Students exploring a small canyon in Illinois. Geology is everywhere!

PRELUDE

And Just What Is Geology?

Civilization exists by geological consent, subject to change without notice.

—*Will Durant (1885–1981)*

LEARNING OBJECTIVES

By the end of this prelude, you should understand . . .

- the scope and applications of geology.
- the foundational themes of modern geologic study.
- how geologists employ the scientific method.

P.1 In Search of Ideas

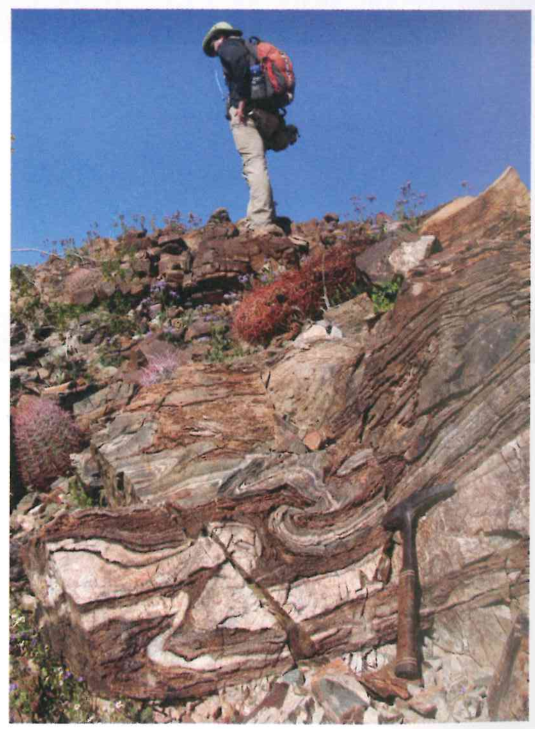
We arrived in the late-night darkness, at a campsite in western Arizona. Here in the desert, so little rain falls over the course of a year that hardly any plants can survive, and rocks crop out on many hills. Under the dry sky, there's no need for tents, so we could sleep under the stars with our sleeping bags on a bed of sand. At dawn, the red rays of the first sunlight made the slope of the steep-sided hill near our campsite start to glow, and we could see our target, a prominent ledge of rusty-brown rock that formed a shelf at the top of the hill. To reach it, though, we'd have to climb a steep slope littered with jagged boulders.

After a quick breakfast, we loaded our day packs with water bottles and granola bars, slathered on a layer of sunscreen, and set off toward the slope. It was the breezeless morning of what was going to be a truly hot day, and we wanted to gain elevation before the sun rose too high in the sky. After a tiring hour finding our way through the boulder obstacle course, we reached the base of the ledge and decided to take a rest before ascending the final cliff. But just as we leaned back to rest our backs against a rock, we heard an unnerving vibration. Somewhere nearby, too close for comfort, a rattlesnake shook an urgent warning with its tail. Rest would have to wait, and we scrambled up the ledge. It was the right choice, for the view from the top of the surrounding landscape was amazing (**Fig. P.1a**). But the rocks beneath our feet were even more amazing. Close up, we could see curving ribbons of light and dark layers, cut by stripes of white quartz. The ledge preserved the story of a distant age in our planet's past when the rock we now stood on was kilometers below ground level and was able to flow like soft plastic, but ever so slowly (**Fig. P.1b**). We now set to the task of figuring out what it all meant.

Geologists—scientists who study the Earth—do indeed explore remote deserts, high mountains, damp rainforests, frigid glaciers, and deep canyons (**Fig. P.2**). Such efforts can strike people in other professions as a strange way to make a living. This sentiment underlies the Scottish poet Walter Scott's (1771–1832) description of geologists at work: "Some rin uphill and down dale, knappin' the chucky stones to pieces like sa' many roadmakers run daft. They say it is to see how the warld was made!" But Scott had it right—to see how the world was made, to see how it continues to evolve, to find its resources, to protect against its natural hazards, and to predict what its future may bring. These are the questions that have driven geologists to

FIGURE P.1 Geologic exploration provides beautiful views, and mysteries to solve.

(a) A view of the western Arizona desert is not just beautiful—it holds clues to the Earth's past and to the changes taking place today.



(b) The contortions of the rock layers speak of a time when the rock flowed, like soft plastic.

explore the Earth, on all continents and in all oceans, from the equator to the pole and everything in between.

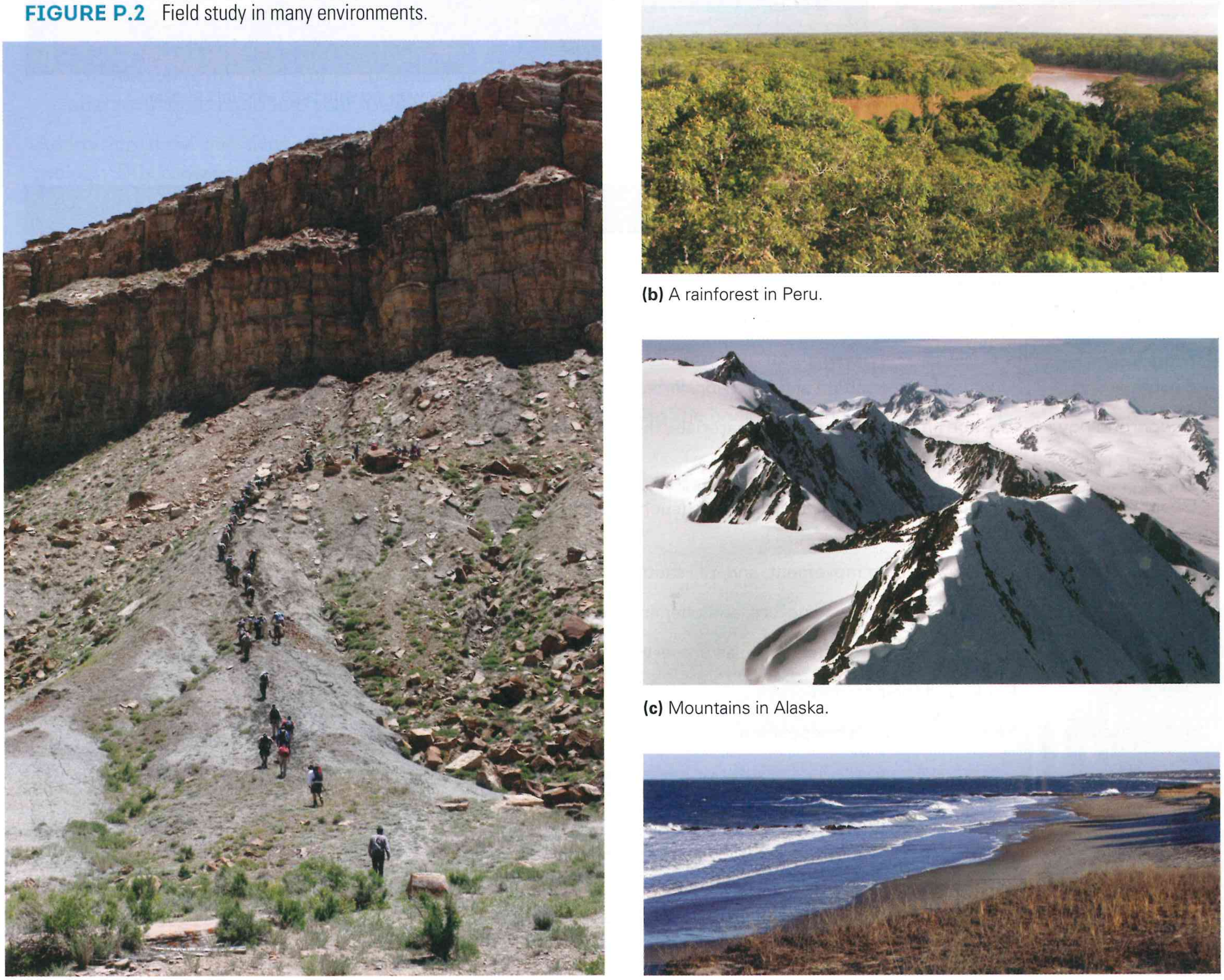
Geologic discovery continues today, with a variety of techniques. While some geologists continue to work in the field with hammers and hand lenses, others have moved into laboratories that employ sophisticated electronic instruments to analyze microscopic quantities of earth materials down to the scale of atoms (**Fig. P.3a**). Still others use satellites to detect the motions of continents or the stability of volcanoes, and use high-speed computers to locate earthquakes or analyze the flow of underground water (**Fig. P.3b**). For over two centuries, geologists have pored over the Earth in search of ideas to explain the processes that form and change our planet. In this Prelude, we look more closely at the questions geologists ask and have tried to answer. You'll see that many of these answers are not just of academic interest but have implications for society as a whole.

P.2 The Nature of Geology

Geology (also called geoscience) is the study of the Earth. It encompasses fundamental studies to characterize the formation and composition of the Earth, the causes of mountain building and ice ages, the long-term record of life's evolution, and the long-term history of climate change. Geology also addresses practical problems such as how to keep pollution out of groundwater, how to find oil and useful minerals, and how to avoid landslides. You can get a sense of the different kinds of problems that geologists work on by examining a list of the many subdisciplines of geology (**Table P.1**).

Hundreds of thousands of people worldwide pursue careers in geology, mostly in energy, mining, water, engineering, and

FIGURE P.2 Field study in many environments.



(a) A desert cliff in Utah.

(b) A rainforest in Peru.

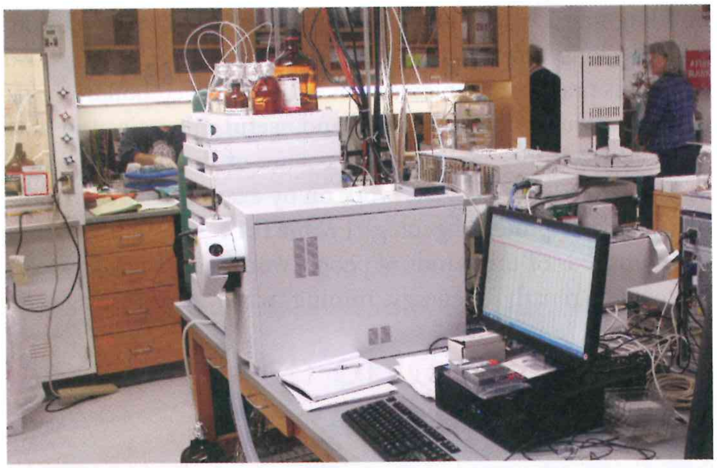
(c) Mountains in Alaska.

(d) The shore in Massachusetts.

environmental companies. A smaller number work in universities or colleges, government-sponsored geological surveys, and research laboratories. Nevertheless, since most people reading this book will not become professional geologists, it's fair to ask the question, "Why should people, in general, study geology?"

First, geology may be one of the most practical subjects you can learn. When news reports begin with "Scientists say . . ." and

FIGURE P.3 Much of geologic study today takes place in the laboratory or in other research facilities using high-speed computers.



(a) Analytical equipment in a geology research laboratory.

(b) A computer facility working with large amounts of data.

TABLE P.1 Principal Subdisciplines of Geology (Geoscience)

Name	Subject(s) of Study
Engineering geology	Aspects of geology relevant to understanding slope stability, or to building tunnels, dams, mines, roads, or foundations
Environmental geology	Interactions between the environment and geologic materials, and contamination of geologic materials by pollutants
Geochemistry	Chemical composition and behavior of materials in the Earth, and chemical reactions in natural environments
Geochronology	The age (in years) of geologic materials, the Earth, and extraterrestrial objects
Geomorphology	Landscape formation and evolution
Geophysics	Physical characteristics of the Earth (such as Earth's magnetic field and gravity field), and causes of forces in the Earth
Hydrogeology	Groundwater, its movement, and its reaction with rock and soil
Mineralogy	physical properties, structure, and chemical behavior of minerals
Paleontology	Fossils and the evolution of life as preserved in the rock record
Petrology	Rocks and their formation
Sedimentology	Sediments and their deposition
Seismology	Earthquakes and the Earth's interior as revealed by earthquake waves
Stratigraphy	The succession of sedimentary rock layers and the record of Earth's history that they contain
Structural geology	Rock deformation (bending and breaking) in response to the application of force associated with mountain building
Tectonics	Origin and significance of regional-scale geologic features
Volcanology	Volcanic eruptions and their products, and volcanic hazards

then continue with "an earthquake occurred today off Japan," or "landslides will threaten the city," or "chemicals from a toxic waste dump will ruin the town's water supply," or "there's only a limited supply of oil left," or "the floods of the last few days are the worst on record," the scientists that the reports refer to are geologists. In fact, ask yourself the following questions, and you'll realize that geologic processes, phenomena, and materials play major roles in daily life:

- Do you live in a region threatened by landslides, volcanoes, earthquakes, or floods (**Fig. P.4a**)?
- Are you worried about the price of energy or about whether there will be a war in an oil-supplying country (**Fig. P.4b**)?
- Do you ever wonder where the copper in your home's wires comes from? Or the lithium in the battery of your cell phone?
- Have you seen fields of green crops surrounded by desert and wondered where the irrigation water comes from?
- Would you like to buy a dream house near a beach or a river?
- Are you following news stories about how toxic waste can migrate underground into your town's well water?

Addressing these questions requires a basic understanding of geology. This knowledge may help you avoid building your home on a hazardous floodplain or fault zone, on an unstable slope, or along a rapidly eroding coast. With an understanding of groundwater, you may be able to find a good site for a well. With knowledge of the geologic controls on resource distribution, you may be able to invest more wisely in the resource industry or understand the context of political choices regarding energy policy.

Second, the study of geology gives you an awareness of the planet that no other field can. As you will see, the Earth is a complicated world, where living organisms, oceans, atmosphere, and solid rock interact with one another in a great variety of ways. Geologic study reveals Earth's antiquity (it's about 4.54 billion years old) and demonstrates how the planet has changed profoundly during its existence. What our ancestors considered to be the center of the Universe has become, with the development of geologic perspective, our "island in space" today. And what was believed to be an unchanging orb originating at the same time as humanity has become a dynamic planet that existed long before people did—and continues to evolve.

Third, the study of geology puts the accomplishments and consequences of human civilization in a broader context. View the aftermath of a large earthquake, flood, or hurricane, and it's clear that the might of natural geologic phenomena greatly exceeds the strength of human-made structures. But watch a bulldozer clear a swath of forest, a dynamite explosion remove the top of a hill, or a prairie field evolve into a housing development, and it's clear that people can change the face of the Earth at rates often exceeding those of natural geologic processes.

Finally, when you finish reading this book, your view of the world may be forever colored by geologic curiosity. If you walk in the mountains, you may remember that mountains rise and fall over time in response to forces that shape and reshape the Earth's surface. If you hear about a natural disaster, you may think about the various phenomena that trigger disasters. And as you drive past rock exposures along a highway, you won't just see featureless masses of gray but will pick out layers and structures providing a record of the Earth's very long history.

P.3 Themes of this Book

A number of narrative themes appear—and reappear—throughout this text. These themes, listed below, can be viewed as the book's overall take-home message.

- *Geology is a synthesis of many sciences:* The study of geology can help you understand physical science in general, for

FIGURE P.4 Geology provides insight into natural hazards and resource exploration.

(a) Collapsed buildings in the aftermath of an earthquake.

(b) Coal is one of many resources that comes from the Earth.

geology applies many of the basic concepts of physics and chemistry to the interpretation of visible phenomena. As you learn about the Earth, you'll also be learning about the behavior of matter and energy, and about the nature of chemical reactions.

- *The Earth has an internal structure:* The Earth is not a homogeneous ball, but rather it consists of concentric layers. From center to surface, Earth has a core, mantle, and crust. We live on the surface of the crust, where it meets the atmosphere and the oceans.
- *The outer layer of the Earth consists of moving plates:* In the 1960s, geologists recognized that the crust, together with the uppermost part of the underlying mantle, forms a 100- to 150-km-thick semi-rigid shell called the **lithosphere**. Large cracks separate this shell into discrete pieces, called **plates**, which move very slowly relative to one another (**Fig. P.5**). The theory that describes this movement and its consequences is called the **theory of plate tectonics**, and it is the foundation for understanding most geologic phenomena. Plate movements yield earthquakes, volcanoes, and mountain ranges, and cause the map of Earth's surface to change very slowly over time.
- *We can picture the Earth as a complex system:* The Earth is not static, but rather it is a dynamic entity whose components can move and change over time. Our planet's interior, solid surface, oceans, atmosphere, and life all interact with one another in many ways to yield the land, oceans, and air in which we and other species of organisms can live. Geologists refer to this interconnected web of interacting materials and processes as the **Earth System**. Within the Earth System, certain materials cycle among different types of rock, among rock, sea, and air, and among all of these entities and life (**Fig. P.6**). Over time, the distribution of these materials among various components of the Earth System can change, as can the characteristics of the components.
- *The Earth is a planet:* Despite the uniqueness of the Earth System, we can think of Earth as a planet, formed like the other planets of the Solar System. But because of the way the Earth System operates, our planet differs from other planets by having plate tectonics, an oxygen-rich atmosphere and liquid-water ocean, and abundant life.
- *The Earth is very old:* Geologic data indicate that the Earth formed 4.54 billion years ago—plenty of time for geologic processes to generate and destroy landscapes, for life forms to evolve, and for the map of the planet to change. Plate movement at rates of only a few centimeters per year can move a continent thousands of kilometers if those movements continue for hundreds of millions of years. There is time enough to build mountains and time enough to grind them down, many times over. The Earth has a history, and it extends far into the past, long before human ancestors appeared.
- *The geologic time scale divides Earth's history into intervals:* To refer to specific portions of geologic time, geologists developed the **geologic time scale** (**Fig. P.7**). The last 541 million years comprise the *Phanerozoic Eon*, and all time before that falls in the *Precambrian*. The Precambrian can be further divided into three main intervals named, from oldest to youngest: the *Hadean*, the *Archean*, and the *Proterozoic Eons*. The Phanerozoic Eon, in turn, can be divided into three

FIGURE P.5 A simplified map of the Earth's plates. The arrows indicate the direction each plate is moving, and the length of the arrow indicates plate velocity (the longer the arrow, the faster the motion).

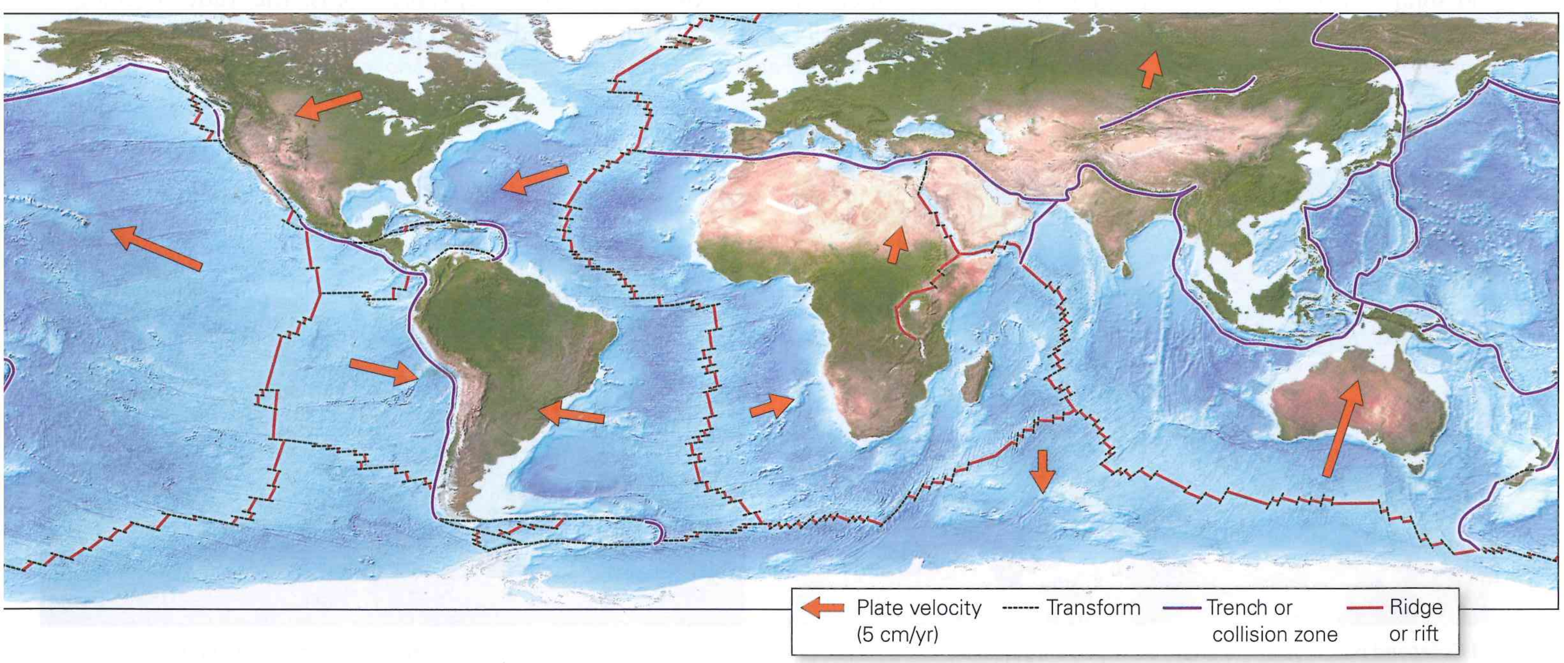
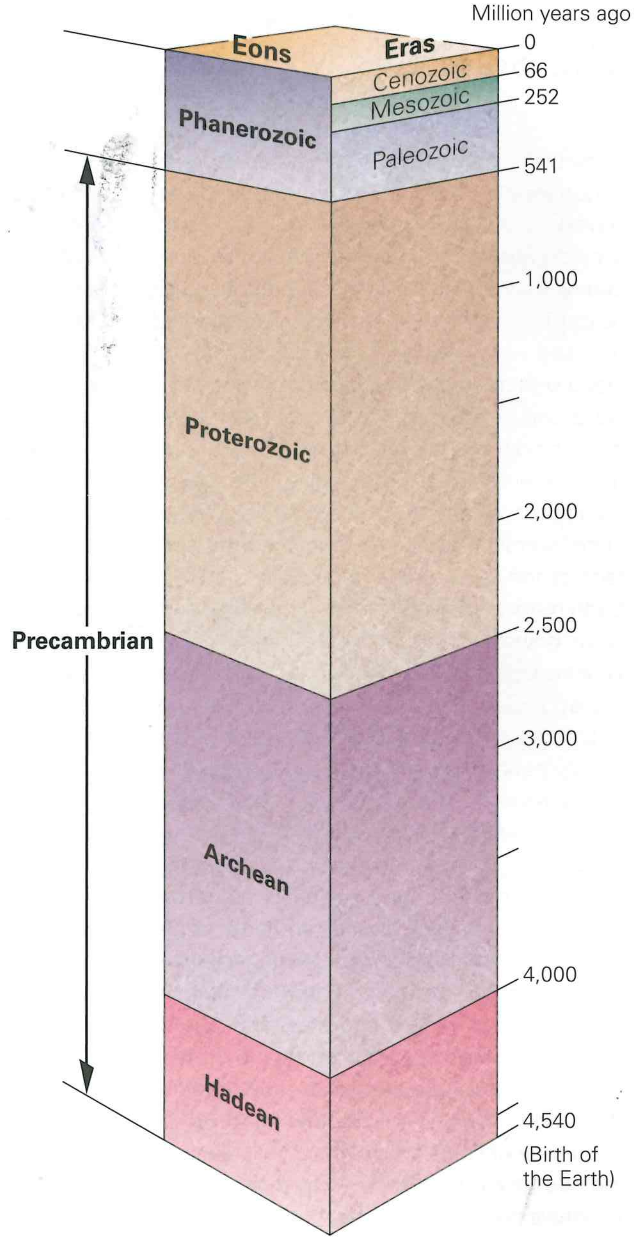


FIGURE P.6 In this scenic view in Switzerland, we see many aspects of the Earth System—air, water, ice, rock, life, and human activity.

main intervals named, from oldest to youngest: the *Paleozoic*, the *Mesozoic*, and the *Cenozoic Eras.*

- *Internal and external processes drive geologic phenomena: Internal processes* are driven by heat from inside the Earth. Plate movement is an example. Because plate movements cause mountain building, earthquakes, and volcanoes, we consider all of these phenomena internal processes. *External processes* are driven by energy coming to the Earth from the Sun. The heat produced by this energy drives the movement of air and water, which grinds and sculpts the Earth's surface and transports the debris to new locations, where it accumulates. The interaction between internal and external processes forms the mountains, canyons, beaches, and plains of our planet. As we'll see, **gravity**—the pull that one mass exerts on another—plays an important role in both internal and external processes.
- *Geologic phenomena affect society:* Volcanoes, earthquakes, landslides, floods, groundwater, energy sources, and mineral reserves are of vital interest to every inhabitant of this planet. Therefore, throughout this book we emphasize the linkages among geology, the environment, and society.
- *Physical aspects of the Earth System are linked to life processes:* All life on this planet depends on such physical features as the minerals in soil; the temperature, humidity, and composition of the atmosphere; and the flow of surface and subsurface water. And life in turn affects and alters physical features. For example, the oxygen in Earth's atmosphere comes from photosynthesis, a life activity in plants. This oxygen in turn permits complex animals to survive and affects chemical reactions among air, water, and rock. Without the physical Earth, life could not exist; but without life, this planet's surface might have become a frozen wasteland, like that of Mars, or a cloud-enshrouded oven, like that of Venus.
- *The Earth has changed dramatically in many ways over geologic time and continues to change:* The landscape that you see outside your window today is not what you would have seen a thousand, a million, or a billion years ago. Over Earth history, the planet's surface, composition of the atmosphere, and sea level have all changed. Change continues today, and

FIGURE P.7 The geologic time scale.



(a) The scale has been divided into eons and eras.

One thousand years ago = 1 **Ka**
(Ka stands for kilo-annum)

One million years ago = 1 **Ma**
(Ma stands for mega-annum)

One billion years ago = 1 **Ga**
(Ga stands for giga-annum)

(b) Abbreviations for time units.

BOX P.1 CONSIDER THIS . . .

The Scientific Method

Sometime during the past 200 million years, a large block of rock or metal, which had been orbiting the Sun, slammed into our planet. It made contact at a site in what is now the central United States, a landscape of flat cornfields. The impact of this block, a meteorite, released more energy than a nuclear bomb—a cloud of shattered rock and dust blasted skyward, and once-horizontal layers of rock from deep below the ground sprang upward and tilted on end beneath the gaping hole left by the impact. When the dust had settled, a huge crater surrounded by debris marked the surface of the Earth at the impact site. Later in Earth history, running water and blowing wind wore down this jagged scar. Some 15,000 years ago, sand, gravel, and mud carried by a vast glacier buried what remained, hiding it entirely from view (**Fig. BxP.1**). Wow! So much history beneath a cornfield. How do we know this? It takes scientific investigation.

The movies often portray science as a dangerous tool, capable of creating Frankenstein's monster, and scientists as nerdy characters with thick glasses and poor taste in clothes. In reality, **science** is simply the use of observation, experiment, and calculation to explain how nature operates, and scientists are people who study and try to understand natural phenomena. Scientists guide their work using the **scientific method**, a sequence of steps for systematically analyzing scientific problems in a way that leads to verifiable results. Let's see how geologists employed the steps of the scientific method to come up with the meteorite-impact story.

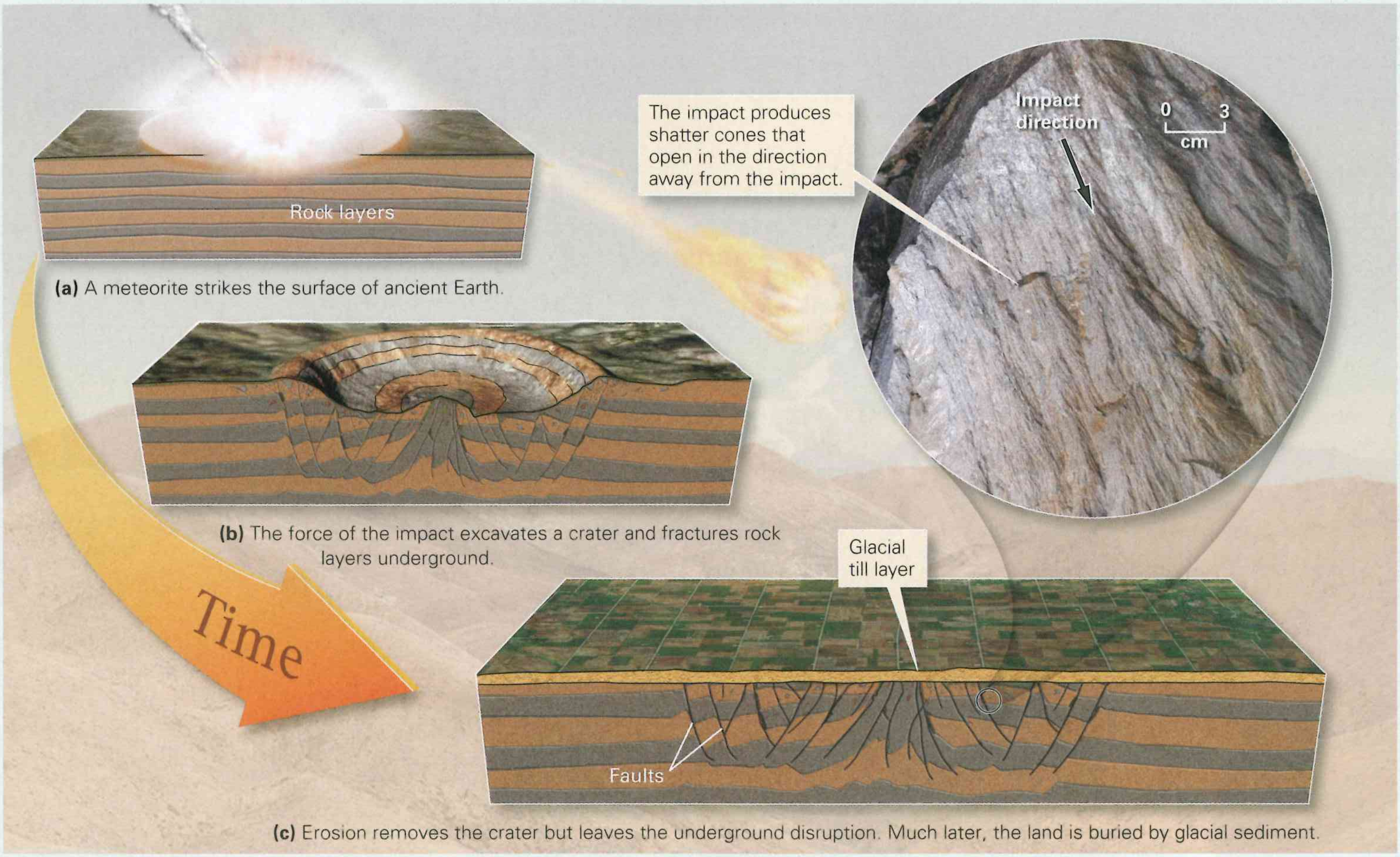
1. *Recognizing the problem.* Any scientific project, like any detective story, begins by identifying a mystery. The cornfield mystery came to light when water drillers discovered limestone, a rock typically made of shell fragments, just below the 15,000-year-old glacial sediment. In surrounding regions, the rock beneath the glacial sediment consists of sandstone, a rock made of cemented-together sand grains. Since limestone can be used to build roads, make cement, and produce the agricultural lime used in treating soil, workers stripped off the glacial sediment and dug a quarry to excavate the limestone. They were amazed to find that rock layers exposed in the quarry were tilted steeply and had been shattered by large cracks. In the surrounding regions, all rock layers are horizontal like the layers in a birthday cake, the limestone layer lies underneath the sandstone, and the rocks contain relatively few cracks. Curious geologists came to investigate, and they soon realized that the geologic features of the land just beneath the cornfield presented a problem to be explained: what phenomena had brought limestone up close to the Earth's surface, had tilted the layering in the rocks, and had shattered the rocks?
2. *Collecting data.* The scientific method proceeds with the collection of observations or clues that point to an answer. Geologists studied the quarry and determined the age of its rocks, measured the orientation of the rock layers, and documented (made a written or photographic record of) the fractures that broke up the rocks.
3. *Proposing hypotheses.* A scientific **hypothesis** is merely a possible explanation, involving only natural processes, that can explain a set of observations. Scientists propose hypotheses during or after their initial data collection. In this example, the geologists working in the quarry came up with two alternative hypotheses: either the features in this region resulted from a volcanic explosion, or they were caused by a meteorite impact.
4. *Testing hypotheses.* Since a hypothesis is just an idea that can be either right or wrong, scientists must put hypotheses through a series of tests to see if they work. The geologists at the quarry compared their field observations with published observations made at other sites of volcanic explosions and meteorite impacts, and they studied the results of experiments designed to simulate such events. If the geologic features visible in the quarry were the result of volcanism, the quarry should contain rocks formed by the freezing of molten rock erupted by a volcano. But no such rocks were found. If, however, the features were produced by an impact, the rocks should contain **shatter cones**, tiny cracks that fan out from a point. 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 the test!

aspects of the Earth System are changing faster than ever before because of human activity.

- *Most of the resources that we use come from geological materials:* Modern society uses vast quantities of oil, gas, coal, metal, concrete, and other materials. All of these come from the Earth.
- *Science comes from observation, and people make scientific discoveries:* Science does not consist of subjective guesses or arbitrary dogmas but rather of a consistent set of objective statements resulting from the application of the scientific method (Box P.1). Every scientific idea must be tested thoroughly and should be used only when supported by documented observations. Further, scientific ideas do not appear out of nowhere; they are the result of human efforts. Wherever possible, this book shows where geologic ideas came from, and tries to answer the question, "How do we know that?"

As you read this book, please keep these themes in mind. Don't view geology as a list of words to memorize but rather as an interconnected set of concepts to digest. Most of all, enjoy yourself as you learn about the most fascinating planet in the Universe.

FIGURE BxP.1 An ancient meteorite impact excavates a crater and permanently changes rock beneath the surface.



Theories are scientific ideas supported by an abundance of evidence; they have passed many tests and have failed none. Scientists are much more confident in the correctness of a theory than of a hypothesis. Continued study in the quarry eventually yielded so much evidence for impact that the impact hypothesis came to be viewed as a theory. Scientists continue to test theories over a long time. Successful theories withstand these tests and are supported by so many observations that they become part of a discipline's foundation. (As you will discover in Chapter 3, geologists consider the idea that continents have moved around the surface of the Earth to be a theory because so much evidence supports it.) However, some theories may eventually be disproven and replaced by better ones.

In a few cases, scientists have been able to devise concise statements that completely describe a specific relationship or phenomenon. Such statements, called **scientific laws**, apply without exception for a given range of conditions. Newton's law of gravitation serves as an example—it is a simple mathematical expression that always defines the invisible pull exerted by one mass upon another. Note that scientific laws do not in themselves explain a phenomenon, and in this way they differ from theories. For example, the law of gravity does not explain why gravity exists, but the theory of evolution does explain why evolution occurs.

GUIDE TERMS