

A night sky with the Milky Way galaxy visible, arching across the upper half of the frame. Below the sky, a landscape of dark, layered rock formations (mesas) is visible under a dark, starry sky. The horizon shows a faint orange glow, likely from city lights or a low sun.

EARTH SCIENCE

STEPHEN
MARSHAK

ROBERT
RAUBER



EARTH SCIENCE

The Earth, The Atmosphere, and Space





EARTH SCIENCE

The Earth, The Atmosphere, and Space

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DEDICATION

To Kathy, Emma, David, and Michelle
(My bedrock, through uplift and subsidence.)

—STEVE MARSHAK

To Ruta, Carolyn, Josh, Molly, Stacy, and Fabian
(My sunshine, no matter how big the storms.)

—BOB RAUBER

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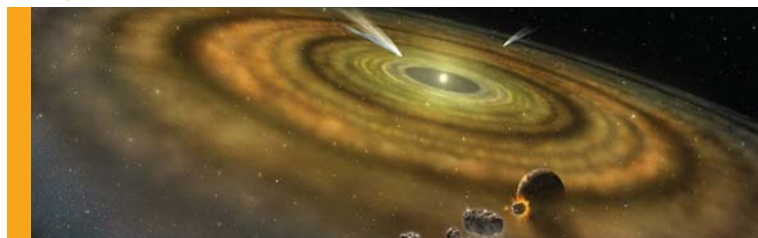
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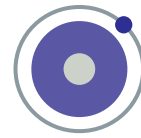
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PREFACE

Narrative Themes

Why do earthquakes, volcanoes, floods, and landslides happen? What causes mountains to rise? Does climate change through time? Where's the record of evolution? When did the Earth form and by what process? How can we find valuable metals and where do we drill to find oil? What drives violent storms? Is there an edge to the Universe? Could there be life on other planets or moons? Why are there oceans? The study of Earth Science addresses these important questions and many more.

Earth Science provides an introduction to the study of our planet and its context in space. It addresses the essence of four different disciplines: geology, oceanography, atmospheric science (including meteorology), and astronomy. As such, this book will help you understand what's beneath your feet, what's over the horizon, what is up in the sky, and what is far beyond the highest clouds.

Because of the diversity of topics covered in *Earth Science*, it's important to keep in mind a set of narrative themes while reading this book. These themes, listed below, serve as the building blocks from which you can construct your personal understanding of our amazing planet and of the Universe that it flies through.

1. Our planet's land, water, atmosphere, and living inhabitants are dynamically interconnected, and materials constantly cycle among various living and nonliving reservoirs on, above, and within the planet. Researchers refer to this complex network of interconnecting features and phenomena as the *Earth System*.
2. The Earth is a planet, formed like many other planets from dust and gas. But, in contrast to other planets, the Earth is a dynamic place on which new geologic features continue to form and old ones continue to be destroyed. A combination of special conditions, such as the distance from the Sun, chemical composition, the appearance of liquid oceans, and the presence of life, makes our planet truly unique in our Solar System. Quite literally, there's no place like home! While there may be exoplanets (planets orbiting other stars) that resemble the Earth, we'll very likely never interact with them.
3. The Universe, Solar System, and the Earth are all very old. Researchers suggest that the Universe began in the Big Bang about 13.8 billion years ago, that our Solar System originated around 4.57 billion years ago, and that the birth of the Earth took place 4.54 billion years ago. During this deep time, our planet's surface, subsurface, and atmosphere have changed, and life has evolved.
4. Unlike all other planets or moons in the Solar System, the Earth's outer shell, the lithosphere, consists of about 20 plates. The *theory of plate tectonics* states that these plates slowly move relative to one another so that the map of our planet continuously changes. Plate interactions cause earthquakes and volcanoes, build mountains, shift oceans, provide gases that make up the atmosphere, and affect the distribution of life on Earth.
5. Internal processes (driven by the Earth's internal heat—and manifested by plate motions) and external processes (driven by heat from the Sun) interact at the Earth's surface to produce complex landscapes.
6. Knowledge of the Earth, its oceans, and its atmosphere can help society to understand such dangerous natural hazards as earthquakes, tsunamis, volcanoes, landslides, storms, and floods. In some cases, this knowledge can help to reduce the injury and devastation that these hazards can cause.
7. Energy and mineral resources come from the Earth and are formed by geologic phenomena. Geologic studies can help locate these resources and mitigate the consequences of their use.
8. Physical features of the Earth are linked to life processes, and vice versa. Therefore, the history of life links intimately to the history of the physical Earth. The careful study of rocks can provide a rich record of this history.
9. The water in the oceans constantly moves and moderates the climate by transporting heat around the world. And where the ocean interacts with the land, fascinating coastal landscapes develop.
10. Our planet's atmosphere has changed dramatically over the course of the Earth's history. If you went back a billion years in time, the atmosphere would be unbreathable and you would suffocate. In modern times, this precious blanket of air has been significantly affected by the activities of society.
11. The atmosphere constantly moves, sometimes smoothly, sometimes violently. A variety of dangerous storms can develop in association with atmospheric movements, and these cannot be predicted more than a few days in advance.
12. Climates on the Earth vary with latitude, elevation, and distance from the sea, and the position of continents with respect to climate belts has changed over the course of geologic time. On a shorter time scale, both climate and sea level can change, sometimes very significantly, so that regions that were once dry can become shallow seas, and places that were once warm can later become covered in ice. Human society, during the past couple of centuries, has become a major agent of change on our planet.
13. We have much to learn by looking upward and examining the Universe beyond the Earth. Modern instruments and spacecraft have answered many questions, but with each answer, more questions arise about our Solar System, stars, galaxies, and the array of bizarre and beautiful objects that lie at inconceivable distances from us.
14. Science comes from observation, and people make scientific discoveries based on those observations. Earth Science utilizes ideas from physics, chemistry, and biology, so the study of Earth Science provides an excellent means to improve science literacy.

These narrative themes serve as the *take-home message* of this book, a message that we hope students will remember long after they finish their introductory Earth Science course. In effect, the themes provide a mental framework on which students can organize and connect ideas to develop a modern, coherent image of our planet in its context.

Pedagogical Approach

Students learn best from textbooks when they can actively engage with a combination of narrative text and narrative art. Some students respond more to words, which help them to organize information, provide answers to questions, fill in the essential steps that link ideas together, and develop a personal context for understanding information. Other students respond more to images that illustrate processes. Still others respond to question-and-answer-based active learning, an approach by which students “practice” their knowledge in real time. *Earth Science* provides all three of these learning tools. The text has been crafted to be engaging and to carry students forward along a narrative arc, the art has been configured to tell a story (see “Narrative Art and *What an Earth Scientist Sees*”), the chapters are laid out to help students internalize key principles (see “Organization”), and the online activities have been designed both to engage students and to provide active feedback (see “New *Smartwork5 Online Tutorial and Assessment System for Earth Science*”). In-text features have also been thoughtfully developed to guide students to a richer understanding of and fuller engagement with unfamiliar concepts (see “Pedagogical Features Designed to Help Students Master the Concepts”).

A note about units: Scientists the world over use the metric system for describing distances, weights, temperatures, and other physical features. But many of the students using this book grew up using the English system of units. To help students visualize and appreciate units, and to see the relationship between metric and English units, we provide both. The conversions we provide are sometimes exact and sometimes approximate, to reflect the precision of a measurement provided. For example, if we describe a distance as more or less 1,000 kilometers, we’ll provide the conversion as 600 miles (instead of 621.37 miles), for it would be misleading to specify one unit as an approximation and the other is a precise one.

Organization

The topics covered in this book have been arranged so that students can build their knowledge of Earth Science on a foundation of overarching principles. This book contains five parts.

Part I begins by considering how the Earth formed, and how it’s structured, overall, from surface to center. With this basic background, students can delve into plate tectonics, the grand unifying theory of Earth Science. Plate tectonics appears early in the book, so that students can gain an appreciation for the “action” underlying geology, and they can then use plate tectonics theory as a foundation from which they can interpret and link the ideas presented in subsequent chapters. Knowledge of plate tectonics, for example, helps students understand the suite of chapters on minerals, rocks, and the rock cycle. Knowledge of plate tectonics and rocks together, in turn, provides a basis for understanding volcanoes, earthquakes, and mountains. And then, with this background, students can see how the map of the Earth, and its inhabitants, have changed throughout the vast expanse of geologic time. We dedicate a unique chapter to energy and mineral resources, an especially relevant topic given present-day global interest in sustainability.

Part II hones in on the landscapes of the Earth’s surface, the visible part of our planet. We’ll understand how landscapes result from a never-ending battle between uplift (ultimately driven by plate tectonics) and erosion (ultimately driven by energy from the Sun). We begin by

understanding surface movements in general, most dramatically manifested by landslides. Then, we consider our planet’s freshwater, the landscapes associated with water movement, and the challenges presented by floods and the loss of water supplies. We conclude this part by looking at the dramatic landscapes developed in realms of extreme climates.

Part III takes us offshore, into the ocean. We begin by examining the water of this realm, focusing on its characteristics, its movements, and the life within it. We conclude by considering the interface between water and the solid Earth, both beneath the oceans and along its shores.

Part IV of the book introduces students to the Earth’s atmosphere. We begin by describing the character and evolution of the atmosphere and the overall composition of air. We then develop an understanding of how and why air moves, and how this movement leads to weather systems and storms. The book provides a particular focus on the devastating drama of thunderstorms, tornados, hurricanes, and mid-latitude cyclones, because of the impact these can have on society. This part then culminates with an examination of the scientific and social elements of climate change.

Part V, this book’s final part, goes beyond the confines of the Earth and heads into outer space. We’ll see how new discoveries provide answers to age-old questions about where our planet came from, and what the distant future holds. Students will learn how our knowledge of space has advanced over the centuries, what the other objects of our Solar System look like, and how the Sun and the stars produce energy. This part ends by taking a voyage to the farthest reaches of the Universe, which we learn about by analyzing light that began its journey to Earth billions of years before our planet had even formed.

Although we organized the chapters in *Earth Science* in a particular way that provides an overall direction to our narrative, we have ensured that this book is flexible, and that chapters can be assigned in a different sequence. Therefore, each chapter is self-contained, and we reiterate relevant material where necessary. This flexibility allows instructors to choose their own strategies for teaching Earth Science.

Special Features of This Text

Narrative Art and *What an Earth Scientist Sees*

To help students visualize topics, this book is lavishly illustrated. The figures are designed to provide a realistic context for interpreting features and phenomena without overwhelming students with extraneous detail. In this edition, many drawings and photographs have been integrated into *narrative art* that has been laid out, labeled, and annotated to tell a story—the figures are drawn to teach! Subcaptions are positioned adjacent to the relevant parts of a figure, labels point out key features, and balloons provide important detail. Subparts have been arranged to convey time progression, where relevant. The color schemes in the drawings have been tied to those of relevant photos, so that students can easily visualize the relationships between drawings and photos. In some examples, photographs are accompanied by annotated sketches labeled *What an Earth Scientist Sees*, which help students to be certain that they actually see the specific features that the photo was intended to show. The in-text art also serves as the foundation for the robust suite of videos, animations, and simulations that give students a fuller and more dynamic means for visualizing complicated processes that happen over long periods of time (see “Narrative Art Videos, Animations, and Simulations”).

Earth Science at a Glance

In addition to individual figures, each chapter contains at least one dramatic *Earth Science at a Glance* illustration. These illustrations either expand on a particular topic or provide a synopsis of many topics in a beautiful, artistic rendering. Renowned British artist Gary Hincks hand-painted the majority of these. Others were developed by the book's lead artist, Stan Maddock, and his colleagues. These illustrations provide a way for students to visualize key concepts . . . at a glance.

How Can I Explain? Features

Unique *How Can I Explain* features in every chapter provide simple, fun, hands-on projects that help students to better visualize and master key concepts. These exercises are particularly useful for future educators, as the projects can easily translate into effective lesson plans for grade-school classes.

Box P.3 How can I explain . . .

The difference between potential and kinetic energy

What are we learning?
That one kind of energy can transform into another.

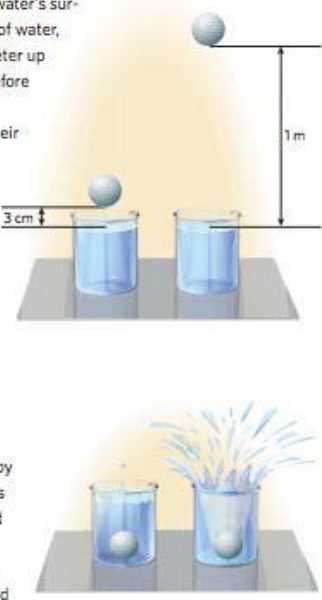
What you need:
Two golf balls, two full cups of water, and paper towels.

Instructions:

- Drop one golf ball into the first cup from a couple of centimeters (about an inch) above the water's surface.
- Drop the second golf ball into the second cup of water from a meter (about one yard) above the water's surface.
- Remove both balls and compare how much water remains in each cup.

What did we see?


- The ball falling from just above the water's surface displaced only a small amount of water, whereas the ball falling from one meter up hit the water much harder and therefore displaced a lot more water.
- The height of the balls represents their potential energy, and the amount of water displaced represents an amount of kinetic energy. The golf ball that fell from the higher position had more energy to start with because by raising the ball up a meter, you provided it with more potential energy. When it dropped, that potential energy was converted into kinetic energy. The ball that fell from the lower height had less potential energy to convert to kinetic energy by the time that it arrived at the water's surface, so it hit the water softly and displaced less water.
- The potential energy of the balls is due to gravity. An object being pulled on by gravity stores energy until it can move. The higher it is, the more it could move, so the more energy it holds.



Pedagogical Features Designed to Help Students Master the Concepts

Each chapter begins with a series of *learning objectives* that frame the major concepts of the chapter for the students. Every chapter section ends with a *Take-Home Message*, a brief summary that helps students identify and remember the highlight of the section before moving on to the next. These also contain a quick question, challenging students to engage. *See for Yourself* features guide students on virtual field trips, via *Google Earth™*, to locations around the globe or in the sky where they can apply their newly acquired knowledge to the interpretation of real-world geologic features. *How Can I Explain* features, described above, drive student interaction with the course material by providing simple hands-on projects that illustrate important concepts. *Did You Ever Wonder* panels prompt students to connect new information to their existing knowledge base by asking Earth Science-related questions that they have probably already thought about. *Consider This* boxes help students connect the course concepts to real-life applications, or to understand the concepts more thoroughly. *Science Toolboxes* give students brief, accessible introductions or reviews of basic science terms and concepts that can help them better grasp the chapter

Take-home message . . .

 An ordinary thunderstorm has a vertical, non-rotating updraft and tends to dissipate fairly quickly. Squall-line thunderstorms form in a row along a strong front or along storm-generated cold pools. The most violent thunderstorms, supercells, form where there is vertical wind shear in addition to strong instability. A supercell has a tilted rotating updraft, a particularly broad anvil, and an overshooting top.

Quick Question

Why do supercell thunderstorms tend to survive for a relatively long time?

material. And the two-page *Chapter Review* spreads are useful for easy reference and as study guides for students. All the review questions are tagged to the learning objectives from the beginning of the chapter in order to make them more useful as assignable questions for the instructor. Every review section also includes visual and applied questions designed not only to test basic knowledge but also to stimulate critical thinking.

Up-to-Date Coverage of Current Topics

Earth Science reflects the latest research and discoveries in the discipline, to help students understand the events and discoveries that have been featured in news headlines and recognize the relevance of these events to their own lives.

Media and Assessment Resources

Narrative Art Videos, Animations, and Simulations

Accompanying *Earth Science* at no cost to students or instructors is a rich collection of over sixty new animations and videos that illustrate

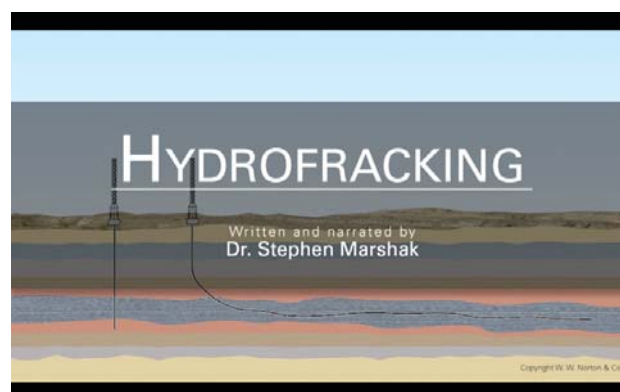
Earth Science processes and course concepts. Animations developed by Stephen Marshak and Alex Glass (Duke University) utilize a consistent style, applying a 3-D perspective to help students grasp active earth science phenomena. Some of these animations are simulations that allow students to control aspects and variables of an Earth Science



process. In the *Narrative Art Videos*, Stephen Marshak enhances explanations of core concepts in the text by describing the processes displayed in animated versions of the book's figures. This full suite of visual resources is available to students at digital.wwnorton.com/earthscience, through the Marshak YouTube channel, and in the LMS Coursepacks. The suite is additionally available to instructors at the book's Instructor Resources page and on an easy-to-use USB flash drive.

Real-World Videos

In addition to the suite of original videos, animations, and simulations that we described above, instructors and students will have access to over a hundred real-world videos, showing earth science—and earth scientists—in action. These videos have been carefully selected by Tobin Hindle of Florida Atlantic University. Teaching notes and classroom discussion questions to accompany the videos are available in the Interactive Instructors Guide, and selected videos are available in the Smartwork5 tutorial and assessment system, with accompanying questions and feedback. Over eighty real world videos are available at digital.wwnorton.com/earthscience, in the LMS Coursepacks, in the online Interactive Instructors Guide, and on the instructor USB flash drive.



New Smartwork5 Online Tutorial and Assessment System for Earth Science

The Smartwork5 online tutorial and assessment system features visual assignments that provide students with answer-specific feedback and links to the relevant section of the ebook for every question. Students get the coaching they need to work through assignments, while instructors get real-time assessment of student progress via automatic grading and detailed item analysis. Smartwork5 can also be integrated directly into instructors' campus Learning Management Systems (LMS), so that students benefit from single-sign on and instructors benefit from assignment results automatically reporting to the LMS gradebook.

Smartwork5 questions are written by and for earth science educators, in service of the textbook's learning objectives. Among the many question types available in Smartwork5 are ranking, sorting, and labeling tasks that take advantage of the visual nature of the course material and challenge students to think about real-world situations. Questions based on the Narrative Art Videos, Animations, Simulations, and Real World Videos help students prepare for class, or to apply what they've learned. Finally, Smartwork5 also provides basic reading quizzes and *Geotour*-guided inquiry activities that use *Google Earth*[™].

Smartwork5 comes free with all new texts in any format, or can be purchased standalone at digital.wwnorton.com/earthscience for a fraction of the price of other online homework systems.

Additional Instructor Materials

Lecture PowerPoints and Art Files

- *Enhanced Lecture PowerPoints*—Designed for instant classroom use, these highly visual slides utilize photographs and line art from the book, along with notes, in a form that has been optimized for use in the PowerPoint environment. All art has been relabeled and resized for projection. *Enhanced Lecture PowerPoints* also include in-class active learning prompts and exercises.
- *Labeled and Unlabeled Art PowerPoints*—These include all art from the book formatted as JPEGs that have been pre-pasted into PowerPoints. We offer one set in which all labeling has been stripped and one set in which labeling remains.
- *Labeled and Unlabeled Art JPEGs*—We provide a complete file of individual JPEGs for art and photographs used in the book. Again, artwork is available with and without labels, so it may be used in presentations, quizzes, exams, etc.

- *Semesterly PowerPoint Update Service*—W. W. Norton & Company offers a semesterly update service that provides new, current-event-based PowerPoint slides, with instructor support, tying events in the news to core concepts from the text.

Instructor's Manual

The instructor's manual, prepared by Heather Cook of California State University San Marcos, Geoff Cook of University of California, San Diego, and Julia Domenech-Eckberg, is designed to help instructors prepare lectures, homework, and exams. Each chapter contains:

- Learning objectives
- Complete answers to end-of-chapter Review and On Further Thought questions
- Descriptions of all Animations and Simulations, plus suggested classroom uses and discussion questions
- Teaching notes and discussion questions for the Real World Videos
- Activity ideas to implement active learning in class
- A correlation between Marshak/Rauber's *Earth Science* and Tarbuck and Lutgen's *Earth Science 14th Edition* for those looking to make the switch.

Interactive Instructor's Guide (IIG)

Searchable by chapter, phrase, topic, or learning objective, the Interactive Instructor's Guide instantly provides multiple ideas for teaching: video clips, powerpoints, animations, and other class activities and exercises. This repository of lecture and teaching materials functions both as a course prep tool and as a means of tracking the latest ideas in teaching the Earth Science course.

Test Bank

The Test Bank, authored by Heather Cook, Geoff Cook, and Julia Domenech-Eckberg, has been written to assess the text's learning objectives using carefully vetted and well-rounded questions. Every item in the Test Bank has been reviewed to ensure scientific accuracy. Each chapter features 50 multiple-choice questions, 10 short-answer or essay questions that test student's critical thinking and knowledge-application skills, and several art-based questions using modified images from the text. Finally, each question is tagged by text section, learning objective, difficulty level, and Bloom's taxonomy level.

LMS Coursepacks

Available at no cost to professors or students, Norton Coursepacks bring high-quality Norton digital media into a new or existing course in your campus Learning Management System. For each chapter, the Norton Coursepack offers:

- Reading Quizzes by Marianne Caldwell of Hillsborough Community College

- Links to Videos, Animations, and Simulations
- Links to the ebook
- Vocabulary Flashcards
- Link to download the See for Yourself and GeoTours kmz files
- GeoTours activities
- Test Bank questions in your campus LMS format

Norton Coursepacks are available for Blackboard, Canvas, Moodle, and Desire2Learn.

Geotours Workbook, Second Edition

Created by Scott and Beth Wilkerson of DePauw University, and Stephen Marshak, *Geotours Workbook* contains active-learning exercises arranged by topic that take students on virtual field trips in *Google Earth™* to see outstanding examples of Earth science at locations around the world. Each Geotour is accompanied by a worksheet that includes instructions and multiple choice questions. The Workbook accompanies a custom-made *Google Earth™* kmz file created by Scott and Beth Wilkerson, available for free download by all instructors and students using *Earth Science* at digital.wwnorton.com/earthscience. The *Geotours Workbook* can be packaged for free with *Earth Science* and includes complete user instructions and advanced instruction. Request a sample copy from your local Norton representative to preview each worksheet.

See for Yourself Google Earth™ Sample Site File.

Earth Science users who simply want access to sample field sites for classroom presentations or distribution to students can download the sites from digital.wwnorton.com/earthscience.

ebook-digital.wwnorton.com/earthscience

Compatible with all computers and mobile devices, the Norton ebook reader provides intuitive highlighting, note taking, and bookmarking functionalities. The Norton ebook for *Earth Science* includes dynamic features that engage students, such as our animations, Narrative Art Videos, and links to *Google Earth™* See for Yourself sites. To help focus student reading, instructors can share notes with their class, including images and video. Reports on student and class-wide time-on-task allow instructors to monitor student reading and engagement. The Norton ebook reader can also be integrated into your campus learning management system. When integration is enabled, students can click on a link to the ebook from their campus LMS and be redirected. The *Earth Science ebook* is available for purchase at digital.wwnorton.com/earthscience

See for yourself— Using Google Earth™

Visiting Field Sites Identified in the Text

There's no better way to appreciate geology than to see it firsthand in the field. The challenge is that the great variety of geologic features that we discuss in this book can't be visited from any one locality. So even if your class can take geology field trips during the semester, you'll at most see just a few geologic settings. Fortunately, *Google Earth*™ makes it possible for you to fly to spectacular geologic field sites anywhere in the world in a matter of seconds—you can take a virtual field trip electronically. Using related options, you can also look at stars in the sky.

In each chapter in this book, a *See for Yourself* provides sites that you can explore on your own computer (Mac or PC) using *Google Earth*™ software, or on your Apple/Android smartphone or tablet with the appropriate *Google Earth*™ app.

To get started, follow these three simple steps:

- 1 Check to see whether *Google Earth*™ is installed on your personal computer, smartphone, or tablet. If not, download the software from earth.google.com or the app from the Apple or Android app store.
- 2 Each *See for Yourself* site provides a thumbnail photo and brief description of the site (highlighting what you will see), as well as the latitude and longitude of the site.
- 3 Open *Google Earth*™, and enter the coordinates of the site in the search window. As an example, let's find Mt. Fuji, a beautiful volcano in Japan. We specify the coordinates in the book as follows:

Latitude 35°21'41.78"N, Longitude 138°43'50.74"E

Type these coordinates into the search window as:

35 21 41.78N, 138 43 50.74E

Note that the degree (°), minute (′), and second (″) symbols are optional and can be left as blank spaces.

When you click Enter or Return, your device will bring you to the viewpoint right above Mt. Fuji, illustrated by the thumbnail on the left. Note that you can use the tools built into *Google Earth*™ to vary the elevation, tilt, orientation, and position of your viewpoint. The thumbnail on the right shows the view you'll see of the same location if you tilt your viewing direction and look north.



View looking down.

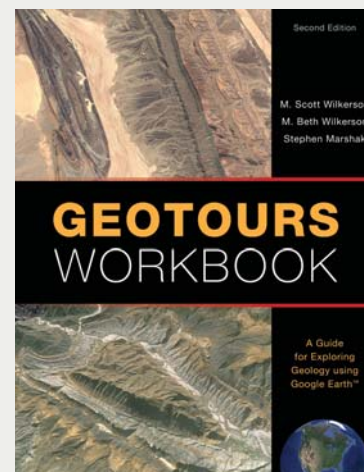


View looking north.

Need More Help?

Please visit <https://digital.wwnorton.com/earthscience> to find a video showing you how to download and install *Google Earth*™, more detailed instructions on how to find the *See for Yourself* sites, additional sites not listed in this book, links to *Google Earth*™ videos describing basic functions, and links to any hardware and software requirements. Also, notes addressing important *Google Earth*™ updates will be available at this site.

We also offer a separate book—the *Geotours Workbook, Second Edition* (ISBN 978-1-324-00096-9)—that identifies even more interesting geologic sites to visit, provides active-learning exercises linked to the sites, and explains how you can create your own virtual field trips.



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This book and its parent, *Earth: Portrait of a Planet*, have benefited greatly from input by expert reviewers for specific chapters, by general reviewers of the entire book, and by other reviewers who have provided helpful feedback for this volume. These reviewers include:

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Rebecca Teed, *Wright State University*

Leanne Sue Teruya, *San Jose State University*

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Bob Rauber is a professor of atmospheric sciences at the University of Illinois at Urbana-Champaign, where he also serves as the department head. He holds a B.S. in Physics and a B.A. in English from the Pennsylvania State University, as well as M.S. and Ph.D. degrees in Atmospheric Science from Colorado State University. In addition to teaching and writing, Bob oversees a research program that focuses on the development and behavior of storms. To carry out this work, Bob flies into hazardous weather in specially equipped airplanes—during these flights, he's so intent on recording data that he usually doesn't notice the bouncing and lightning. Bob has won several campus teaching awards, is a Fellow of the American Meteorological Society (AMS), and serves as Publication Commissioner for the AMS. In addition to research papers and *Earth Science*, his textbook writing credits include lead authorship of *Severe and Hazardous Weather: An Introduction to High Impact Meteorology*.



EARTH SCIENCE

The Earth, The Atmosphere, and Space



PRELUDE

Welcome to Earth Science!

By the end of the Prelude **you should be able to . . .**

- A.** describe the variety of subjects that an Earth Science course encompasses.
- B.** evaluate whether a news story pertains to an aspect of Earth Science, and how.
- C.** understand the concept of the Earth System and describe its key components.
- D.** explain why studying our Universe can help us understand our home planet and to address practical issues.
- E.** analyze an example of a scientific investigation.
- F.** recall some of the key themes of Earth Science.



P.1 Introduction

Our C-130 Hercules transport plane rose from the frozen surface of the Ross Sea, along the coast of Antarctica, and turned south. We were heading to a field site about 250 km away where, with luck, we'd be able to spend the next month studying cliff exposures of some very unusual rocks (Fig. P.1). The plane climbed past the smoking summit of Mt. Erebus, Earth's southernmost volcano, and for the next hour, flew along the Transantarctic Mountains, a long range of rugged ridges that divides the continent into two parts, East Antarctica and West Antarctica. Over millions of years, snow that accumulated in Antarctica's cold climate built into vast *glaciers*, sheets and rivers of solid ice that last all year and slowly flow across the ground. The glacier of East Antarctica covers most of the

continent and locally attains a thickness of over 3 km (2 miles). Between the Transantarctic Mountains and the far side of East Antarctica, over 2,500 km (1,500 miles) away, the surface of this glacier forms a high plain of blinding white called the Polar Plateau.

While marveling at this stark panorama—so different from the forests, grasslands, farms, and cities of more populated regions on Earth—we heard the engines slow and felt the Hercules begin to descend. As the plane approached a glacier's surface, just below the cliff that we hoped to study, the pilot lowered the landing gear, a huge tricycle of Teflon-coated skis. Shouting above the engine noise, a crew member reminded us of the emergency procedure: "If you hear three short blasts of the siren, hold on for dear life!"

Seconds later, the skis slammed into small frozen snowdrifts that formed wave-like ripples on the surface of

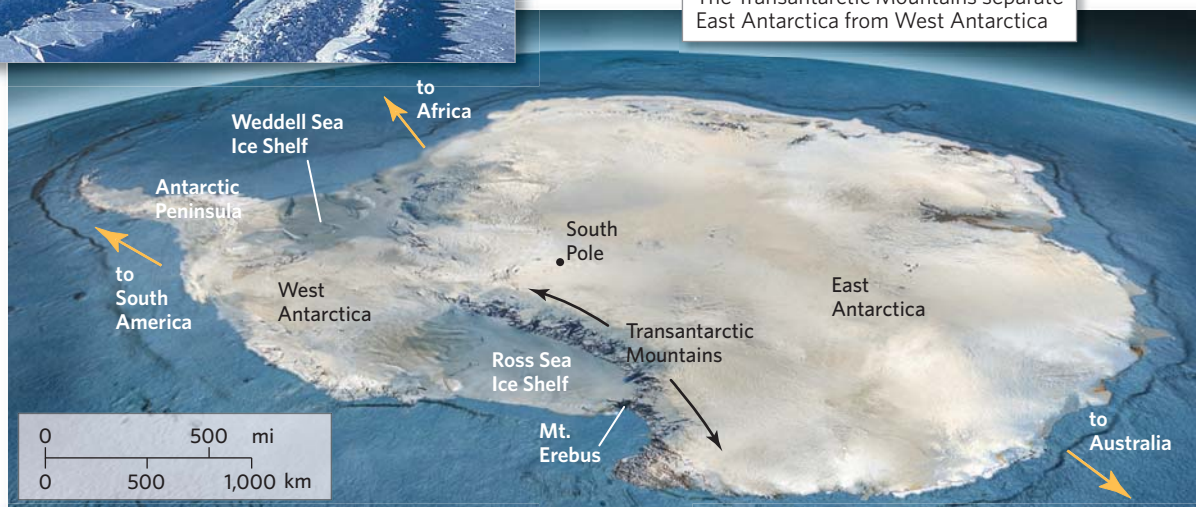
On a sea cliff along the coast of France, we see sunlight, air, water, rock, soil, and life all interact to form a fascinating landscape.

A plane dropping geologists on a snowfield



Figure P.1 Geologic fieldwork in Antarctica unlocks the mysteries of an icebound continent.

The Transantarctic Mountains separate East Antarctica from West Antarctica



The smoking summit of Mt. Erebus



Sledding to a field site with crates of supplies



the glacier. *Wham, wham, wham, wham!* It felt as though a fairy-tale giant was shaking the plane. Then, as fast as it began, the shaking stopped, and we were airborne again, looking for a softer landing surface. We finally touched down at a location where soft snow blankets the hard glacial ice of the Polar Plateau. The ramp at the tail of the plane was lowered and, bundled against the frigid gale generated by the plane's still-roaring propellers, we jumped out and unloaded food, fuel, stoves, tents, sledges, and snowmobiles. The instant the cargo was out, the ramp rose, the Hercules trundled off, and though it struggled to attain takeoff speed in the thick snow, it finally rose skyward.

When the glint of the plane's metal skin had passed beyond the horizon, the silence of Antarctica hit us—no dogs barked, no leaves rustled, and no traffic rumbled in this land of black rock, white ice, and blue sky. It would take us almost two days, even with the aid of powerful snowmobiles, to haul sledges of food and equipment to our field site, where we would spend the next month collecting rock samples and mapping their distribution. Why go to so much effort and expense to study an exposure of rocks? The Scottish poet Walter Scott (1771–1832) asked the same question, and provided a colorful answer: “Some rin uphill and down

dale, knapping the chucky stanes to pieces wi' hammers, like sae many road-makers run daft—they say it is to see how the world was made!”

Indeed, to see how the world was made. Field expeditions like the one we've just described, along with analyses carried out with instruments in laboratories and calculations run on computers, have led to an explosion of discoveries about the land, sea, and atmosphere of Earth. When we add observations made with telescopes and space probes of the myriad objects that populate the **Universe** (all of space, and everything within it), we can begin to understand not only the wonder of our home planet, but also its context in the broadest sense (**Fig. P.2**). Read on, and you can share in these discoveries and develop a personal image of the land beneath your feet, the landscapes between you and the horizon, the sea that surrounds the land, the atmosphere that surrounds Earth, and the objects that sparkle in the night sky above.

P.2 What's in an Earth Science Course?

Defining Earth Science and Its Components

For most of humanity's existence, speculation about the natural world lay in the realm of philosophy, and people attributed natural features in their surroundings to supernatural phenomena. But, beginning a few thousand years ago, and accelerating in the past few hundred years, study of the natural world and its surroundings became the focus of **science**, the systematic analysis of

natural phenomena based on observation, experiment, and calculation. Science has evolved into several distinct disciplines, most of which may already be familiar to you. For example, if someone asks, “What is *chemistry*?” you might respond that it's the study of chemicals and reactions between them. Similarly, if someone asks, “What is *physics*?” you might respond that it concerns the study of matter and energy, and if someone asks, “What is *biology*?” you might respond that it's the study of living organisms.

If someone asks, “What is Earth Science?” you might be stumped. That's because **Earth Science** combines many disciplines (**Fig. P.3**). It includes **geology**, the study of our planet with a focus on the materials that compose it, the phenomena that change it, and its long-term history. It includes **oceanography**, the study of the water and life in the oceans, as well as the way in which ocean water moves and interacts with land and air. And it includes **atmospheric science**, the study of the air layer that surrounds the Earth. Atmospheric science, in turn, includes both meteorology and climate science. **Meteorology** focuses on the *weather*, meaning the condition of the atmosphere at a given location and time, as well as the movement of air and its consequences. **Climate science** focuses on a region's overall annual pattern of weather averaged over many years—its *climate*—and how that pattern changes over time. High school or college courses entitled Earth Science also commonly introduce the basics of **astronomy**, or *space science*, the study of planets, stars, and other objects of the Universe. Learning about astronomy provides a framework of knowledge on which to build an understanding of the formation and history of our own



Figure P.2 A spectacular view from NASA's Hubble Space Telescope of a distant region of space.

Figure P.3 The various disciplines of Earth Science.



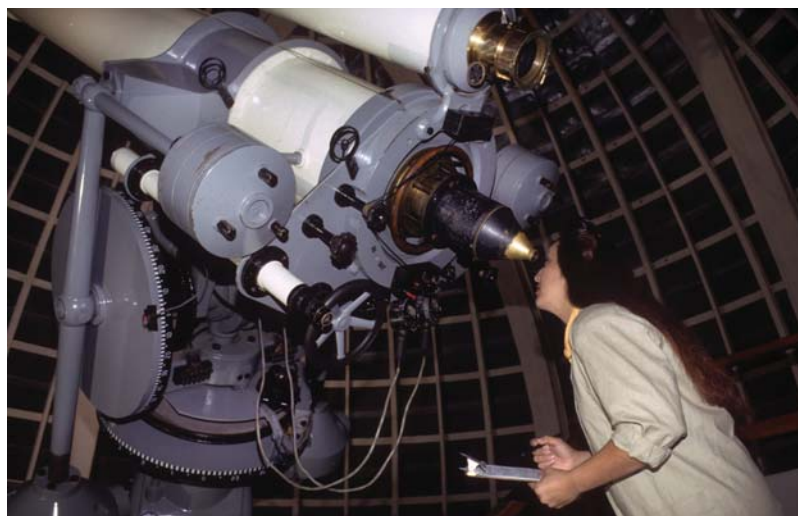
(a) A geologist studies a rock face.



(b) Oceanographers sample the seas.



(c) Atmospheric scientists monitor and analyze the atmosphere.



(d) Astronomers explore the cosmos.

planet. In sum, we see that an Earth Science course covers the nature, origin, and evolution of all of our natural surroundings. It's a broad subject, indeed!

How Scientists Work

The information discussed in this book comes from the work of scientists. Popular media often characterize scientists as awkward loners with poor taste in clothing. Who are they, really? In an Earth Science course, you'll see that **scientists** are people who spend their careers in search of ideas to explain the way our Universe operates. They carry out their search in many different ways. At any given time, at locations all around the world, *field scientists* scale cliffs (**Fig. P.4a**), fly into storms (**Fig. P.4b**), plow through stormy seas, or stargaze from mountaintops. Meanwhile, *laboratory scientists* peer

down microscopes, adjust electronic equipment, or mix test tubes of chemicals (**Fig. P.4c**); and *computational scientists* program computers or devise equations to provide *models*—simulations—of natural phenomena. In Earth Science, both computer and physical models can help us visualize processes that take place too slowly or too quickly to see in real time, or can characterize objects that are too small or too large to measure directly (**Fig. P.5**).

As you study Earth Science, you'll have an opportunity to see how scientists conduct **research**, the process of seeking to understand natural phenomena through observation, experiment, and calculation. You'll see that research does not involve reliance on subjective guesses, but rather anchors in the development of a consistent set of testable concepts, following the basic tenets of the

Figure P.4 Research takes place in many environments.



(a) Cliff exposures in the desert of Utah provide a record of the Earth's past.



(b) To learn about storms, researchers fly into one and take measurements.



(c) Laboratories provide an opportunity to carry out controlled experiments.

scientific method (**Box P.1**). Some scientists focus their research on defining new principles that can profoundly change our understanding of nature—think of Charles Darwin, Marie Curie, or Albert Einstein—whereas others focus on practical matters, using the results of their research to improve our lives, find our resources, and

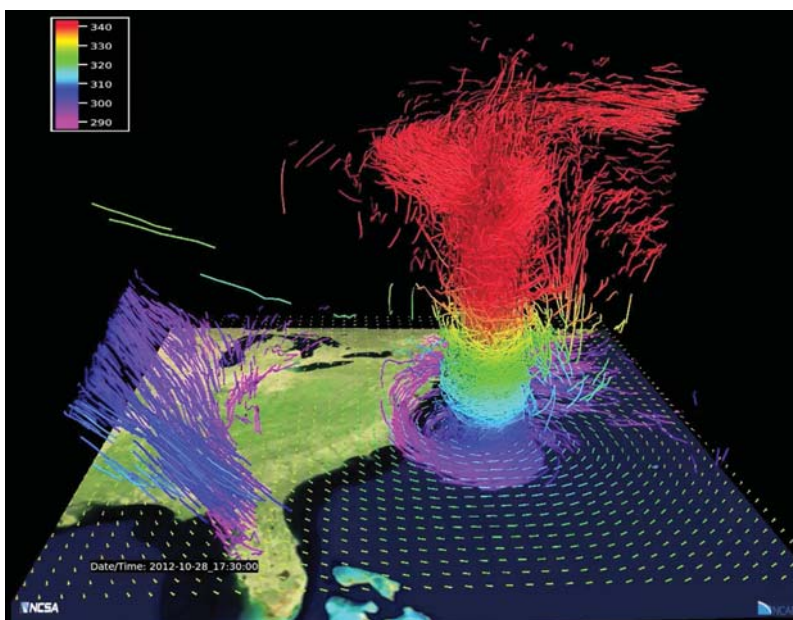
protect our environment. To drive home the point that science is a human endeavor, this book highlights where, when, and how ideas originated so that you can answer the question, “How do we know that?”

Who are the scientists that make the discoveries we’ll be focusing on in this book? When a headline begins with “Scientists say . . .” and then continues with “an earthquake shook Japan today,” or “the supply of oil may be running out,” the scientists under discussion are *geologists*. If the

Figure P.5 Use of models in Earth Science.



(a) A stream of water flowing over sand can simulate the evolution of a river.



(b) A computer model simulating air flow and air temperature variations during Hurricane Sandy of 2012. Lines indicate air movement and color indicates temperature (purple = cool; red = warm).

Box P.1 Consider this . . .

The scientific method

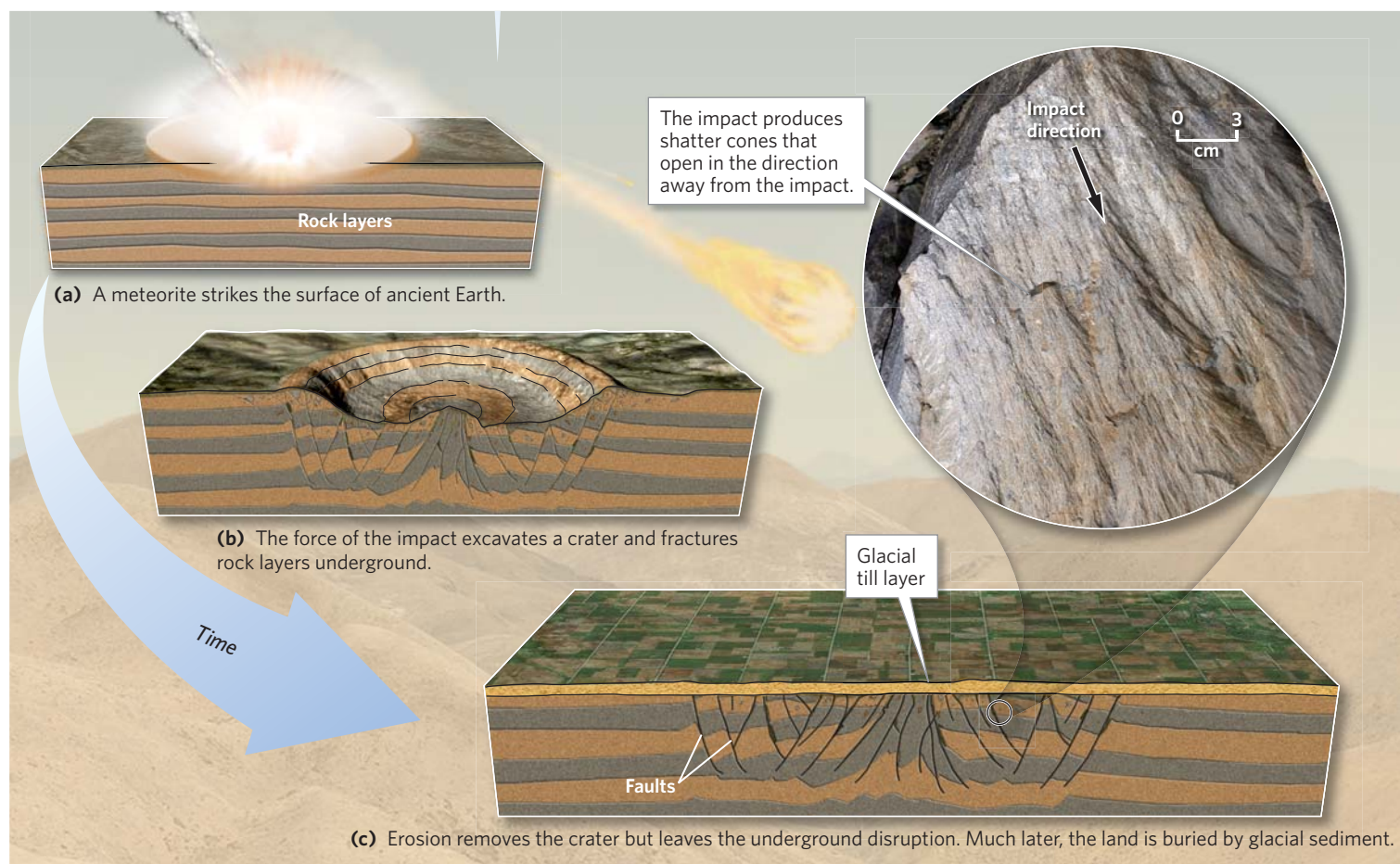
Sometime during the past 200 million years, a large block of rock or metal zoomed in from outer space and slammed into our planet at a site in what is now the midwestern United States, a landscape that today hosts flat cornfields. The impact of this *meteorite* blasted debris skyward and carved a deep, bowl-shaped depression called a *crater*. The impact also shattered rock beneath the crater, and it caused layers of rock that had been buried deeply below the ground surface to spring upward and tilt on end. In the millions of years that followed, flowing water and blowing wind carried away the debris and wore down the crater until the depression had disappeared entirely. But this process of *erosion* did not carve deeply enough to remove the fractures and tilted rock layers that the impact produced. Some 15,000 years ago, sand, gravel, and mud carried by a vast glacier, much like the one that covers Antarctica today,

buried the area and completely hid evidence of the impact from view (Fig. BxP.1). So much history beneath a cornfield! How do we know this? It took years of scientific research!

Scientists commonly guide their research by using the **scientific method**. Let's consider the idealized components of the scientific method and see how researchers applied them to come up with and verify the meteorite-impact story.

- *Recognizing the problem:* Any scientific project, like any detective story, generally begins by identifying a problem, the scientific word for "mystery." The cornfield mystery came to light when workers drilling a water well discovered that limestone, a rock commonly made of shell fragments, lies just below a thin blanket of 15,000-year-old sediment left behind by glaciers. In surrounding regions, the rock directly beneath the glacial sediment consists of sandstone, a rock made of sand grains. In fact, outside of the mysterious cornfield, the limestone layer lies underneath the sandstone layer. Because limestone can be used

Figure BxP.1 An ancient meteorite impact has excavated a crater and permanently changed rock beneath the surface.



to make cement and to produce the agricultural lime used in improving soil, it's valuable, so workers bulldozed off the glacial sediment and dug a quarry to excavate the limestone. They were surprised to find that rock layers exposed in the quarry were tilted steeply and had been shattered pervasively by large cracks, for in surrounding regions, the rock layers are horizontal, like the layers in a birthday cake, and contain relatively few cracks. What phenomenon brought limestone up close to the Earth's surface, tilted the layering in the rocks, and shattered the rocks? Curious geologists, like crime-scene investigators, journeyed to the quarry to find out.

- **Collecting data:** To better characterize a problem, and to help solve a problem, scientists collect **data**, sets of observations, measurements, or calculations. Data serve as clues. To collect data on the quarry problem, geologists went into the quarry, measured the orientation of the rock layers, and *documented* (made a written or photographic record of) the fractures that broke up the rocks. Note that in this example, data comes from analyzing natural features formed long ago. In other cases, data might come from experiments or computer models. Observations, experiments, and calculations should be *repeatable*, in the sense that another researcher following the same procedure should obtain the same result.
- **Proposing hypotheses:** A scientific **hypothesis** is merely a possible natural explanation that can explain a set of data. Scientists may propose hypotheses before, during, or after their initial data collection. In this example, the geologists came up with two alternative hypotheses to explain the features in the quarry: (1) the features formed during an ancient volcanic explosion; and (2) the features are a consequence of an ancient meteorite impact.
- **Testing hypotheses:** Because a hypothesis is just an idea that can be either right or wrong, scientists must put a hypothesis through a series of tests to determine if it might be correct, or if it can't be correct. Often, these tests involve making *predictions* of what scientists will see if they make more observations or if they conduct an experiment or calculation. If none of the original hypotheses passes the tests, the problem remains unsolved, and researchers try to come up with new hypotheses. If a hypothesis does pass a test, it could be right.

The geologists at the quarry compared their field observations with previously published observations made at known sites of volcanic explosions and meteorite impacts, and they conducted experiments designed to simulate such events. They learned that if the geologic features visible in the quarry were the result of volcanism, the quarry should contain certain distinctive types of rocks. But no such rocks were found. If, however, the features were the result of an impact, the rocks should contain *shatter cones*, uniquely shaped cracks. Shatter

cones can be overlooked, so the geologists returned to the quarry specifically to search for them—and found them in abundance. The impact hypothesis passed this test, and remained a possibility!

Scientists don't always see the entire path to solving a problem when they start working on it. In fact, at first they might not recognize the problem to be solved. So they don't always follow the components of the scientific method in a specific sequence. Furthermore, serendipity often plays a role in research, in that scientists may stumble onto a new problem or solution without planning on it. And while ideally, scientists try to confirm results by repeating observations, experiments, or calculations, in Earth Science this isn't always possible because the phenomena under study may have happened in the very distant past, or in locations that are very far away. In fact, some questions just can't be answered fully using available resources and methods, so we have to accept that some interpretations remain uncertain.

In common English, the word *theory* often substitutes for the word *hypothesis*. For example, you may see a sentence like, "The scientist's proposal is only a theory," or "The author of the article proposes many theories," with the implication that a theory is just an idea that's as likely to be wrong as it is to be right. In scientific discussion, however, a **theory** is a scientific idea supported by an abundance of evidence. In other words, it's a robust idea that has passed many tests and has, so far, failed none. Scientists have much more confidence in the validity of a theory than they do in the validity of a hypothesis. In the example we described above, continued study in the midwestern quarry eventually yielded so much evidence favoring the impact hypothesis that the hypothesis came to be viewed as a theory. Scientists continue to test theories over a long time. Commonly, the tests involve making predictions based on the theory. Successful theories, those that are supported by many observations and lead to many successful predictions, eventually become part of a discipline's foundation. However, some theories may eventually fail a test, and if so, scientists discard them and search for better ideas.

In some cases, scientists have been able to devise concise statements that completely describe a specific relationship or phenomenon. Such a statement, called a **scientific law**, applies without exception for a defined range of conditions. Newton's law of gravitation serves as an example: it's a simple mathematical expression that always defines how fast an object accelerates (speeds up) when pulled on by another mass. Note that scientific laws do not, in themselves, explain a phenomenon, and in this regard, they differ from theories. For example, the "law of gravity" does not explain how *gravity*, the force that causes masses to attract each other, operates, but the "theory of evolution" does provide an explanation of why species evolve over time.