HAROLD LEVIN | DAVID KING, JR.

THE EARTH THROUGH TIME

Eleventh Edition

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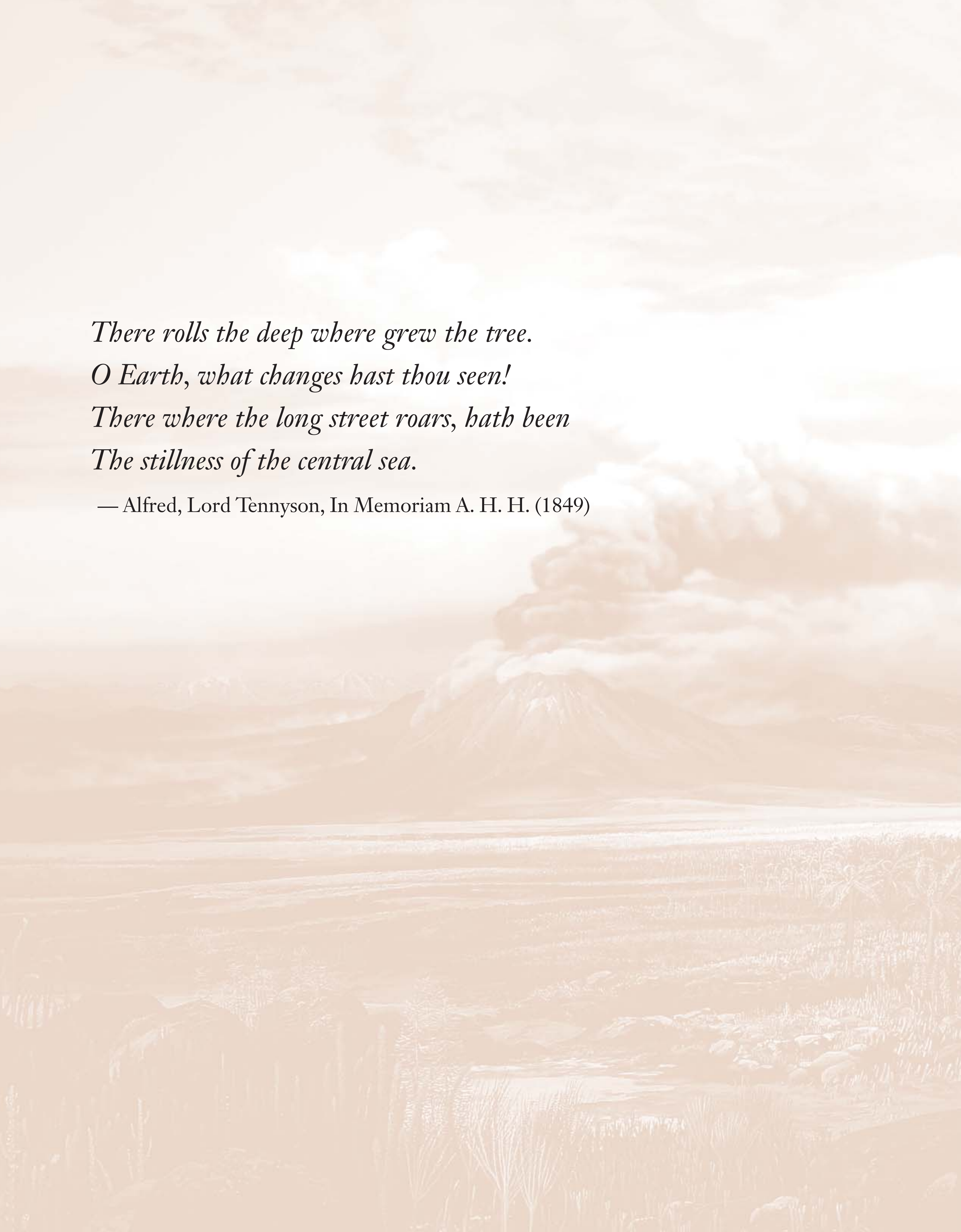
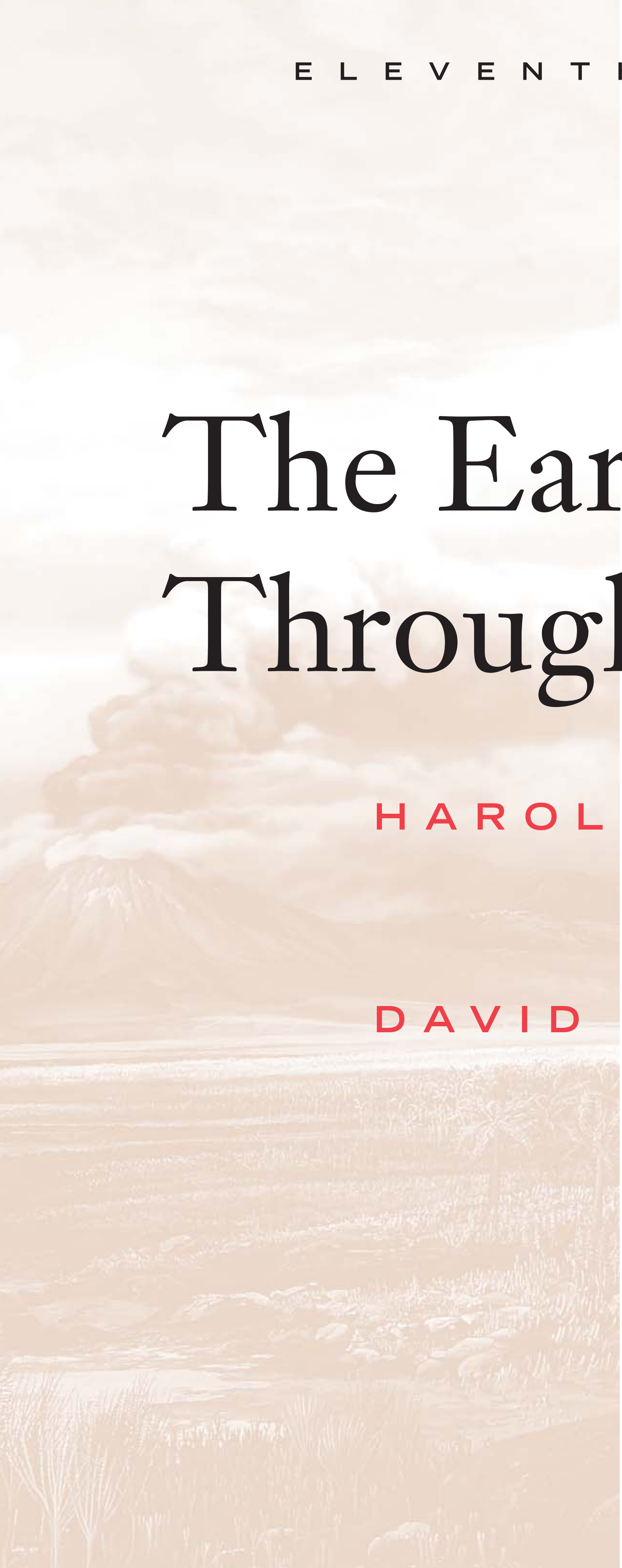
ELEVENTH EDITION

The Earth Through Time



There rolls the deep where grew the tree.
O Earth, what changes hast thou seen!
There where the long street roars, hath been
The stillness of the central sea.

— Alfred, Lord Tennyson, In Memoriam A. H. H. (1849)



ELEVENTH EDITION

The Earth Through Time

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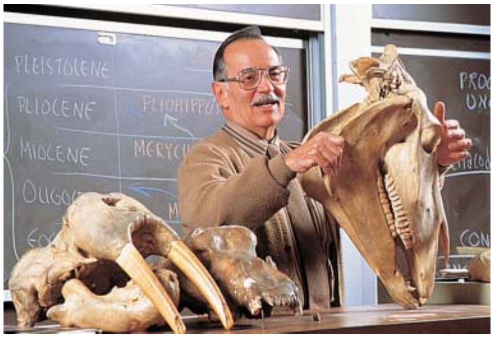
ABOUT THE AUTHORS



Harold ("Hal") Levin began his career as a petroleum geologist in 1956 after receiving bachelor's and master's degrees from the University of Missouri and a doctorate from Washington University. His fondness for teaching brought him back to Washington University in 1962, where he is currently professor emeritus of geology and paleontology in the Department of Earth and Planetary Sciences. His writing efforts include authorship of ten editions of *The Earth Through Time*; four editions of *Contemporary Physical Geology*; *Life Through Time; Essentials of Earth Science*; and co-authorship of *Earth: Past and Present*, as well as nine editions of *Laboratory Studies in Historical Geology*; and *Ancient Invertebrates and Their Living Relatives*.

For his courses in physical geology, historical geology, paleontology, sedimentology, and stratigraphy, Hal has received several awards for excellence in teaching. The accompanying photograph was taken during a lecture on life of the Cenozoic Era. The horse skull serves to illustrate changes in the teeth and jaws of grazing animals in response to the spread of prairies and savannahs during Miocene and subsequent epochs.

Dedication: *This book is dedicated to my wife Kay, who has cheerfully endured my preoccupation with preparing this textbook, and to Noah, Lillie, Eli, Mollie, Natalie, Emily, Caitlyn, Hannah, and Candis. May they have the wisdom to treat the Earth kindly*. -Hal Levin

David T. King, Jr. holds the rank of Professor of Geology at Auburn University. A graduate of the University of Missouri-Columbia, David has 35 years of postdoctoral experience in teaching and research in the fields of sedimentology and stratigraphy. He has worked on Paleozoic carbonates of Texas and the U.S. midcontinent, on the Jurassic hydrocarbon basins of southern Alabama and Mississippi, and on Cretaceous and Cenozoic strata in the U.S. Gulf Coast and in Belize. Since 1996, his main area of academic research has been cosmic impact in marine waters over geological time. Dr. King is a former Commissioner of the North American Commission on Stratigraphic Nomenclature (1997–2000), and he was a gubernatorial appointee to the Alabama state licensure board for geologists (2005–2014). He teaches introductory, advanced, and graduate courses in geology on many aspects of stratigraphy and planetary geology. Photo: At Hawaii Volcanoes National Park, Hawai'i Island; overlooking the summit caldera of Kilauea volcano.

Dedication: *This book is dedicated to my wife, Lucille, who has been with me on so many geological field trips, explorations, and adventures. Also, I dedicate this book to all my geology students at Auburn University*. -David King

PREFACE

Students may enroll in an Earth history course for many reasons. Usually, it is simply to satisfy a college science requirement. Those of us who teach the course, however, strive to provide a better reason. We hope to instill in our students knowledge about how our planet became a haven for life; how *change* has dominated Earth's history; and how change will continue to challenge us in the future. In the geological past, change has been driven by natural forces. Now we humans, so widely distributed on Earth and so great in numbers, are an additional driving force of change. More often than not, we cause changes that are harmful. These are reasons why our students need to more fully understand the long history of this small and fragile planet. They need to learn from its history, its catastrophes, and its successes.

This textbook chronicles the Earth's story from the time the Sun began to radiate its light, to the beginning of human civilization. It is a history that began about 4,560 million years ago after our planet had gathered most of its mass from a rotating cloud of dust, gases, and meteorites. From that time to the present, the Earth has experienced climatic shifts from widespread warmth to ice ages. The floors of the oceans have alternately expanded and contracted in area. Continents have drifted thousands of kilometers, coalesced, then splintered apart. Rocks have been thrust skyward to form lofty mountains, and placid landscapes have been disrupted by earthquakes or buried in floods of fiery lava.

For about the past 3 billion years, life has existed on our planet. Fossil remains of that life attest to biological achievements and failures in coping with changing conditions. There are lessons to be learned from our planet's biological history—lessons that will help us anticipate and act wisely to dangers we may face in the future.

Learning what has happened on Earth in the past is sufficient reason to study Earth history. A course in Historical Geology, however, has value in many other ways as well. As a science, it informs us about a way to answer questions, how discoveries are made, and how to tell the difference between valid and faulty assumptions. All of this comes by way of the scientific method. The term "scientific method" may sound a bit formidable to students, but it is really the rational way we ask questions, make educated assumptions about the answers, and test those answers by observation or experimentation. As one example, we might infer from the widespread occurrence of same-aged glacial sediments that there was a past episode of cooling of the planet. This leads us to ask why cooling occurred. Was it the result of changes in the amount of radiation received from the Sun, a shift in the Earth's axis of rotation, changes in the composition of the atmosphere, or major changes in the distribution of continents? Earth scientists test each of these ideas in the laboratory and examine rocks of the appropriate age to find the best answer. That answer is always tentative and subject to new discoveries. Usually, the answer relates to reciprocal actions of all the Earth's *systems:* the atmosphere, biosphere, and solid Earth. In this book, students will read about such an integrated approach to answering questions about the geological past in the pages ahead.

The Earth Through Time is designed for the undergraduate student who has little previous acquaintance with geology. Students exploring the possibility of an academic major in geology, however, can be confident that the text will provide the necessary background for advanced courses. We have included basic information about minerals, igneous, and metamorphic rocks so that the text can be used either for a single, self-contained first course, or for the second course in a two-semester sequence of Physical Geology followed by Historical Geology.

THE ELEVENTH EDITION

The goal of *The Earth Through Time* is to present the history of the Earth, and the science behind that history, as simply and clearly as possible. We have strived to make the narrative more engaging, to convey the unique perspective and value of historical geology, and to improve the presentation so as to stimulate interest and enhance the student's ability to retain essential concepts, hopefully, long after the final exam.

In this eleventh edition, we have revised numerous figures and updated large passages of text to include the newest developments in the ever-changing field of the geological history of the Earth. For example, new discoveries about the history of growth and development of supercontinents, especially during Proterozoic, and the temporal and spatial distribution of ice ages and related expansion of glacial ice sheets through time have been added to this edition. This textbook includes new discoveries regarding cosmic impact events on Earth, as well as new findings about the causes and effects of Earth's great mass extinctions.

HOW DOES *THE EARTH THROUGH TIME* HELP STUDENTS LEARN?

The Earth Through Time has several features within each chapter to engage the student and promote learning.

- **Questions for Review** allows students to test their understanding of material in a chapter and to further process what they have learned.
- **Chapter Summaries**. Each chapter ends with a summary of essential concepts, affording students a condensed overview of the chapter. If the summary statement is not fully understood, it is a clue to revisit the topic in the chapter.
- **Key terms** are printed in **boldface** the first time they are used. A list of Key Terms is provided at the end of each chapter, along with the page number on which they are defined. The student can see the key terms defined again in the book's **Glossary**.
- So that students can anticipate what lies ahead, each chapter begins with a list of **Key Chapter Concepts**.
- **Caption questions** occur beneath many text figures. These draw attention to the figure content and how it relates to the figure's chapter content.
- **Appendices**, which can be found on the Book Companion Site on the Internet, include a **Classification of Living Things** that helps students place fossils described in the text in the text within their taxonomic group. The appendices also include a map of the **Physiographic Provinces of the United States**, a **Periodic Table and Symbols for Chemical Elements** (useful as as a reference when reading the sections on mineral composition and radioactive elements), **Convenient Conversion Factors, Notes on Exponential Scientific Notation, Rock Symbols**, and a simplified **Bedrock Geology of North America**.
- Most chapters include one or two special sections that expound on the geological features in well-known parks. Titled **HISTORICAL GEOLOGY IN PARKS**, these special sections show readers examples of where they can see geological features that are discussed in that chapter. The geology of these selected parks is strongly connected with the topic of the chapter where they occur.

INSTRUCTOR RESOURCES

Instructor resources include **Instructor's Manual**, **Test Bank**, and **Lecture PowerPoints**, which were prepared by David King. The Instructor's Manual contains many useful features and includes answers to end-of-chapter questions as well. Instructional resources may be provided to those adopters qualified under our adoption policy. Please contact your local Wiley sales representative directly or through our website (www.wiley.com/college).

STUDENT RESOURCES

To help students understand, retain, and appreciate the information in their Historical Geology textbook, *The Earth Through Time* is accompanied by an extensive set of supporting materials.

The **Book Companion Site** (www.wiley.com/college/levin) features simple-to-use and highly effective study tools prepared by David King, which will help students isolate and retain key information from the text, prepare efficiently for exams. The website includes:

- **Student Study Guide**, which prepares students for tests and quizzes by providing a concise chapter summary, key terms, and self-quiz with answer key. Answers to figure-caption questions are in this guide as well.
- **Chapter Quizzes**, which provides immediate results on completion of each quiz.
- **Web Links**, which allows students to explore external resources for topics examined in each chapter.
- **Appendix to the textbook**, which contains a helpful set of reference materials that are useful for students and is available at the Book Companion Site, which is online.

ACKNOWLEDGMENTS

Some of the changes in this edition resulted from the suggestions of an insightful and diligent group of thoughtful and dedicated professors who reviewed the text in anticipation of this new edition. Other changes are based on research by David King. In particular, our sincere thanks must go to those at John Wiley and Sons who encouraged this new edition.

Ryan Flahive provided the stimulus and encouragement to move this new edition forward. Others at Wiley who played key roles in producing this new edition include Nichole Urban, Leslie Lahr, Ruth Pepper, Lisa Passmore, and Billy Ray. And in Chennai, there was Abidha Sulaiman and her copyediting staff and art team. We thank all of you so much for your help and patience. Finally, the authors are grateful for the opportunity to work with such an outstanding publisher as John Wiley and Sons, Inc.

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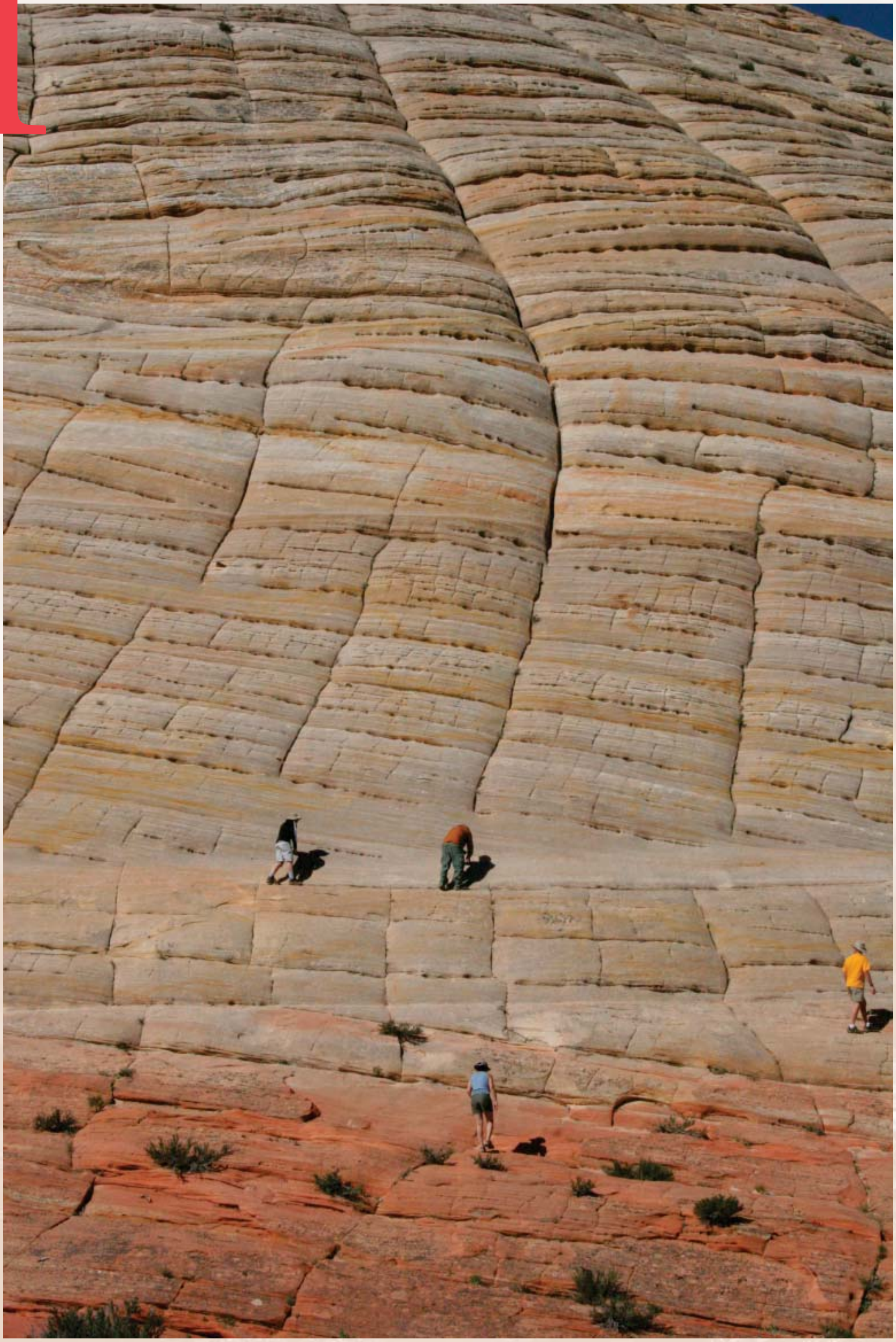


Glen R. Osburn

Orange, brown, and white cross-bedded Navajo Sandstone exposed in Checkerboard Mesa, Zion National Park, Utah. *The linear patterns are the results of wind blowing layers of sand across ancient sand dunes.*

CHAPTER 1

The Science of Historical Geology

A million years is nothing. This planet lives and breathes on a much vaster scale.
—Michael Crichton, *Jurassic Park*

OUTLINE

Key Chapter Concepts

- The study of events in the Earth's past can commonly be used to predict future events.
- The Earth and its living things have undergone continuous change during the past 4.56 billion years (4,560,000,000 years).
- Physical geology examines the structure, composition, and processes that affect the Earth today. Historical geology builds on physical geology and considers all past events on Earth.
- The scientific method is a way to find answers to questions and solve problems. It involves collection of information through observation and experimentation, formulation of answers, and validation by testing.
- The three most pervasive themes in the history of Earth are the immensity of geological time, plate tectonics, and biological evolution.

Welcome to the amazing history of our planet! Here you will discover many astonishing events of the past and learn how we came to understand them. You will learn the intriguing story of how life developed on Earth and ultimately how human life evolved.

Our planet formed about 4.56 billion years ago. Since that time, it has circled the Sun like a small spacecraft observing a rather average star. Between about 300,000 and 150,000 years ago, a species of primate we call *Homo sapiens* (Latin: *wise human*) evolved on Earth. Unlike earlier animals, these creatures with oversized brains and nimble fingers asked questions about themselves and their surroundings. One thing that humans wondered about is the planet we live on.

Even ancient people sought answers to questions about the Earth. In frail wooden ships, they probed the limits of the known world, fearing that they might tumble from its edge or be consumed by dragons. Their descendants came to know our planet as an imperfect sphere, and they began to examine every obscure recess of its surface. In harsher regions, exploration proceeded slowly. It has been only within the last 100 years or so that humans penetrated into the deep interior of Antarctica and probed initially the depths of the ocean and outer limits of our atmosphere and into space. Today, except for a few areas of great cold or dense tropical forest, the continents are well charted. New frontiers for exploration now lie on and beneath the floor of the ocean and outward into space.

WHY STUDY EARTH HISTORY?

Earth's spectacular history deserves to be closely examined, for it permits us to see the future. We expect that many events of the past will happen again. Nearly everything that can happen to the Earth, has happened to the Earth in the past. We owe it to ourselves and to our home planet to look carefully at those events and attempt to understand them.

From the time of its origin to the present day, Earth has undergone continuous modification. Continents have been covered by vast inland seas. They also have ponderously drifted across the face of the globe and slowly collided with other landmasses to form lofty mountain ranges (Fig. 1-1). Massive glaciers have buried vast tracts of forest and prairie. Earth has witnessed recurrent earthquakes, rampant volcanism, catastrophic impacts of meteorites and asteroids, and major changes in the chemistry of the ocean and atmosphere. Along with these physical changes, life on Earth has also undergone change; sometimes slow, but occasionally swift. And in many instances, there have been extinctions of species.

All these events of the geological past have relevance to our lives today. By discovering why they occur, we can better predict the future. For example, we are carefully examining climatic trends of the past so we can better understand today's climatic changes. With knowledge of Earth's history, we can plan ahead. We can help in the effort to avoid further damage to this planetary haven in space that is our home. Aside from these concerns, an important reason to study Earth history is simply to better understand our favorite and unique planet and its amazing forms of life.

GEOLOGY LIVES IN THE PRESENT AND THE PAST

For convenience, we divide the body of knowledge called *geology* into **physical geology** and **historical geology**. The word "convenience" is appropriate here. This is because many aspects of physical geology are necessary to understand the Earth's history. Conversely, many events in our planet's 4.56 billion-year history determine the Earth's physical characteristics. Topics such as weathering and soils, mass wasting, the behavior of streams, glaciers, winds, ground water, ocean waves and currents, and geological resources are typical subjects found in physical geology textbooks. Historical geology addresses Earth's origin and evolution, distribution of lands and seas through time, the growth and reduction of mountains, and the succession of animals, plants, and other living things that lived in the ocean and on continents down through the ages. The historical geologist sees the *results* of past geological events and works backward in time to find their *cause*. The process rather reminds us of the "Crime Scene Investigator," who arrives on the scene of a heinous crime and must reconstruct what happened from whatever clues he or she can find.

Geology primarily focuses on Earth, but its view has broadened to include other planets. This increase in scope is appropriate because geological knowledge is employed in interpreting the images of the surfaces of other planets and their moons, in estimating the power of volcanoes on another planet such as Venus, and in identifying rocks and minerals from Earth's Moon.

Geologists also study other planets and solar system materials like meteorites (Fig. 1-2) to discover

Harold Levin

FIGURE 1-1 The magnificent Canadian Rocky Mountains viewed from Malign Lake, British Columbia. These mountains were initially uplifted over 80 million years ago. Their present appearance results from further uplift and much erosional sculpting during subsequent geological periods down to the present day.

Harold Levin

FIGURE 1-2 Stony meteorite resting on snow of the Antarctic Ice Cap. The contrast of dark meteorites on white snow makes Antarctica a good place for collecting meteorites. The meteorite is composed of iron and magnesium silicate minerals. Its diameter is about 8 cm.

how the planets (including Earth) may have formed. With sophisticated instruments, they scrutinize images of planets or interpret data transmitted by space probes and planetary exploration rovers (Fig. 1-3). Other geologists unravel the structure of mountain ranges, attempt to predict hazards like earthquakes and volcanic eruptions (Fig. 1-4), or study the behavior of glaciers, streams, or underground water.

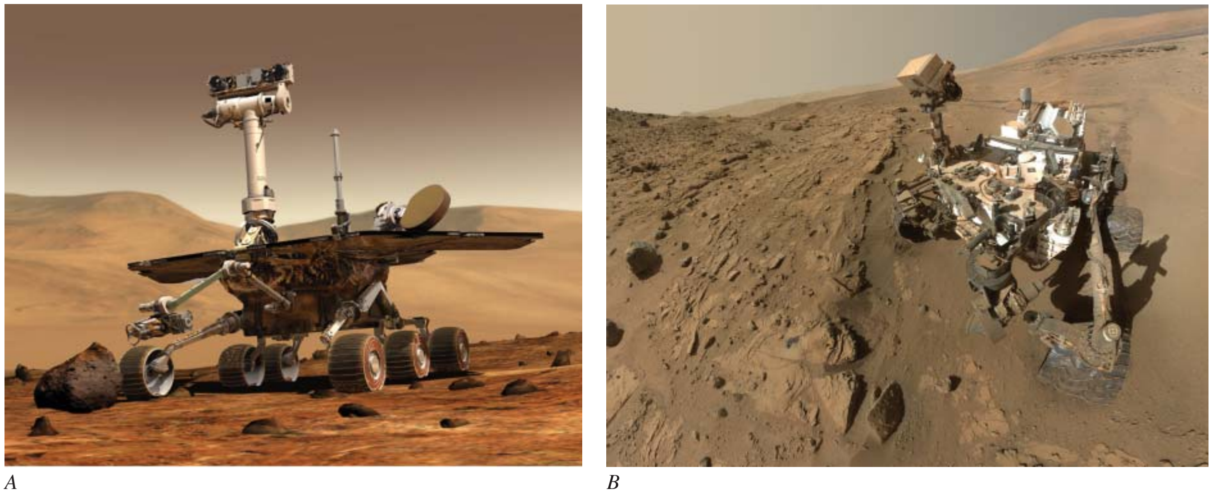
Many "exploration geologists" search for fossil fuels and the metallic ores vital to our modern way of life. This requires knowledge of both physical and historical geology. To understand where to find resources, exploration geologists draw on their knowledge of Earth history, astronomy, physics, chemistry, mathematics, and biology. For example, a petroleum geologist must understand the physics of moving fluids, the chemistry of oil and gas, and the biology of the organisms found as fossils (Fig. 1-5), which are used to trace subsurface rock layers.

Because geology incorporates information from so many other scientific disciplines, it is an integrated science, because it draws on information from many sources. All sciences are integrated to some degree, but geology is particularly so.

A WAY TO SOLVE PROBLEMS: THE SCIENTIFIC METHOD

Geologists, both physical and historical, employ the same procedures used by scientists in other disciplines. Those procedures are called the **scientific method**. The scientific method is a systematic way to uncover answers to questions, solutions to problems, and evidence to prove or disprove ideas and beliefs.

A scientific investigation often begins with a *question*. It proceeds to the collection of *data* (facts from observations and experiments), and is followed by the development of an **hypothesis**, which fits all the data and is likely to account for observations in the future as well as the present. Then, an hypothesis is tested



Courtesy of NASA and the Jet Propulsion Laboratory

NASA/Newscom

FIGURE 1-3 (A) NASA's robotic rover *Opportunity* on Mars in 2004. Its instruments photographed rock outcrops and found evidence for the former presence of water on the red planet. (Rendition by artist Corby Waste of the Jet Propulsion Laboratory). **(B) NASA's *Curiosity* Mars rover uses the camera at the end of its arm in April and May 2014**. The camera took dozens of component images combined into this self-portrait (or "selfie"), where the rover drilled into a sandstone target called "Windjana" on the Martian surface. Most of the component frames of this mosaic view were taken during the 613th Martian day, or sol, of *Curiosity's* work on Mars.

USGS/CVO

FIGURE 1-4 Geologist studies a disastrous mudflow resulting from the eruption of Mount St. Helens, Washington State, in 1980. Mount St. Helens is in the background. The eruption devastated nearly 600 square kilometers and killed 57 people.

Cushman Foundation for Foraminiferal Research

FIGURE 1-5 Fossil shells of microscopic foraminifera (fossil plankton). These are examples of distinctive shells of single-celled animals (foraminifera) that lived in ocean water and at the sea floor. Foraminifera are widely used to identify rock formations and estimate the ages of those formations using samples obtained while drilling for oil and natural gas. From the Yorktown Formation, between 2 and 16 million years old. (Note scale bar of 500 µm, or 0.5 mm.).

and critically examined by other scientists, so it subsequently may be confirmed, modified, or discarded. In some cases, several hypotheses may be proposed to explain the same set of data, and each is tested until the "best" one emerges. The best hypothesis is the simplest one that explains all facts and observations. For example, the origin of the universe and the origin of life have each been the subject of several hypotheses.

An hypothesis that survives repeated challenges and is supported by accumulating favorable evidence may be elevated to a ***theory***. A theory has survived such intense scrutiny that it can be accepted with more confidence than a hypothesis. Examples are the theory of relativity, plate tectonics theory, evolutionary theory, and atomic theory.

It is important to understand that the term "theory" has very different meanings to scientists than to the public. To a scientist, a theory represents knowledge that has a very high probability of being correct. The term "theory" does not imply a lack of knowledge or that it is just someone's opinion or a good guess.

The search for scientific truth does not end with the formulation of a theory. Even after a theory has been firmly established, it must continue to survive rigorous testing derived from advances in science and technology that its author could not have foreseen. If a theory continues to triumph over every challenge, it can be raised to the level of a **scientific law**, such as the law of gravitational attraction.

An Example of the Scientific Method

Nearly a half-century ago, research began on several geological observations that raised questions about the origin of the Mediterranean Sea.

The Observations. Several geological observations were important to this investigation. The four most important are listed here.

1. Geological samples from the beneath the bottom of the Mediterranean showed that microscopic fossil plants and animals changed in character abruptly about 6 million years ago. Older fossils disappeared, and the ones younger than about 6 million years were the same species as fossils from same-age sediments of the Atlantic Ocean.

2. Enormous buried river gorges were found seaward of the present deltas of the Rhone River in France (Fig. 1-6) and several rivers in northern Africa.
3. A hard layer of sedimentary rock was discovered at a depth of about 100 m below the sea floor by seismic instruments. Later, when drilled for samples, it was found to be made of rock gypsum. Rock gypsum forms from the evaporation of sea water.
4. Dome-shaped rock structures lying below the sea floor were discovered by echo-sounding instruments. When drilled later, these features were found to be composed of rock salt. Rock salt forms where vast quantities of sea water is evaporated.

The Questions. Some scientific questions arose from these observations. Those questions included the following.

1. Why did the species of microscopic plants and animals suddenly change in the Mediterranean about 6 million year ago?
2. What process formed the large gorges (deep canyons) beyond the present mouths of Mediterranean rivers like the Rhone?
3. What could have caused the formation of the thick layer of rock gypsum and the dome-shaped masses of rock salt—both of which must have formed from the evaporation of vast quantities of sea water?

In 1970, geologists Kenneth J. Hsu and William B. F. Ryan boarded the oceanographic research vessel *Glomar Challenger* to search for answers (Fig. 1-7). They drilled the Mediterranean sea floor to obtain samples. As drilling progressed, they recovered a sample from the surface of the hard layer. It consisted of pebbles of hardened sediment that had once been soft, deep-sea mud, plus granules of gypsum (a mineral commonly formed by the evaporation of sea water). However, not a single pebble was found to indicate that the sediment had been carried to the sea from surrounding land areas.

In the days following, samples of solid gypsum were repeatedly brought on deck as drilling penetrated the hard layer—clearly, it was a bed of rock gypsum. The composition and texture of the rock gypsum suggested it had formed by evaporation on desert flats. But sediment above and below the rock gypsum layer contained tiny marine fossils, indicating not a desert-like environment, but normal open-ocean conditions.

The Hypothesis. The time had come to *formulate a hypothesis that the Mediterranean Sea was once a desert*. Hsu and Ryan proposed that about 20 million years ago, the Mediterranean was a broad seaway linked to the Atlantic by narrow straits, like the present Strait of Gibraltar. Tectonic movements of Earth's crust closed the straits. Turned into a giant salt lake, the Mediterranean began to evaporate and shrink. Evaporation concentrated the various salts that were dissolved in the water, and this increasing salinity exterminated scores of marine species.

As evaporation continued, the remaining brine became so saturated that minerals dissolved in it were forced to precipitate—that is, they were forced to separate from the solution. This formed the hard layer of rock gypsum. Different salts precipitate at different rates, and the remaining brine in the central, deeper part of the basin was rich in sodium and chlorine ions,

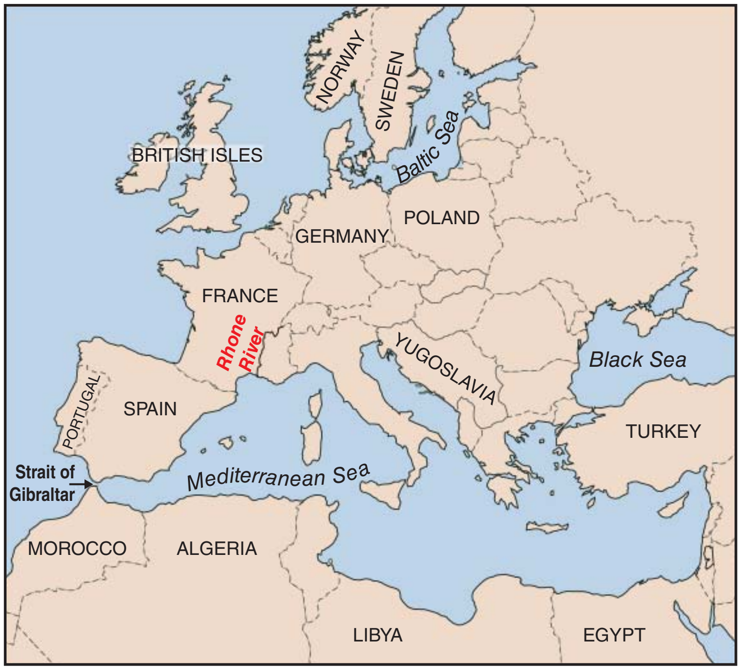


FIGURE 1-6 **Mediterranean region**. When the Mediterranean was a desert, the Rhone River no longer entered at sea level, but flowed down a steep slope and over time eroded a gorge over a kilometer deep. That gorge is now buried beneath younger sediment.


© Corbis

FIGURE 1-7 The Deep Sea Drilling Vessel *Glomar Challenger*. The prominent derrick at midship allows roughnecks on the drilling floor to hoist lengths of pipe upward, and then add that new length of pipe to the pipe already "in the hole." In 1970, while operating in the Mediterranean, the *Glomar Challenger* brought up drill cores indicating the Mediterranean was once a desert.

so the water evaporated to precipitate sodium chloride (the mineral halite, rock salt, or common salt).

In the hypothesis of Hsu and Ryan, the dried-up Mediterranean had become a vast "Death Valley" 3000 meters deep. Streams entering the basin from Europe and Africa now had steep gradients, enabling them to erode spectacular gorges. Then, about 5.5 million years ago, new crustal movements caused the Strait of Gibraltar to open. A gigantic torrent of water poured into the Mediterranean basin at a velocity of 140 kilometers per hour. The deluge quickly eroded a rapidly deepening gorge that was over seven kilometers wide. It would have been an astonishing spectacle to observe. As the obstruction that once barred Atlantic waters from flowing into the Mediterranean basin was being eroded, the rate of water flow increased enormously. The Mediterranean would have been filled in only about two years. In that same period of time, the global sea level would have dropped about 9.5 meters as a result.

Evidence for the erosion of the obstruction that had barred Atlantic waters from entering the Mediterranean basin was found in cores drilled in the sea floor in preparation for a proposed Africa–Europe tunnel project. The cores reveal a deep, 200 kilometer long channel filled with the loose sediment.

The turbulent currents racing down the slope tore into the hardened salt flats, grinding them into the pebbles observed in the first sample taken by the *Glomar Challenger*. As the basin refilled, marine organisms returned, mostly migrants from the Atlantic. Soon layers of oceanic ooze were deposited above the old hard layer.

Long after the Mediterranean Basin was refilled, pressure from the weight of overlying sediments forced the salt to flow plastically upward to form giant domes of rock salt.

The questions about the faunal changes, the salt and rock gypsum deposits, the unusual pebbly sediment, and the deeply buried gorges were now answered. The scientific method had worked well, and *the hypothesis that the Mediterranean Sea was once a desert* could now be critically examined by other geologists. This example of how questions can be solved by the scientific method demonstrates how geologists are like detectives probing the rocks for clues to the complex past of our planet.

The Theory. The hypothesis has survived critical examination over the past five decades and is on its way to being accepted as a *theory*. It is important to understand that the term *theory*, as used in science, does not mean a guess or hunch. As spelled out by the National Academy of Sciences, a scientific theory is a well-established explanation of some aspect of the natural world that is based on a body of facts that have been repeatedly confirmed.

THREE GREAT THEMES IN EARTH HISTORY

Earth's history is like a novel, with grand, sweeping themes. The three major themes—intensely interacting themes—are deep time, plate tectonics, and the evolution of life.

Deep Time

Recognition of the immensity of geological time is the single most important contribution to human knowledge made by geology. Geologists look back across 4.56 billion years of Earth history, from our planet's chaotic birth to the present. Compared to the average duration of a human life, it is a span of time so huge as to be essentially impossible to comprehend. It is not surprising, therefore, that our ancestors believed hills and valleys were changeless and eternal and that the planet originated only a few thousand years ago.

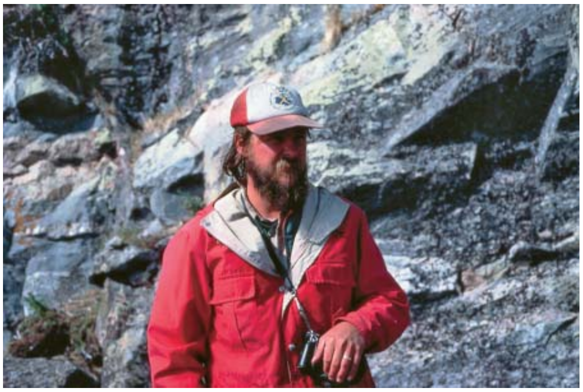
Eventually, we came to realize that the slow and relentless work of erosion reduces mountains to plains, that valleys are the result of long periods of erosion, and that sands and gravels produced by erosion have been turned to rock. These changes clearly required vast amounts of time.

But how much time? And which event preceded—or followed—another? To answer these questions, it was necessary to find the **absolute age** of rocks in years. A way to do so was enabled by the discovery of *radioactivity* in 1896.

Certain atoms are unstable, causing them to be radioactive. This means they decay by expelling particles of their nuclei, converting themselves into stable "daughter" atoms, mostly of different elements. A well-known example is uranium, which is radioactive and continually expels particles. The rate of this decay can be accurately measured. The term **half-life** expresses the rate of decay. Half-life is the time required for one-half of the original quantity of radioactive atoms to decay.

As an example, the radioactive element uranium-235 has a half-life of approximately 704 million years. This means that after 704 million years pass, only half (50%) of the original uranium-235 in a mineral will remain. After a second 704 million years pass, half of that half (25%) will have decayed. Thus, a rock that contains only 25% uranium-235 and 75% of the daughter atoms must be 1,408 million years old (704 + 704). Using this method, some Earth rocks have been calculated to be 4.04 billion years old (Fig. 1-8), and some minerals at the Earth's surface are as old as 4.38 billion years.

Before the discovery of radioactivity, geologists were able to determine only if particular layers or bodies of rock were *older* or *younger* than others. This determined a rock's **relative age**. Relative age determinations provided a framework in which to place events of the geological past. Through relative dating, geologists developed a *geological time scale*, and with dating through radioactive decay, that time scale was calibrated in actual years. We will examine how this was accomplished in Chapter 3.



Samuel A. Bowring

FIGURE 1-8 Geologist Samuel Bowring stands before some of Earth's oldest rocks. Named the Acasta Gneiss (pronounced "nice"), this most ancient of rock formations is found at the Earth's surface in Canada's Northwest Territories. Radioactive dating methods indicate it is 4.04 billion years old, having survived 87% of Earth's 4.56-billion-year history.

Plate Tectonics

A significant number of events in both physical and historical geology are related to a grand unifying concept termed **plate tectonics**. "Tectonics," from the same Greek word as "architecture," refers to large-scale deformation of rocks in Earth's outer layers. The term "plate" is given to large slabs of Earth's outer layers, or what is called the lithosphere. The **lithosphere** is the rigid outer layer of Earth (roughly 100 km thick) that includes the **crust** as well as the uppermost part of the **mantle** (Fig. 1-9).

Earth's lithosphere, and thus its surface, is broken into seven large lithospheric plates and about twenty smaller ones. The plates rest on a plastic, easily deformed layer of the mantle called the **asthenosphere**. Probably because of heat-driven convectional flow in the asthenosphere, the plates move. They move almost imperceptibly, only millimeters per year.

Tectonic plates have well-defined edges or "margins." Where two or more plates move apart (diverge) from one another, the plate margins form **divergent boundaries**. Where plates converge, **convergent boundaries** occur. Where plates grind past one another, **transform boundaries** occur. You will encounter these terms again in Chapter 7, where we examine plate tectonics in more detail.

Evolution of Life (Biological Evolution)

Plate tectonics is the "great unifying theory" that explains many physical phenomena in geology. In biology, evolution is the "great unifying theory" for understanding the history of life. Because of evolution, animals and plants living today are different from their ancestors. Evolution is the way that living systems move through time. They have changed in appearance, in genetic characteristics, in the way they function, and in their body chemistry, apparently in response to changes in the environment and competition for food. Fortunately, fossils record these changes through time for us to study. Fossils are also valuable indicators of the age of rocks.

Although Charles Darwin is credited for the concept of evolution, the idea began as early as 2600 years ago, in the seventh century BCE. We find the basic notion of evolution or change through time in the writings of the Greek philosopher Anaximander. But Darwin and his colleague Alfred R. Wallace were the first scientists to propose an hypothesis with convincing evidence. They