others to hypothesize. What is called the scientific method is also not a rigid method way of looking at an issue. The general method scientists 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 **(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 farther 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:

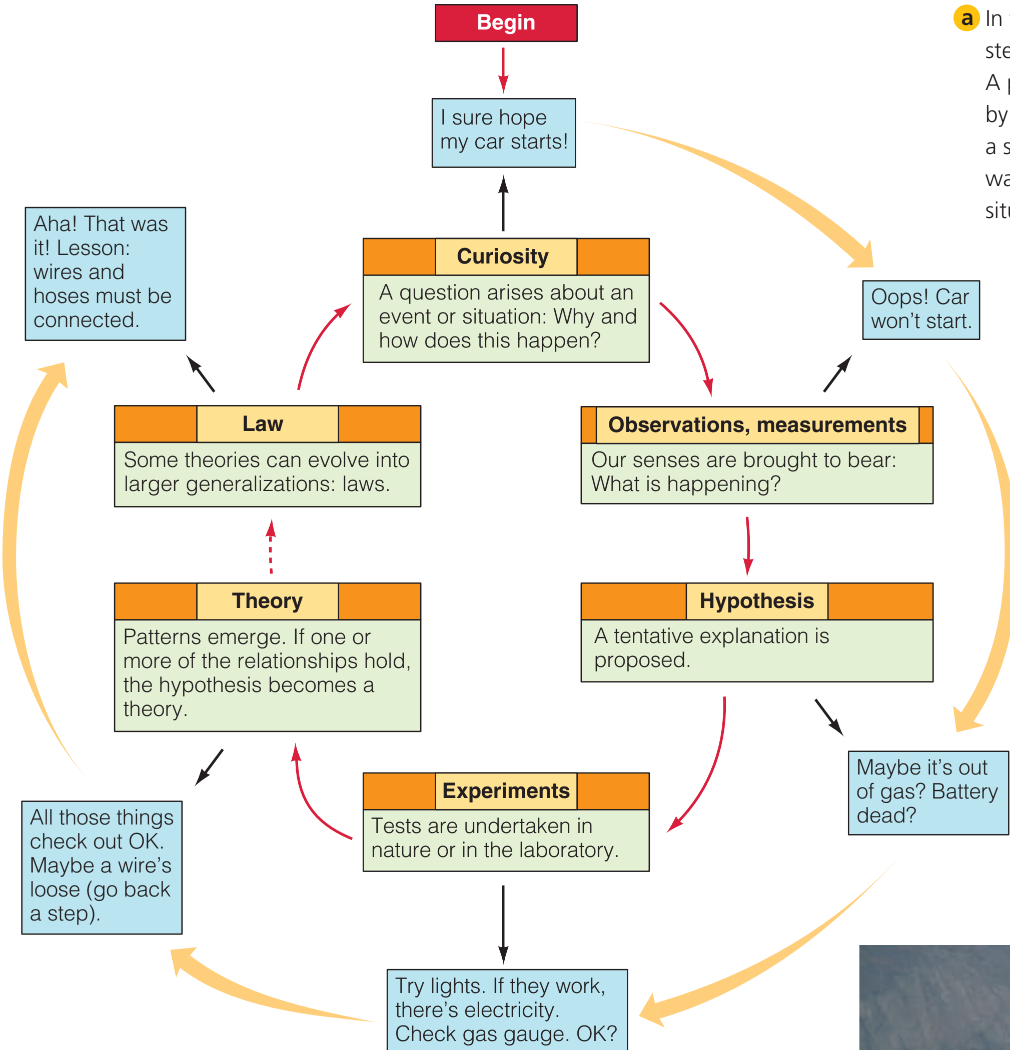
3. You know that cars need electricity to start. You turn on the lights. They work. Electricity is present. The problem is not a lack of electricity.
4. Cars need air to combine with fuel in the engine. Is air present? You take a breath. Air? Yes. The problem is not lack of air.
5. Cars need fuel. Is 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.
7. You put the wire back into place.
8. The car starts! Science wins! The question "Why?" is answered!

On the other hand, 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.

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

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. Our understanding



a In this over simplistic 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.

Tom Garrison

b The underlying method of science describes an attitude. Scientists like to be shown why an idea is correct, rather than simply 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 their high temperature of their tropical environment. They have a hypothesis and will design experiments to resolve it.

Figure 1.4 There is no single "scientific method."

THINKING BEYOND THE FIGURE

What's wrong with the following 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."

is continually evolving as we learn more from the scientific process, and thus the ideas and interpretations presented in books like this one will also continue to evolve. As you read the chapters to come, you will see examples of scientific thought in boxes labeled: "How Do We Know…?"

CONCEPT CHECK

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

What other scientific disciplines are commonly integrated into oceanography?

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.

The formation of Earth and ocean is a long and wonderful story—one we've only recently begun to understand. 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 converting hydrogen and helium to heavier elements including carbon, oxygen, silicon, and iron through the process of **nuclear fusion**. This process is also responsible for generating the light and heat that continues to influence everything from weather and currents to photosynthesis. As they die, some larger stars can produce even heavier elements and eject these materials 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.

1.3a 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 13.8 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 380,000 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.

1.3b 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*, or "milk").[4]

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 2 trillion galaxies in the universe and 100 million to a 100 billion stars in each galaxy. Imagine more stars in the Milky Way than grains of sand on a beach!

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

European Southern Observatory / 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?

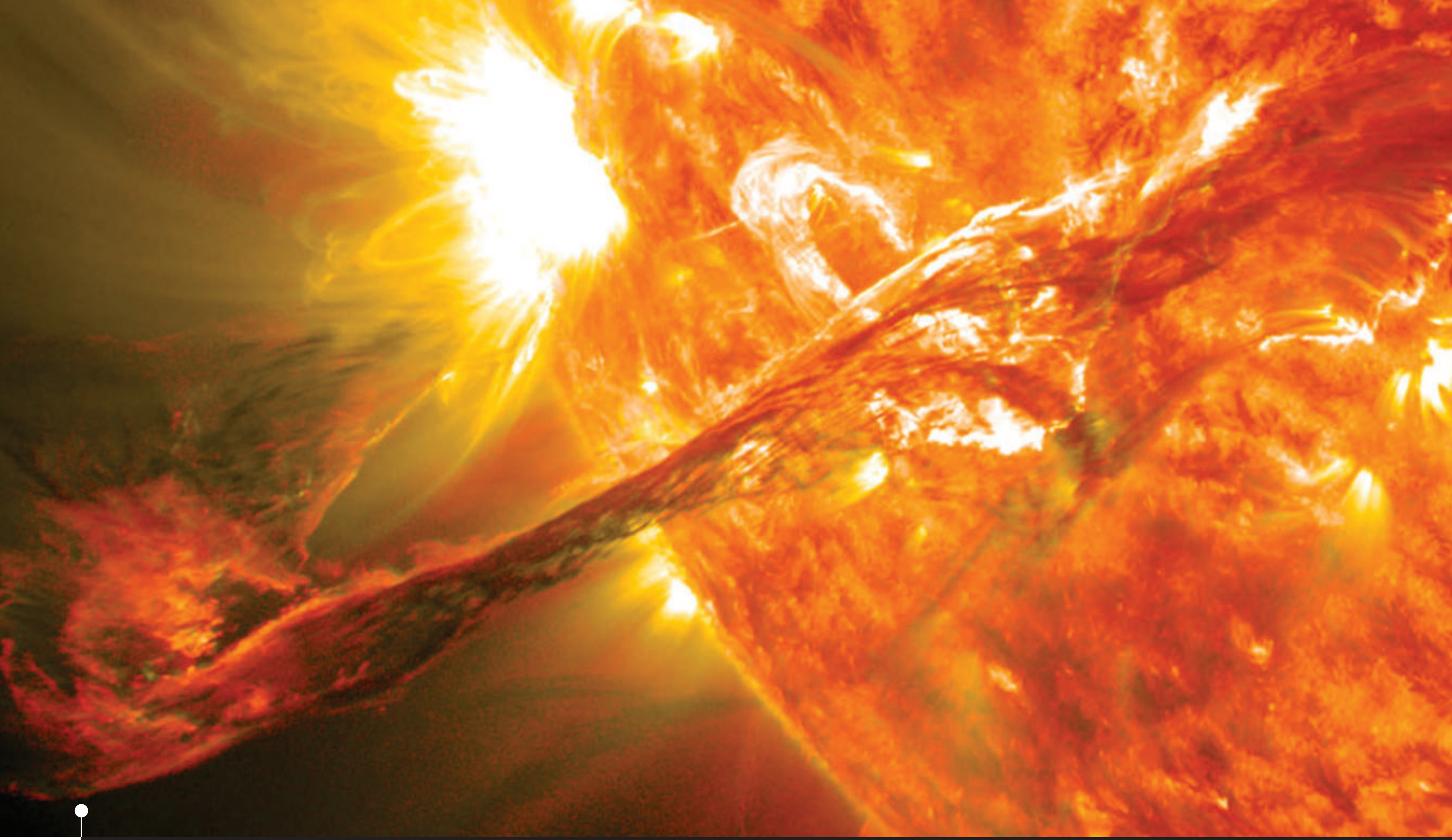


Figure 1.6 A filament of hot gas erupts from our sun's face in September 2012. Like all normal stars, our sun is powered by nuclear fusion—the welding together of small nuclei to make larger ones. These violent reactions generate the heat, light, matter, and radiation that pour from stars into space.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

Our sun is a typical star. 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 220 kilometers per second (half a million miles an hour). Earth has made about 20 circuits of the galaxy since the ocean formed.

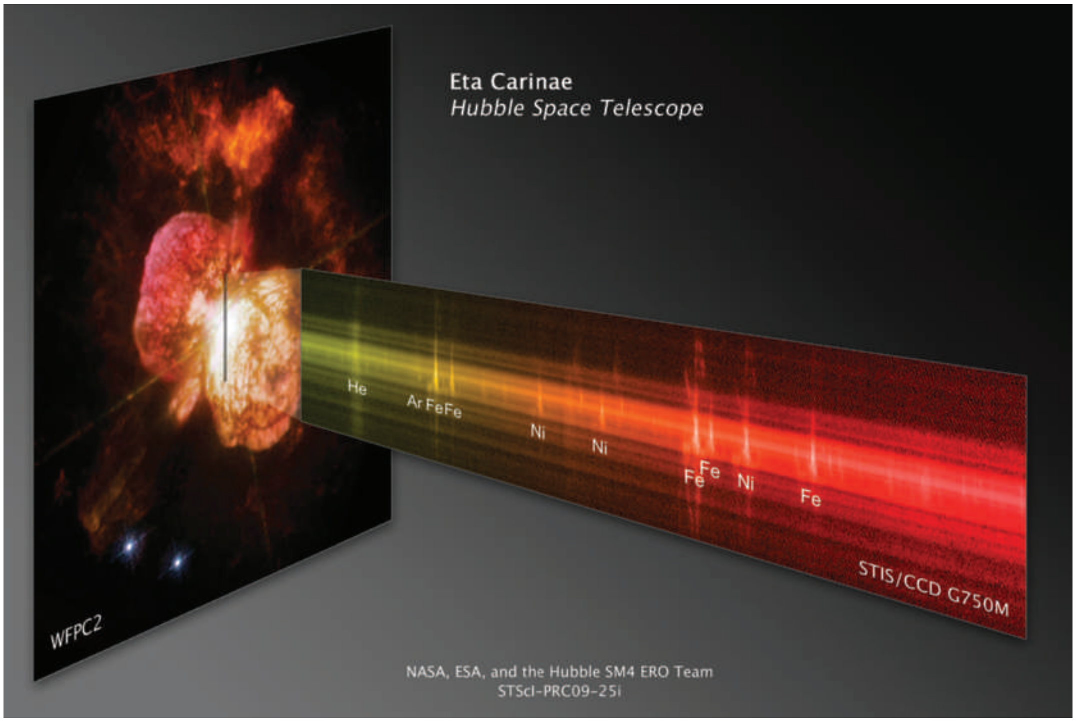
1.3c Stars Make Heavy Elements from Lighter Ones

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 gravity causes it to contract, and the compression raises its internal temperature. When the 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 in the form of light and heat. This rapid release of energy, which marks the transition from *protostar* to *star*, stops the young star's shrinkage.

After fusion reactions begin, the new star eventually 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 **(Figure 1.6)**.

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



NASA Images

Figure 1.7 The dispersion of heavy elements. Light from this huge exploding star reached Earth about 160 years ago. A spectrum of its light (the ribbon extending to the right) shows evidence of iron (Fe) and nickel (Ni) in its shattered atmosphere. In the distant future, it is possible that some of these elements might be swept into a new solar system.

THINKING BEYOND THE FIGURE

Why do you suppose an oceanography textbook begins with a discussion of the origin of heavy elements?

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 also 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 a ring, 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 1.7**). 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.

> **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.**

1.3d 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 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 her arms close to her body, 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.

New planets formed in the disk of dust and debris surrounding the young sun through a process known as

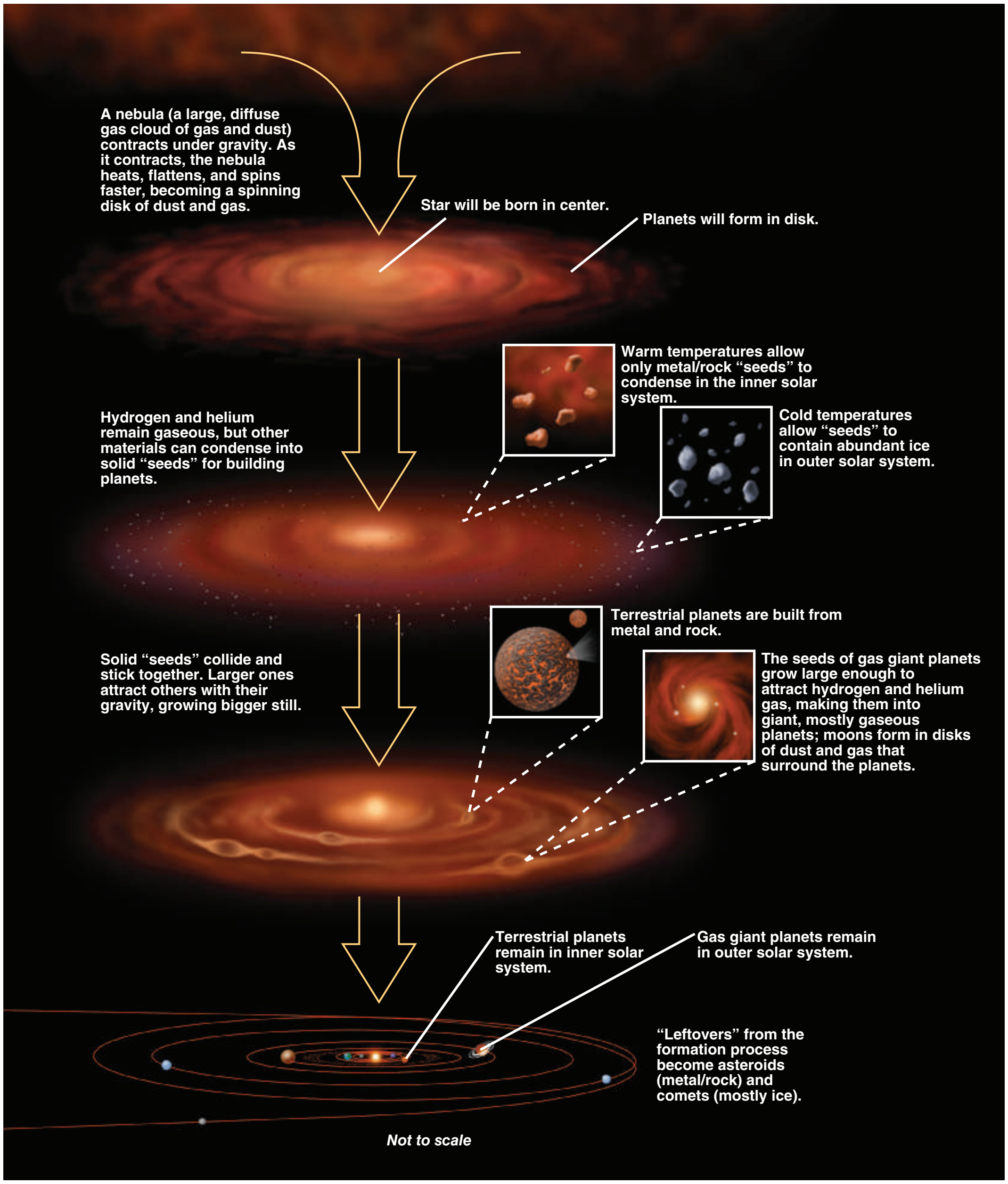


Figure 1.8 The origin of our solar system from the sun's birth to the formation of the inner terrestrial planets and outer gas giant planets.

accretion—the clumping of small particles into large masses. Bigger clumps with stronger gravity pulled in most of the condensing matter **(Figure 1.8)**. The **gas giant planets** of our outer solar system—Jupiter, Saturn, Uranus, and Neptune—were probably first to form. These giant planets are composed of mostly hydrogen and helium as well as methane and ammonia ices because those gases can congeal only at cold temperatures. Near the protosun, where temperatures were higher, the first materials to solidify were substances with high boiling points, mainly metals and certain rocky minerals. This formed the **terrestrial planets** of our inner solar system—Mercury, Venus, Earth, and Mars. The planet Mercury, closest to the sun, is mostly iron, because iron is a solid at high temperatures. Somewhat farther out, in the cooler regions, magnesium, silicon, water, and oxygen condensed. Methane and ammonia accumulated in the frigid outer zones. Earth's array of water, silicon-oxygen compounds, and metals results from its middle position within that accreting cloud.

The period of accretion lasted perhaps 30 to 50 million years. The protosun became a star—our sun—when its internal temperature rose high enough to fuse atoms of hydrogen into helium. The violence of these nuclear reactions sent a solar wind of radiation sweeping past the inner planets, clearing the area of excess particles and ending the period of rapid accretion. Gases like those we now see on the giant outer planets may once have surrounded the inner planets, but this rush of solar energy and particles stripped them away.

This process is probably not rare. Thousands of planets outside our solar system have already been discovered.[5] Estimates suggest that every star has at least one planet

[5]As of early 2020, there were 4,141 planets (in 3,072 planetary systems, including 1,763 multiple planet systems) identified and the list is being constantly updated.

orbiting it, and there are approximately 8.8 billion stars in the Milky Way galaxy with Earth-size planets that likely orbit in habitable zones. How many are ocean worlds?

CONCEPT CHECK

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

Can scientific inquiry probe further back in time than the big bang?

What element makes up most of the detectable mass in the universe? How are the other elements up to the weight of iron formed?

How does the light and heat given off as a byproduct of nuclear fusion affect our ocean?

Outline the main points in the condensation theory of star and planet formation.

Explain why the outer gas giant planets of our solar system look so much different than the inner terrestrial planets.

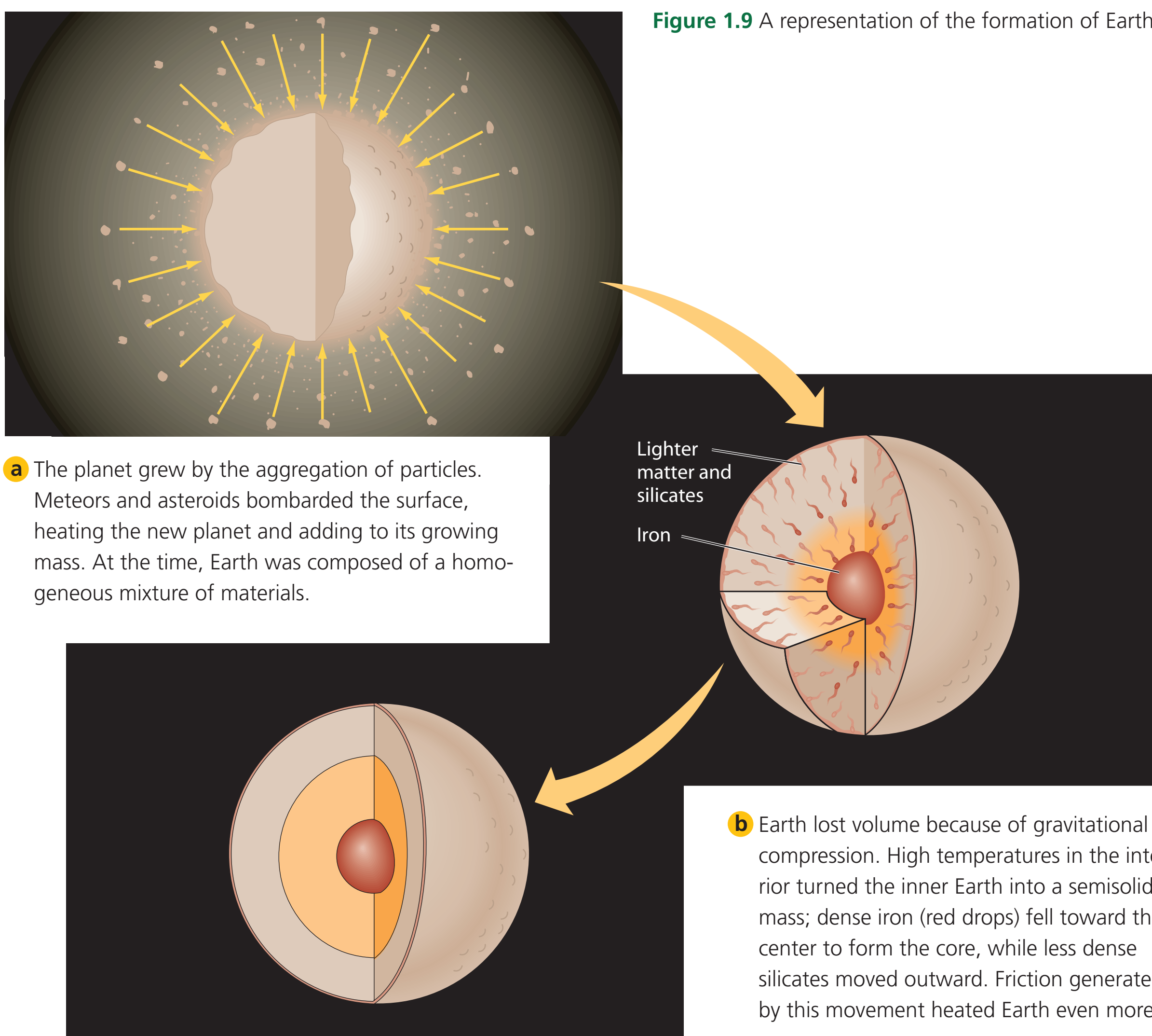
Trace the life of a typical star.

How are the heaviest elements (uranium or gold) thought to be formed?

1.4 Earth, Ocean, and Atmosphere Accumulated in Layers Sorted by Density

The young Earth, formed by the accretion of cold particles, was probably chemically homogeneous throughout. In the midst of the accretion phase, Earth's surface was heated by the impact of asteroids, comets, and other falling debris. This heat, combined with gravitational compression and heat from decaying radioactive elements accumulating deep within the newly assembled planet, caused Earth to partially melt. Gravity pulled most of the iron and nickel inward to form the planet's core. The sinking iron released huge amounts of gravitational energy, which, through friction, heated Earth even more. At the same time, a slush of lighter minerals—silicon, magnesium, aluminum, and oxygen-bonded compounds—rose toward the surface, forming Earth's crust **(Figure 1.9)**.

Figure 1.9 A representation of the formation of Earth.



a The planet grew by the aggregation of particles. Meteors and asteroids bombarded the surface, heating the new planet and adding to its growing mass. At the time, Earth was composed of a homogeneous mixture of materials.

b Earth lost volume because of gravitational compression. High temperatures in the interior turned the inner Earth into a semisolid mass; dense iron (red drops) fell toward the center to form the core, while less dense silicates moved outward. Friction generated by this movement heated Earth even more.

c The result of *density stratification* is evident in the formation of the inner and outer core, the mantle, and the crust.

NASA/JPL-Caltech

a The first stage of the formation of the moon. A planetary body somewhat larger than Mars is thought to have smashed into the young Earth about 4.4 billion years ago.

MARK GARLICK / Science Source

b The rocky mantle of the impactor was ejected to form a ring of debris around Earth, and its metallic core fell into Earth's core and joined with it. This figure illustrates the stages of the moon's formation.

NASA

c Rocks brought from the lunar surface by Apollo astronauts suggest the ejected material condensed soon after to become our moon. This photo was taken from the Apollo 11 spacecraft on its journey home.

Figure 1.10 The formation of the moon.

THINKING BEYOND THE FIGURE

What do you think Earth would be like without its moon?

This important process, called **density stratification**, lasted perhaps 100 million years.[6]

Then Earth began to cool. Its first surface is thought to have formed about 4.6 billion years ago. That surface did not remain undisturbed for long. Shortly after its formation, a planetary body somewhat larger than Mars smashed into the young Earth. The metallic core fell into Earth's core and joined with it, while most of the rocky mantle was ejected to form a ring of debris around Earth. The debris began condensing soon after and became our moon **(Figure 1.10)**.[7] While this was a cataclysmic event at the time, the impact and subsequent formation of our moon played a critical role in creating the tides (see Chapter 11) and stabilizing our axial tilt which helped to moderate seasonal shifts. Could a similar event happen today? The issue is addressed in section 13.3 of Chapter 13.

Radiation from the energetic young sun had stripped away our planet's outermost layer of gases, its first atmosphere, but soon gases that had been trapped inside the forming planet burped to the surface to form a second atmosphere. This volcanic venting of volatile substances—including water vapor—is called **outgassing (Figure 1.11a)**. Volcanic outgassing brought much of the water for Earth's ocean to the planet's surface. The impact of water-containing bodies from space (primarily asteroids and some comets) likely delivered additional water, which was freed during the fiery impacts **(Figure 1.11b)**.[8] As the hot vapors rose, they condensed into clouds in the cool upper atmosphere.

[6]**Density** is an expression of the relative heaviness of a substance; it is defined as the mass per unit volume, usually expressed in grams per cubic centimeter (g/cm^3). The density of pure water is 1 g/cm^3. Granite rock is about 2.7 times denser, at 2.7 g/cm^3.

[7]Recent studies have suggested that there are other scenarios that explain the compositional similarities between the Earth and the moon. Additional research is needed to confirm the likelihood of these proposals.

[8]Isotopic ratios suggest that the water found in asteroids is a better match to the water in our ocean than that of comets. Therefore, current evidence points to asteroids as a more likely source of the majority of water that was delivered from impacting bodies.

a Outgassing. Volcanic gases add water vapor, carbon dioxide, nitrogen, and other gases to the atmosphere. Volcanism was a major factor in altering Earth's original atmosphere; later, the action of photosynthetic bacteria and plants was another.

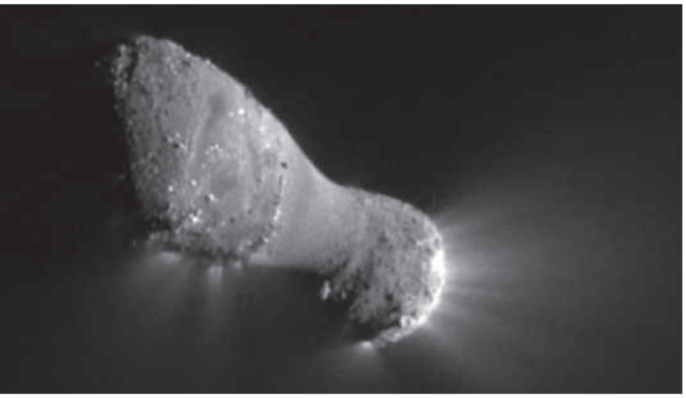
Tom Garrison

Figure 1.11 Sources of the ocean.

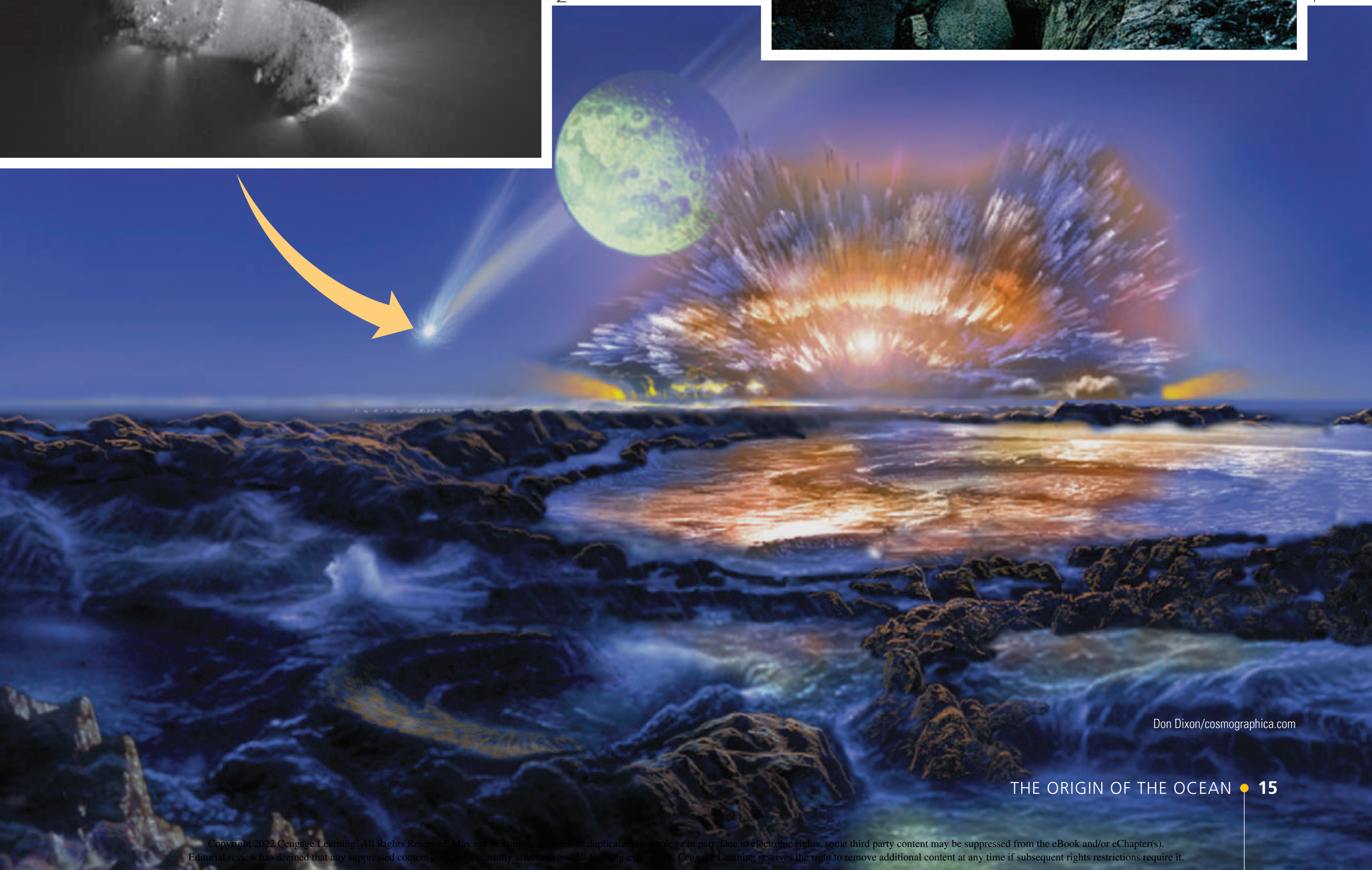
THINKING BEYOND THE FIGURE

Do you think the volume of the ocean is increasing, decreasing, or staying about the same over long periods of time?

b Asteroids and comets may have delivered some of Earth's surface water. Intense bombardment of the early Earth by large these bodies probably lasted until about 3.8 billion years ago. The inset shows a close-up of the nucleus of Comet Hartley-2 taken by the *EPOXI* spacecraft in November, 2010. Frozen carbon dioxide and water ice can be seen jetting from its surface.



NASA/JPL-Caltech/UMD



Don Dixon/cosmographica.com

Earth's surface was so hot that no water could collect there, and no sunlight could penetrate the thick clouds. (A visitor approaching from space 4.4 billion years ago would have seen a vapor-shrouded sphere blanketed by lightning-stroked clouds.) After millions of years, the upper clouds cooled enough for some of the outgassed water to form droplets. Hot rains fell toward Earth, only to boil back into the clouds again. As the surface became cooler, water collected in basins and began to dissolve minerals from the rocks. Some of the water evaporated, cooled, and fell again, but the minerals remained behind. The salty world ocean was gradually accumulating.

These heavy rains may have lasted about 20 million years. Large amounts of water vapor and other gases continued to escape through volcanic vents during that time and for millions of years thereafter. The ocean grew deeper. Evidence suggests that Earth's crust grew thicker as well, perhaps in part from chemical reaction with oceanic compounds.

What was the temperature of the young ocean? Earth's surface temperature has fluctuated since the ocean's formation, but the extent of that fluctuation is another area of controversy. For the first chaotic quarter-billion years, the seas would have been hot and precipitation nearly constant, but that condition did not persist. Temperature variations have been common. Some scientists, for example, believe that the early sun's energy output was about 30% less than it is today. The ocean should have frozen. But differences in the quantity and composition (and even the shape) of particles and volcanic gases in Earth's atmosphere allowed heat to be retained and apparently permitted the ocean's surface to remain largely liquid for the next billion years. Colder periods followed, perhaps freezing the ocean to considerable depth (even at the equator) between 800 and 550 million years ago. Although we are presently unsure of the details, scientists are certain that climate change—often *drastic* climate change—has been a feature of Earth since the beginning.[9]

The composition of the early atmosphere was much different from today's. Geochemists believe it may have been rich in carbon dioxide, nitrogen, and water vapor, with traces of ammonia and methane. Beginning about 3.5 billion years ago, this mixture began a gradual alteration to its present composition, mostly nitrogen and oxygen. At first this change was brought about by carbon dioxide dissolving in seawater to form carbonic acid which then combined with crustal rocks. The chemical breakup of water vapor by sunlight high in the atmosphere also played a role. About 1.5 billion years later, the ancestors of today's green plants produced—by photosynthesis—enough oxygen to oxidize minerals dissolved in the ocean and surface sediments. Additional oxygen than began to diffuse into the air and accumulate in the atmosphere. (This monumental event in Earth's history is called the *oxygen revolution*. You'll read about it in Chapter 13.)

[9]You'll find more on the specific topic of recent climate change in Chapters 8 and 18.

CONCEPT CHECK

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

What is density stratification?

How old is Earth? How do we know?

How was the moon formed?

Why is the presence of our moon important to ocean processes and marine life that will be studied throughout this book?

Is the world ocean a comparatively new feature of Earth, or has it been around for most of Earth's history?

Is Earth's present atmosphere similar to or different from its first atmosphere?

1.5 Life Is Tied to the Ocean

Life, at least as we know it, would be inconceivable without large quantities of water. Water can retain heat, moderate temperature, dissolve many chemicals, and suspend nutrients and wastes. These characteristics make it a mobile stage for the intricate biochemical reactions that allowed life to begin and prosper on Earth.

Life on Earth is formed of aggregations of a few basic kinds of carbon compounds. Where did the carbon compounds come from? There is growing consensus that most of the organic (that is, carbon containing) materials in these compounds were transported to Earth by the comets, asteroids, meteors, and interplanetary dust particles that crashed into our planet during its birth. The young ocean was a thin broth of organic and inorganic compounds in solution.

In laboratory experiments, mixtures of dissolved compounds and gases thought to be similar to Earth's early atmosphere have been exposed to light, heat, and electrical sparks. These energized mixtures produce simple sugars and a few of the biologically important amino acids. They even produce small proteins and nucleotides (components of the molecules that transmit genetic information between generations). The main chemical requirement seems to be the absence (or near absence) of free oxygen, a compound that can disrupt any unprotected large molecule.

Did *life* form in these experiments? No. The compounds that formed are only building blocks of life. But the experiments do tell us something about the commonality and unity of life on Earth. The facts that these crucial compounds can be synthesized so easily and are present in virtually all living forms are probably not coincidental. Those compounds are "permitted" by physical laws and by the chemical composition of this planet. The experiment also underscores the special role of water in life processes. The fact that all life, from a jellyfish to a dusty desert weed, depends on saline water within its cells to dissolve and transport chemicals

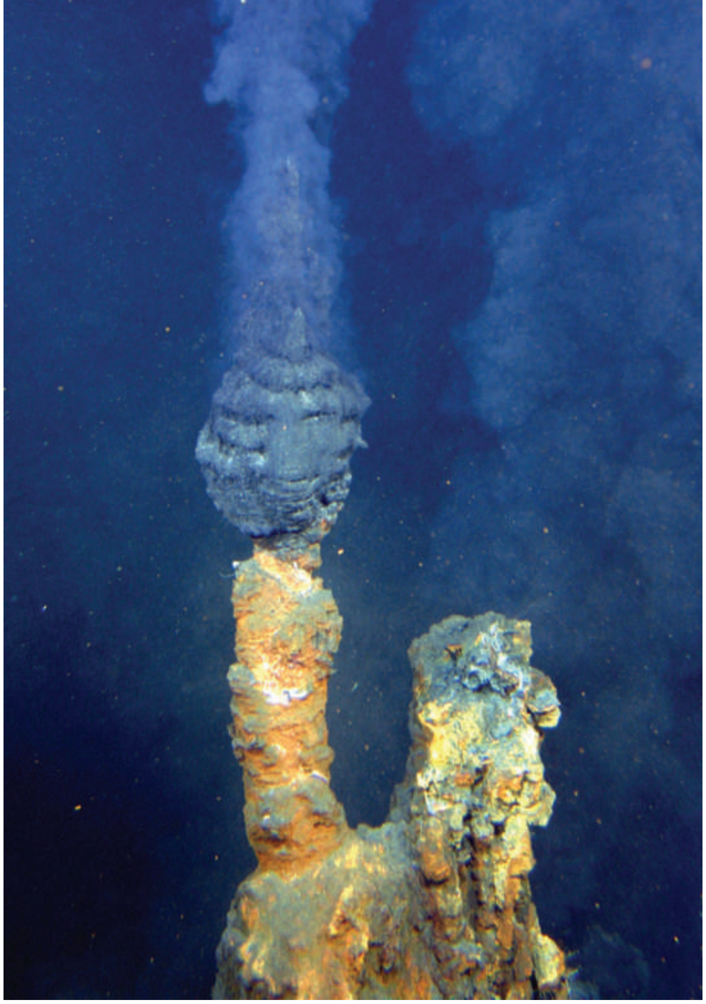


Figure 1.12 An environment for biosynthesis? Weak sunlight and unstable conditions on Earth's surface may have favored the origin of life on mineral surfaces near deep-ocean hydrothermal vents similar to the one shown here. In ancient vents, alkali hydrothermal fluids mixed with more acidic ocean waters to create a proton gradient. This gradient is remarkably similar to the way cells pump protons across their membrane to harness energy.

Image courtesy of New Zealand American Submarine Ring of Fire 2007 Exploration, NOAA Vents Program, the Institute of Geological & Nuclear Sciences and NOAA-OE

Photo by Department of Earth & Space Sciences/ UCLA

Figure 1.13 Fossil of a bacteria-like organism (with an artist's reconstruction) that photosynthesized and released oxygen into the atmosphere. Among the oldest fossils ever discovered, this microscopic filament from northwestern Australia is about 3.5 billion years old.

is certainly significant. It strongly suggests that simple, self-replicating—living—molecules arose somewhere in the early ocean. It also strongly suggests that all life on Earth is of common origin and ancestry.

The early steps in the evolution of living organisms from simple organic building blocks, a process known as **biosynthesis**, are still speculative. As noted above, planetary scientists suggest that the sun was faint in its youth. Perhaps Earth's atmospheric haze was opaque enough to block ultraviolet radiation that would have hindered the formation of complex molecules (and therefore life) at the ocean surface. The first living molecules might have arisen at great depths on clays or pyrite crystals at mineral-rich seeps on the ocean floor **(Figure 1.12)**.

A similar biosynthesis seems unlikely to occur today. Living things have changed the conditions in the ocean and atmosphere, and those changes are not consistent with any new origin of life. For one thing, green plants have filled the atmosphere with oxygen. For another, some of this oxygen (as ozone) now blocks most of the dangerous wavelengths of light from reaching the surface of the ocean. And finally, the many tiny organisms present today would gladly scavenge any large organic molecules as food.

How long ago might life have begun? The oldest fossils yet found, from northwestern Australia, are between 3.4 and 3.5 billion years old **(Figure 1.13)**. They are remnants of fairly complex bacteria-like organisms, indicating that life must have originated even earlier, probably only a few hundred million years after a stable ocean formed. Evidence of an even more ancient beginning has been found in the form of carbon-based residues in some of the oldest rocks on Earth, from Akilia Island near Greenland. These 3.85-billion-year-old specks of carbon bear a chemical fingerprint that many researchers feel could only have come from a living organism. Life and Earth have grown old together; each has greatly influenced the other.

Life on Earth almost certainly evolved in the ocean; the cells of all life forms are still bathed in salty fluids.

HOW DO WE KNOW? 1.1

The Age of Earth and the Ocean?

The age estimates presented in this chapter (and the ones that follow) are derived from data obtained by many researchers using different sources and techniques. One source is meteorites, chunks of rock and metal formed at about the same time as the sun and planets and out of the same cloud. Many have fallen to Earth in recent times. We know from signs of radiation within these objects how long it has been since they were formed. That information, combined with the rate of radioactive decay of unstable atoms in meteorites, moon rocks, and in the oldest rocks on Earth, allows astronomers to make reasonably accurate estimates of how long ago these objects formed.[10]

Remnants of Earth's early surface are rare because (as you'll discover in Chapter 3) nearly all of that material has been recycled into our planet's interior. In 2008, geologists exploring the eastern shore of Hudson Bay in northern Quebec encountered greenish-gray rocks that appeared to be of great age. Those rocks have been dated to about 3.9 billion years old. Small grains of zircon **(Figure A)** found within similar rocks in Australia are even older—some of them appear to be 4.37 billion years old (and so must have formed soon after the moon-forming impact). Inclusions of quartz trapped within the zircons as they crystallized suggest that they formed within molten material rich in dissolved water and silica—evidence that early Earth cooled relatively quickly after the moon formed and supported substantial bodies of surface water. Other Canadian rocks contain 3.85-billion-year-old specks of carbon that bear a chemical fingerprint that many researchers feel could only have come from a living organism.

As for the age of the universe itself, by April 2002, astronomers had obtained very accurate measurements of its rate of expansion. By calculating backward, they found the universe would have begun its expansion 13.8 billion years ago.[11] However, some estimates suggest the universe may actually being up to 2 billion years younger.

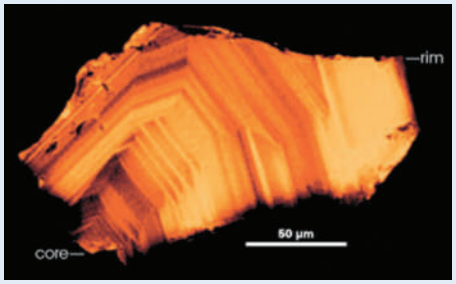


Figure A Small grains of zircon found in rocks in Australia appear to be 4.37 billion years old.

CONCEPT CHECK

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

Are the atoms and basic molecules that compose living things different from the molecules that make up nonliving things? Where were the atoms in living things formed?

How old is the oldest evidence for life on Earth? On what are those estimates based?

Was Earth's atmosphere rich in oxygen when life originated here? How did that oxygen get here?

1.6 What Will Be Earth's Future?

Our descendants may enjoy another 5 billion years of life on Earth as we know it today. But then our sun, like any other star, will begin to die. The sun is not massive enough to become a supernova, but after a billion-year cooling period, the reenergized sun's red giant phase will engulf the inner planets. Its fiery atmosphere will expand to a radius greater than Earth's orbit. The ocean and atmosphere, all evidence of life, the crust, and perhaps the whole planet will be recycled into component atoms and hurled by shock waves into space (as in **Figure 1.14**). Our successors, if any, will have perished or fled to safer worlds. Its fuel exhausted and its energies spent, the sun will cool to a glowing ember and ultimately to a dark cinder. Perhaps a new system of star and planets will form someday from the debris of our remains.

A timeline that shows the history of past and future Earth appears in **Figure 1.15**.

CONCEPT CHECK

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

Have the particles that make up the atoms of your body existed for nearly all of the age of the universe?

What will eventually happen to the Earth and ocean once the sun begins to run out of fuel?

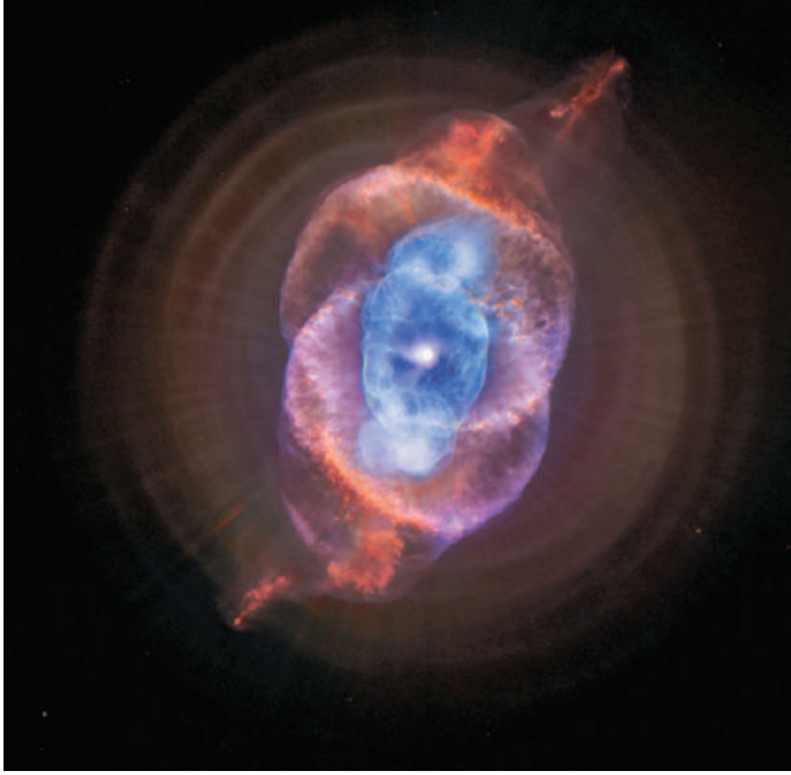
[10]For information on radiometric dating, please see "How Do We Know? 3.1".

[11]By the way, regardless of surprisingly persistent opinion, essentially no evidence supports the contention that Earth is between 6,000 and 10,000 years old.

Figure 1.14 The end of a solar system? This glowing gas in this beautiful nebula once formed the outer layers of a sun-like star that exploded only 15,000 years ago. The inner loops are being ejected by a strong wind of particles from the remnant central star. If planets orbited this star, their shattered remnants are contained in the outward-rushing filaments at the periphery. Perhaps 5 billion years from now, observers 5,000 light years away would see a similar sight as our sun passes the end of its life.

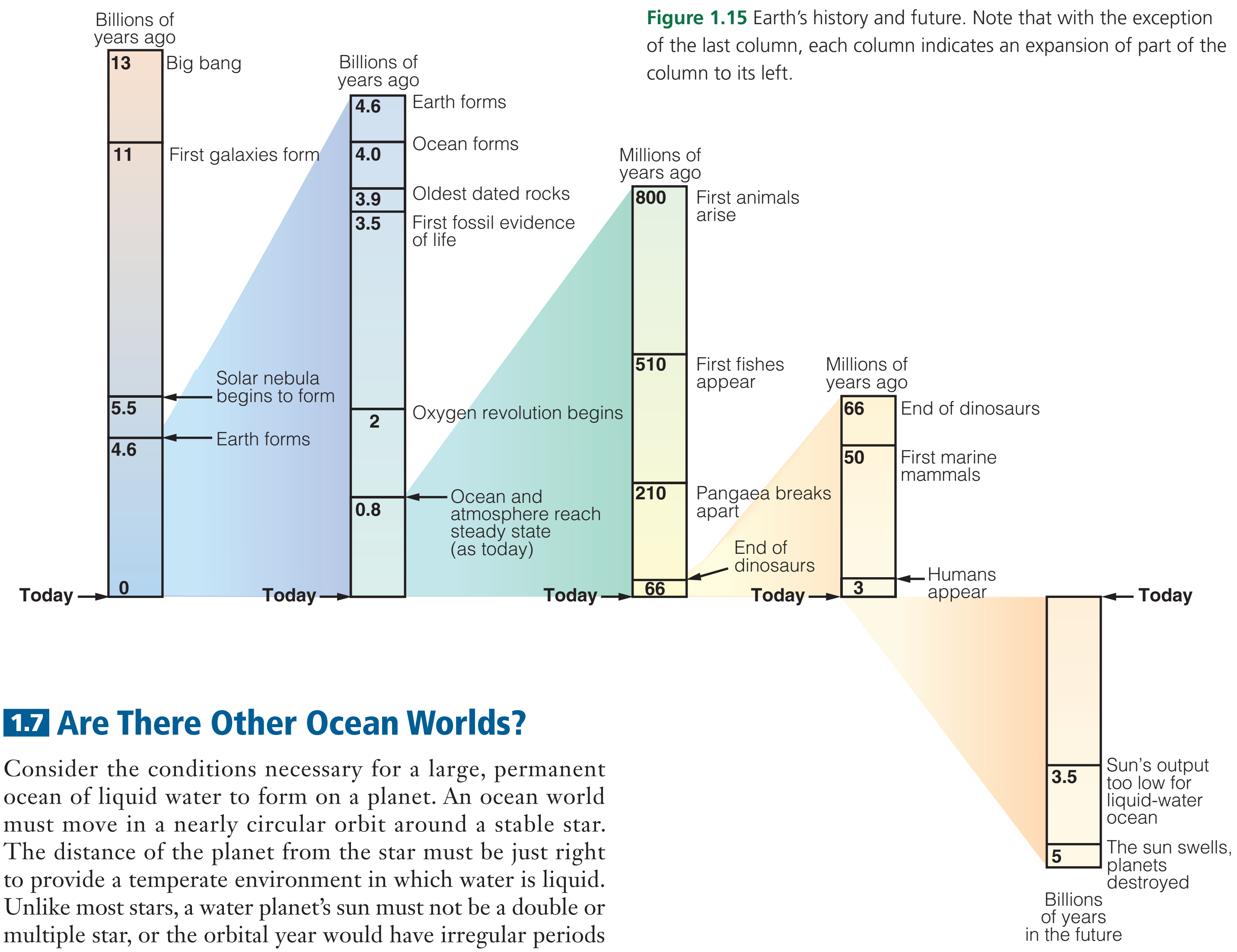
THINKING BEYOND THE FIGURE

Think of the long history of the atoms in your eyes that allow you to read and comprehend this sentence. Now think of their potential future. You might begin to sense something called "deep time."



NASA, ESA, HEIC, and The Hubble Heritage Team (SYSci/AURA)

Figure 1.15 Earth's history and future. Note that with the exception of the last column, each column indicates an expansion of part of the column to its left.



NASA

1.7 Are There Other Ocean Worlds?

Consider the conditions necessary for a large, permanent ocean of liquid water to form on a planet. An ocean world must move in a nearly circular orbit around a stable star. The distance of the planet from the star must be just right to provide a temperate environment in which water is liquid. Unlike most stars, a water planet's sun must not be a double or multiple star, or the orbital year would have irregular periods of intense heat and cold. The materials that accreted to form the planet must have included both water and substances capable of forming a solid crust. The planet must be large enough that its gravity will keep the atmosphere and ocean from drifting off into space.

Earth is currently the only planet that we know of with a liquid water ocean flowing continuously on its surface. However, water itself is not scarce. Scientists have found many other places in the universe that have water in other phases or locations including within distant nebulas and even water molecules drifting free in space. The Orion Nebula alone is thought to create nearly 60 times more water than we have in our entire world ocean each day! Within our solar system, we have evidence that there are large amounts of water and ice in the interiors and atmospheres of the four gas giant planets.Jupiter alone has hundreds of times as much water as Earth does, nearly all of it in the form of ice. The recent *New Horizons* mission to the dwarf planet Pluto even found mountains made from water ice with active glaciers of nitrogen on their slopes. Evidence suggests that there is likely a deep ocean beneath the thick layers of surface ice.

A new generation of NASA (National Aeronautics and Space Administration) missions are starting to focus on the moons of the gas giant planets where vast subsurface oceans are believed to exist. While many of these moons are too far away from the sun to receive enough energy, their elliptical orbits create tidal forces that generate enough internal heat to keep water in its liquid form beneath the surface ice.

Although it might be a bit premature to consider "comparative oceanography" as a career choice, researchers are increasingly certain that liquid water exists (or existed quite recently) on multiple other bodies in our solar system. We can begin to compare and contrast them.

1.7a The Moons of Jupiter and Saturn

Both Jupiter and Saturn are large gas giant planets with dozens of moons. Of these moons, five of them are believed to have subsurface oceans: Jupiter's moons Europa, Ganymede, and Callisto as well as Saturn's Enceladus and Titan.

The spacecraft *Galileo* passed close to Europa—a moon of Jupiter—in early 1997. Photos sent to Earth revealed a cracked, icy crust covering what appears to be a slushy mix of ice and water **(Figure 1.16)**. *Galileo* also detected a distinctive magnetic field, the signature of a salty liquid-water ocean below the ice.

The volume of this ocean is astonishing. Though Europa is slightly smaller than our own moon, its ocean averages about 160 kilometers (100 miles) deep. The amount of water in its ocean is perhaps 40 times that of Earth's! Europa's ocean is probably kept liquid by heat escaping Europa's interior and by gravitational friction of tidal forces generated by Jupiter itself. Though the surface of ice is about 8 kilometers (5 miles) thick and as cold as the surface of Jupiter, the liquid interior of the ocean, cradled deep in rocky basins, may be warm enough to sustain life. No continents emerge from this alien sea.

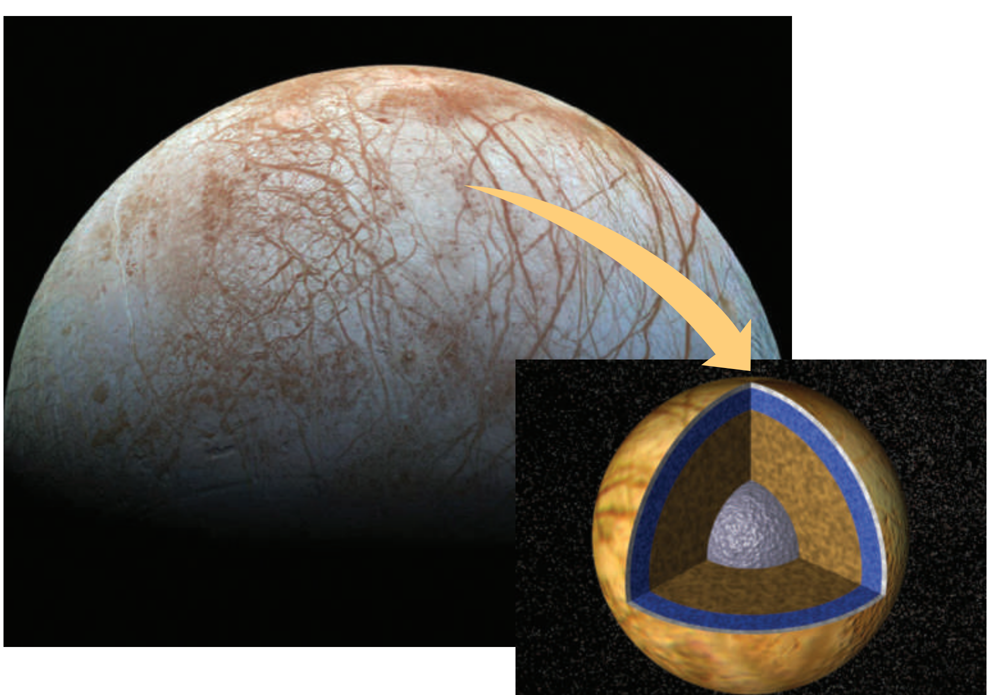
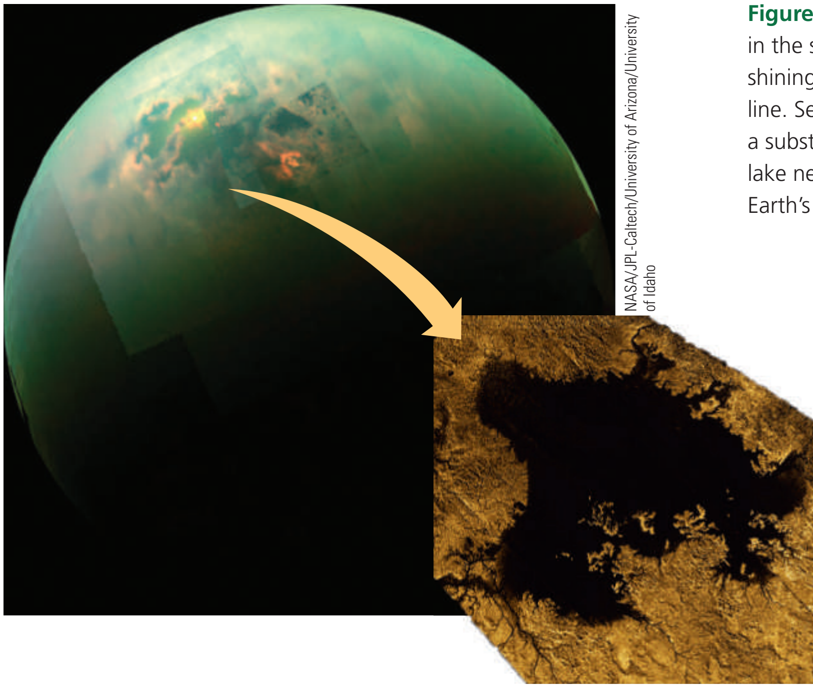


Figure 1.16 The icy, fractured crust of Europa shrouds a potential salty ocean of ice (white cross section) and liquid water (blue cross section) hidden beneath.



NASA/JPL-Caltech/University of Arizona/University of Idaho

NASA/JPL-Caltech/ASI/Cornell

Figure 1.17 The face of Saturn's moon, Titan, the only other body in the solar system known to possess liquid on its surface. Sunlight is shining on the edge of a huge circular storm just below the day/night line. Seas of liquid methane or ethane, seen as dark patches, cover a substantial portion of this large moon's surface. The inset shows a lake near Titan's north pole. It is a bit larger than Lake Superior, one of Earth's largest lakes.

A mission known as the *Europa Clipper* is now being planned to investigate the structure and composition of its interior.

Ganymede, Jupiter's largest satellite, was surveyed by *Galileo* in May 2000; the photographs showed structures strikingly similar to those on Europa. Again, magnetometer data suggested a salty ocean beneath a moving, icy crust.

Between 2005 and 2015, the *Cassini* spacecraft flew close behind Saturn's moon Enceladus. From this vantage point *Cassini*'s cameras detected fountains of ice crystals shooting from gashes on the small moon's surface. The relative warmth of the plumes and the detection of accompanying molecules of methane and carbon dioxide suggest another encrusted liquid-water ocean. To learn more about this the mission to Enceladus, see the Interdisciplinary Connection feature at the end of this chapter.

Must an ocean consist of liquid water? Hydrocarbons have been seen on the surface of Titan, Saturn's largest moon. In addition to harboring a suspected salty ocean under its icy shell, Titan appears to have a cold liquid surface sea of methane, ethane, and other hydrocarbons complete with islands, bays, and peninsulas **(Figure 1.17)**. In early January 2005, *Cassini* detached a small probe (named *Huygens* in honor of the Dutch astronomer who discovered this moon) to travel to Titan. Its cameras photographed drainage channels and other continental details before becoming the first probe to land on a moon in the outer solar system.

1.7b Mars

While some of the moons of Jupiter and Saturn appear to have icy subsurface oceans now, Mars, a much nearer neighbor, may have had an ocean flowing on its surface in the distant past **(Figure 1.18a)**. An ocean could have occupied the low places of the northern hemisphere of Mars between 3.2 and 1.2 billion years ago when conditions were warmer. Current models suggest that early in its history, Mars had a thick atmosphere rich in carbon dioxide, much like the atmosphere of early Earth. Carbon dioxide is a greenhouse gas—it traps the sun's heat like the glass panels of a greenhouse. The atmosphere kept Mars warm and allowed water to flow freely. In 2012, a camera aboard the Mars rover *Curiosity* sent photos from the surface showing clear evidence that water once flowed there. **Figure 1.18b** shows a fractured outcrop of smoothed streambed rock with surfaces eroded by water-driven pebbles. Some bits of gravel at the left of the frame show the characteristic rounded shapes that result from turbulence in stream flow.

Where is the water now? Over the eons, rocks on the Martian surface absorbed the carbon dioxide, and the atmosphere grew thin and cold. The ocean disappeared, its water binding to rocks or freezing beneath the planet's surface. Mars has become much colder in the past billion years, perhaps because of the loss of greenhouse gases in the atmosphere. If a large quantity of water is present today, most of it probably lies at the poles. In 2008, the *Phoenix* lander excavated to permafrost beneath a thin layer of sediment in the northern Martian arctic plain.

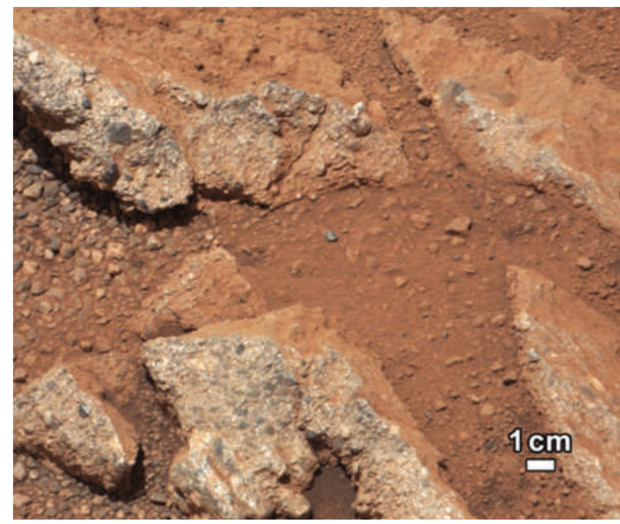
In 2015, NASA released photographs from *Mars Reconnaissance Orbiter* that showed liquid water still intermittently flows down some steep crater slopes during the warmer seasons **(Figure 1.18c)**.

1.7c Extrasolar Planets

As noted earlier, every star may average at least one planet orbiting it. Most of these planets were found either by watching for a star to dim slightly as a planet passed in front of it, often called the *transit method*, or by watching the wobbling path a star takes through space when influenced by the gravity of a massive companion planet. One of these *exoplanets* was directly imaged in 2010, but

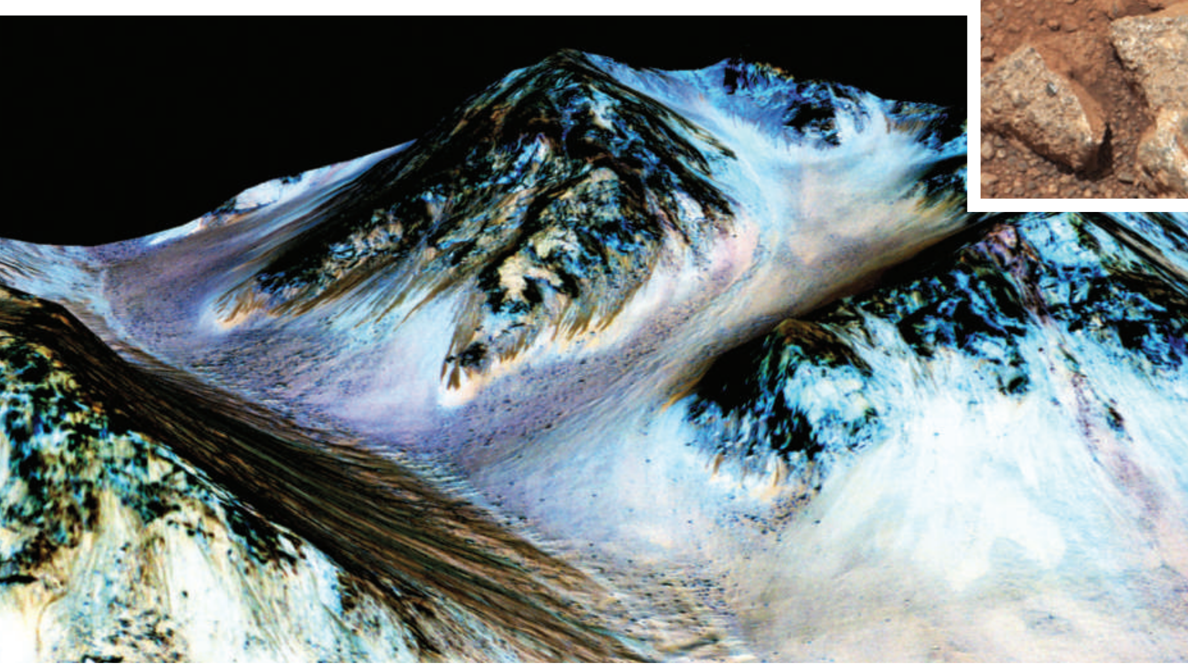
Kees Veenenbos / Science Source

a An artist imagines a wet Mars. The outflow from Mariner Valley into a hypothetical northern hemisphere ocean is shown here.



NASA Images

b In September of 2012, Mars *Curiosity* rover photographed a fractured outcrop of smoothed streambed rock with surfaces eroded by water-driven pebbles. Some bits of gravel at the left of the frame show the characteristic rounded shapes that result from turbulence in stream flow, evidence of a once-wet Mars.



NASA

c This false-color, processed image was taken by Mars *Reconnaissance* orbiter at Hale Crater. The thin, dark streaks on the left side of the figure, known as "recurring slope lineae," are formed by seasonal flows of liquid water moving down the slope of the crater. They are approximately a football field in length.

Figure 1.18 Mars.

its large size and distant orbit suggest it is a Jupiter-like body devoid of liquid water. But smaller and cooler planets with atmospheres containing water vapor and methane have been found around stars nearer the sun. In 2019, the Hubble Space Telescope detected water in the atmosphere of a "super-Earth"—exoplanet with a mass between that of Earth and Neptune—in the habitable zone of its host star. Planets in this zone have an orbital distance from their stars that could allow liquid water to exist on the planet's surface. This planet, known as K2-18b, was the first planet outside our solar system in the habitable zone found to have water in its atmosphere.

insight from
a national geographic explorer 1.1

Courtesy of Bethany Ehlmann

Sediments like these have been found by the *Curiosity* rover at Gale crater.

DR. BETHANY EHLMANN, researcher at NASA's Jet Propulsion Laboratory (JPL), professor of planetary science at the California Institute of Technology, and scientist on the NASA Mars Exploration Program's Curiosity rover mission, discusses how studying rocks on Mars can help us to better understand the origins of life here on Earth and water's role in that origin.

"Rocks may hold the secret to life's origins not only on remote planets like Mars, but also here on Earth."

Mars and Earth have valuable news for each other. The rock record of life's origins on Earth is very limited; less than 1% remains from life's beginnings more than three and a half billion years ago due to rock recycling by plate tectonics. In contrast, about 50% of Mars' surface dates from those ancient days. "This gives us insights into the early history of our solar system," Ehlmann says, "A time when meteorites bombarded terrestrial planets. Studying the first billion years of Mars' history helps answer questions about how Earth evolved to sustain and maintain environments good for life."

The history of Mars is written on rocks. Particularly the history of water—the most crucial clue of all in discovering past life. "We know liquid water shaped Mars' surface," Ehlmann explains. "Lakes, rivers and hot springs were widespread enough to form minerals on Mars three billion years ago." Today, Ehlmann analyzes those ancient minerals by zapping Martian rocks with a laser spectrometer aboard the rover. The laser vaporizes a tiny amount of rock, producing a glowing cloud of plasma. Light from the plasma creates a fingerprint revealing particular atoms and chemical elements that compose the rock, allowing Ehlmann to determine the type of water which formed it. "The grand slam home run of the mission would be detecting preserved organic matter relating to biology in some of the sediments," she says. "Another potentially huge finding would be evidence telling us what sort of environment and climate allowed liquid water on Mars."

A self-portrait of NASA's *Curiosity* rover preparing to drill into a Martian rock target.

NASA

Source: National Geographic

NASA researchers have also detected organic compounds in two gas giant exoplanets. While this does not mean that life exists on these planets, it shows that we can now detect the molecules that are potentially important for biological processes outside our solar system. Might organic gases be a common component in the accretion of other solar systems?

1.7d Life and Oceans?

In our search for life outside of planet Earth, there is one characteristic feature that we look for above all others—water (see "Insight from a National Geographic Explorer 1.1"). As you will see throughout this book, water is a key ingredient that when found in large quantities, can present a relatively stable, three-dimensional environment that shields organisms from potentially damaging radiation. It also provides a rich chemical soup of ions, minerals, and nutrients that life can use to grow and evolve over time. Water is absolutely essential for all life. This has made the search for oceans the centerpiece of our search for extraterrestrial life.

Technology has now allowed us to find evidence of oceans on other planets and moons throughout our solar system and potentially throughout our galaxy. A new generation of sensors, space probes, and landers are being planned to investigate some of these intriguing worlds. Might we find chemical evidence of organisms that currently live, or lived long ago in one of these worlds?

Stay tuned!

CONCEPT CHECK

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

Where else do we find water in the universe? Is it commonly found in liquid form?

What planets and moons do we believe have potential oceans or had an ocean in the past? How are these oceans similar or different our ocean?

If we encounter life elsewhere, would we expect its chemistry and appearance to resemble life on Earth?

INTERDISCIPLINARY CONNECTIONS 1.1

Oceanography is an interdisciplinary science. Every chapter incorporates concepts from multiple disciplines important to a broad understanding of marine science.

Enceladus

NASA's *Cassini* mission made headlines when it flew through the geysers of Enceladus in 2015. This small moon has captivated scientists from all over the world and brought researchers together from many different disciplines to help answer the question of whether life may exist under its icy surface.

Enceladus is one of many dozens of moons that have a confirmed orbit around Saturn. It is approximately one-seventh the size of the Earth and it has a relatively smooth icy shell encasing a liquid water ocean beneath it (**Figure A**). Geysers periodically erupt from the moon's surface, spraying a plume of water vapor and ice particles into space. The orbit of Enceladus around Saturn is elliptical due to another nearby moon that influences its movement. As a result, the tidal forces experienced by Enceladus differ as it quickly orbits Saturn generating heat. Heat in

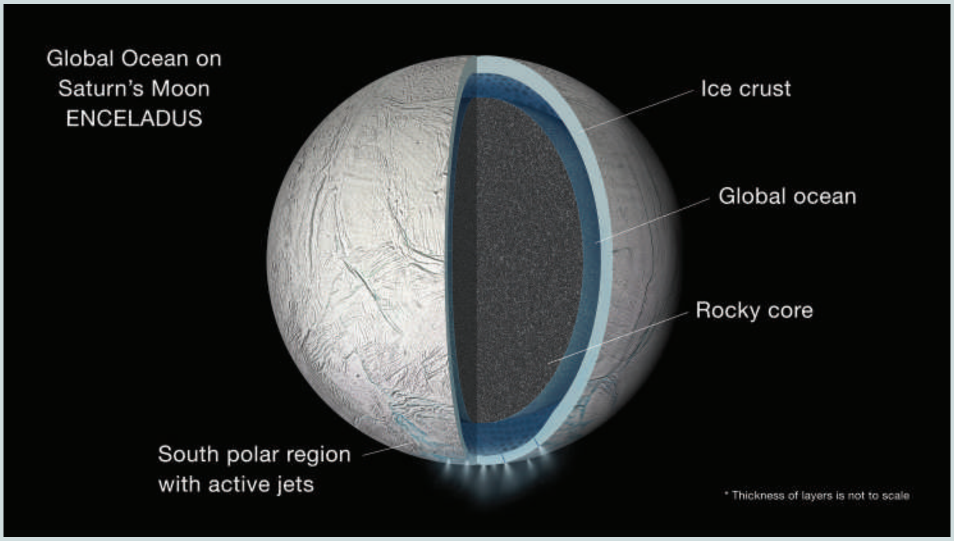


Figure A Cutaway illustration of Enceladus, depicting an icy crust hiding a liquid-water ocean sitting above its rocky core. Layers are not to scale.

Figure B An artist's illustration of Cassini diving into the plume of Enceladus.

the moon's interior likely formed hydrothermal vents on the seafloor beneath the ice resulting in the geysers. Interactions between the water in the ocean and the iron minerals found in the hot rocks are thought to produce molecular hydrogen as a byproduct.

Cassini was able to measure this hydrogen spewing out of the geysers as it made multiple passes over Enceladus's south pole between 2008 and 2015 (**Figure B**). This is notable because on Earth microbes in the ocean can use molecular hydrogen as an energy source near hydrothermal vents. The vents support large communities of marine life. Enceladus therefore has a potential energy source for microbial life in its ocean. While this would be difficult to find any evidence of life locked away under the ice, we can send space probes to fly through the geyser's plume to look for the chemical signatures of potential life beneath the ice.

Which specific concepts from other scientific disciplines are incorporated into this profile?

Chapter in Perspective

In this chapter, you learned Earth is a water planet, possibly one of few in the galaxy. An ocean covering 71% of its surface has greatly influenced its rocky crust and atmosphere. The ocean dominates Earth, and the average depth of the ocean is about 4½ times the average height of the continents above sea level. Life on Earth almost certainly evolved in the ocean; the cells of all life forms are still bathed in salty fluids.

We study our planet using the scientific method, a systematic *process* of asking and answering questions about the natural world. Marine science applies the scientific method to the ocean, the planet of which it is a part, and the living organisms dependent on the ocean.

Most of the atoms that make up Earth and its inhabitants were formed within stars. Stars form in the dusty spiral arms of galaxies and spend their lives changing hydrogen and helium to heavier elements. As they die, some stars eject these elements into space by cataclysmic explosions. The sun and the planets, including Earth, probably condensed from a cloud of dust and gas enriched by the recycled remnants of exploded stars. Earth formed by the accretion of cold particles about 4.6 billion years ago.

Heat from infalling debris and radioactive decay partially melted the planet, and density stratification occurred as heavy materials sank to its center and lighter materials migrated toward the surface. Our moon is thought to have been formed by debris ejected when a planetary body somewhat larger than Mars smashed into Earth.

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. Water-bearing asteroids likely brought additional water to Earth. Life originated in the ocean very soon after its formation—life and Earth have grown old together. We know of no other planet with a similar ocean, but water is abundant in interstellar clouds, and other water planets are not impossible to imagine.

In the next chapter, you will learn that science and exploration have gone hand in hand. Voyaging for necessity evolved into voyaging for scientific and geographical discovery. The transition to scientific oceanography was complete when the *Challenger Report* was concluded in 1895. The rise of the great oceanographic institutions quickly followed, and those institutions and their funding agencies today mark our path into the future.

QUESTIONS FROM STUDENTS[12]

1. You wrote that "Nothing is ever proven absolutely true by the scientific method." What good is it then? Can't we depend on the process of science?

One philosopher of science has described truth as a liquid: It flows around ideas and is hard to grasp. The progressive improvement in our understanding of nature is subject to the limitations inherent in our observations. As our observations become more accurate, so do our conclusions about the natural world. But because observations (and interpretations of observations) are never perfect, truth can never be absolute. In the 1920s, for example, astronomers assumed that the universe was limited to our own Milky Way galaxy. Observations made with a large new telescope on Mt. Wilson in California by Harlow Shapley and Edwin Hubble allowed them to measure more distant objects. Galaxies were discovered in profusion, "like grains of sand on a beach," in Shapley's words. Thus truth changed its shape.

This "fluidity" is not a disadvantage. Scientific thought is not bound by dogma. It is free to winnow good ideas from bad. It provides a durable framework on which to build a sustainable technological civilization. What we have accumulated so far is of inestimable practical and aesthetic value, and we have only scratched the surface.

[12]Each chapter ends with a few questions students have asked us after a lecture or reading assignment. These questions and their answers may be interesting to you, too.

2. What's the difference between a law and a theory? People sometimes say, "It's just a theory…" to criticize an idea.

A *theory* is a synthesis of a large and important body of information about a related group of natural phenomena. A *law* refers to a body of observations that can be summarized in a short mathematical (or verbal) statement. One is not "more true" than the other—both can be statements of facts.

3. Life appears to have arisen on Earth soon after the formation of a stable surface. Could life have formed on other planets?

We have no evidence, direct or indirect, of life on other planets around our sun or elsewhere in the universe. Yet it seems provincial to assume that life could have arisen only here. The formation of organic molecules from simple chemicals receiving energy from lightning, heat, ultraviolet light, and other sources may be quite common, and increasing complexity in these compounds may be a universal phenomenon.

4. Would life on other planets resemble life on Earth?

Organisms elsewhere might be very different. Recall that life on this planet probably arose in the ocean, and all lifeforms here carry an ocean of sorts within their bodies. On a planet without water, the organisms would surely be much different.

For example, on a hypothetical planet with an ammonia ocean, life would not have a structure of cells surrounded by lipid membranes. Lipid membranes are the sheets of fatty molecules that keep the inside of a cell separate from the environment, and ammonia prevents these membranes from forming. Without membranes, cells as we know them are not possible. Notwithstanding this argument, life need not be confined to planets with water. Other life-forms may exist, based on other "brews."

5. Supernovas seem really important. Has anybody ever seen a supernova?

Supernovas are important, indeed—all the heavy elements that make up both you and your surroundings were constructed in them. They are occasionally visible to the unaided eye. Light from an exploding star reached Earth in April or early May of the year 1054 C.E. Its position was recorded by Chinese and Arab astronomers; it was bright enough to be seen in daylight for 23 days. At its brightest, it was far brighter than anything in the night sky, and it was said to cause blind spots in the eyes of those who gave it more than a passing glance. Astronomers have recently found an astonishingly dense remnant of the nova spinning at the center of the existing nebula (see **Figure 1.19**). This star is 19 kilometers (12 miles) across and spins at a rate of 30.2 times per second!

Hundreds of distant novas are visible using large telescopes any time you care to look.

Figure 1.19 This neutron star, a super-dense remnant of the supernova of 1054 C.E., is called a "pulsar" because it emits rapid, regular pulses of energy as it spins.

J. Hester (ASU) et al., CXC, HST, NASA

6. How far away are exploding stars? What if a star became a nova in our neighborhood of the galaxy? Would we notice anything?

It depends on what you mean by "neighborhood," but the outcome of a nearby event could be ugly. The intense bursts of gamma rays and X-rays from a huge supernova (a hypernova) could sterilize everything in part of a galaxy's spiral arm—nothing alive based on water and proteins would survive. The radiation from the disintegration of a sun-like star would be less catastrophic (see again Figure 1.14). Astronomers have detected gamma ray bursts since the 1960s, but only in 2003 was a gamma burst directly associated with the first light from a hypernova. Fortunately the event happened in a distant galaxy.

TERMS AND CONCEPTS TO REMEMBER

accretion
big bang
biosynthesis
condensation theory
density
density stratification
experiment
galaxy
gas giant planets
hypothesis
laws
marine science
Milky Way galaxy
nebula
ocean
oceanography
outgassing
planets
science
scientific method
solar nebula
solar system
stars
supernova
terrestrial planets
theory
world ocean

STUDY QUESTIONS

Thinking Critically

1. Why do we refer to only one world ocean? What about the Atlantic and Pacific oceans, or the Baltic and Mediterranean seas?
2. Which is greater—the average depth of the ocean, or the average elevation of the continents?
3. Can the scientific method be applied to speculations about the natural world not subject to test or observation?
4. What are the major specialties within marine science?
5. Where did Earth's heavy elements come from?
6. Where did Earth's surface water come from?
7. Considering what must happen to form them, do you think ocean worlds are relatively abundant in the galaxy? Why or why not?
8. Earth has had three distinct atmospheres. Where did each one come from, and what were the major constituents and causes of each?
9. How old is Earth? When did life arise? On what is that estimate based? How did the moon form?
10. What is biosynthesis? Where and when do researchers think it might have occurred on our planet? Could it happen again this afternoon?

11. Marine biologists sometimes say that all life-forms on Earth, even desert lizards and alpine plants, are marine. Can you think why?
12. How do we know what happened so long ago?
13. What is density stratification? What does it have to do with the present structure of Earth?
14. Do we know of the existence of other water planets?

Thinking Analytically

1. A light-year is the distance light can travel in one year. Light travels at 300,000 kilometers (186,000 miles) per second. Commercial television broadcasting began in 1939. Television signals travel at the speed of light. How far away would a space probe have to be before it could no longer detect those signals?
2. Density is mass per unit volume. Granite rock weighs about 2.7 g/cm^3, water weighs about 1.0 g/cm^3. Knowing their sizes, how might you determine whether Europa or Ganymede is hiding a large liquid water ocean beneath an icy crust?
3. Can you think of any way an astronomer could detect a large planet orbiting a star without actually seeing the planet? (Hint: How would the star move as the planet orbits it?)