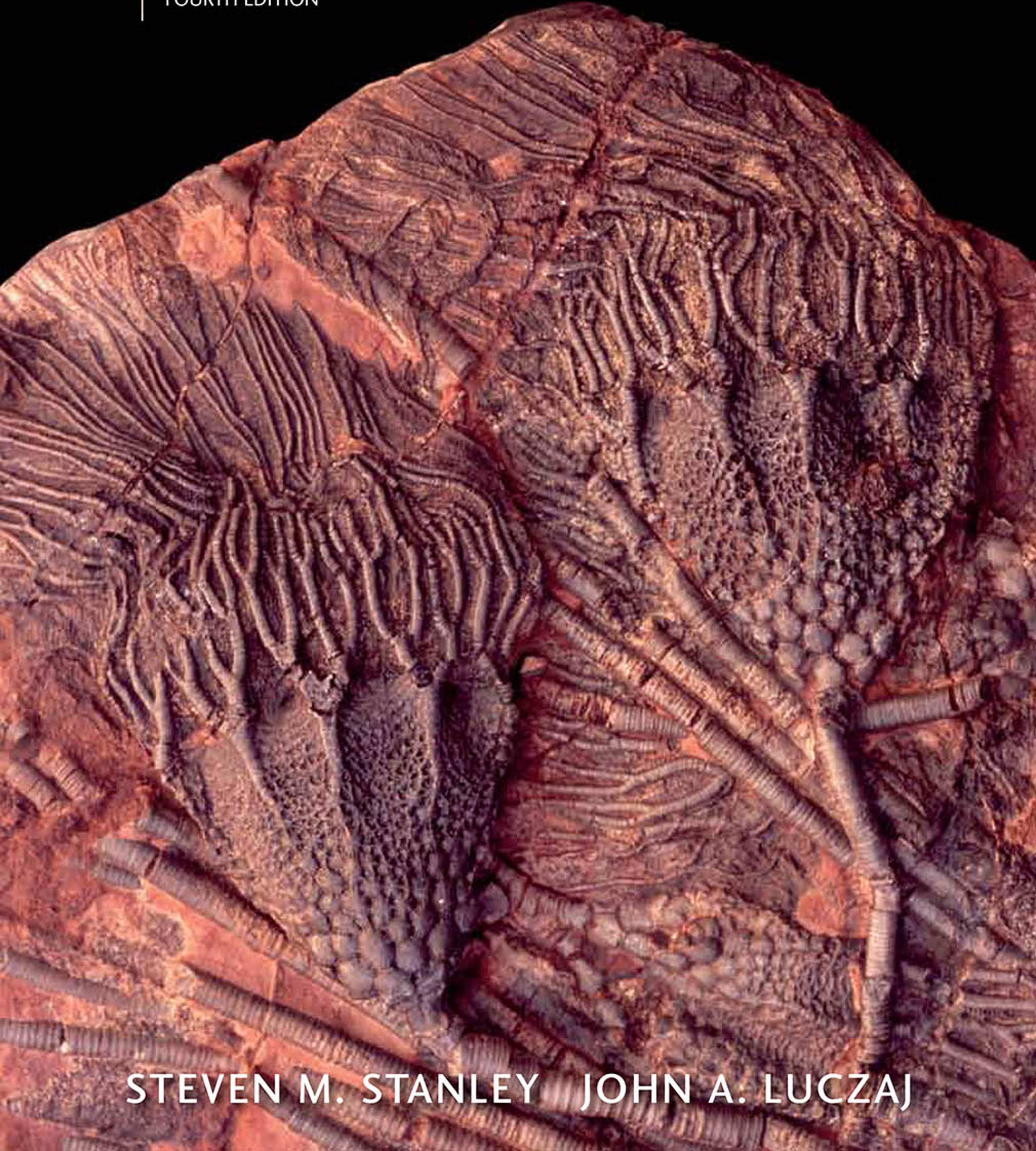
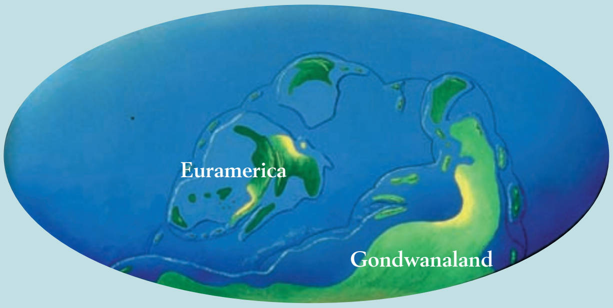
EARTH SYSTEM HISTORY

FOURTH EDITION



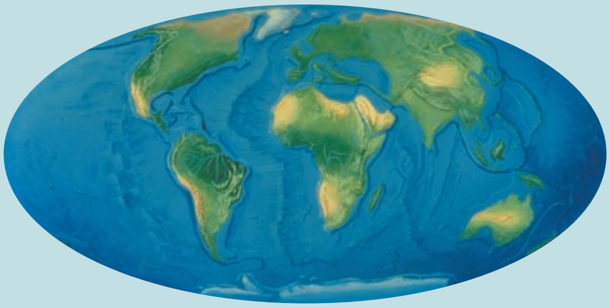
STEVEN M. STANLEY   JOHN A. LUCZAJ

MIDDLE SILURIAN



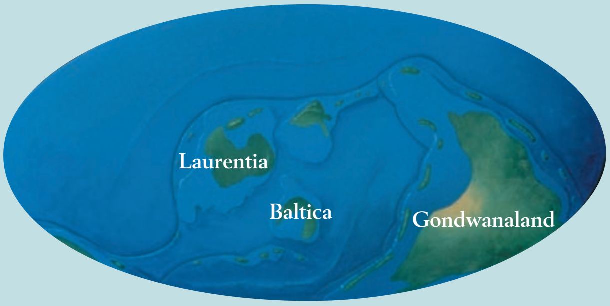
Laurentia and Baltica are sutured to form Euramerica

MIDDLE MIOCENE



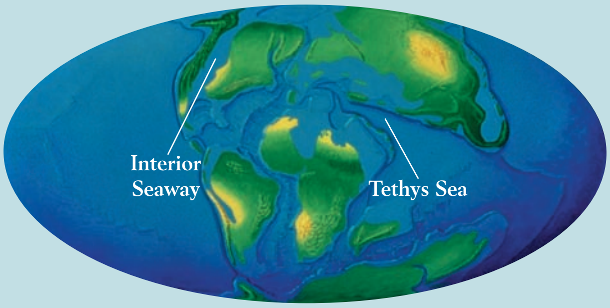
Continents are dispersing

MIDDLE ORDOVICIAN



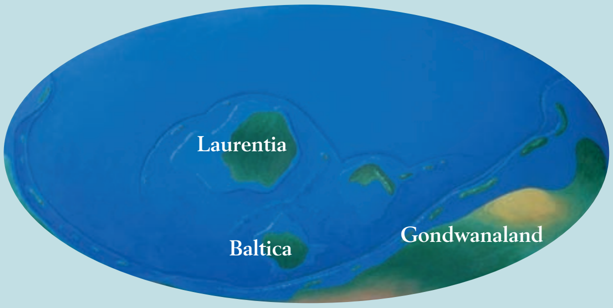
Microcontinents and island arcs are sutured to Laurentia

LATE CRETACEOUS



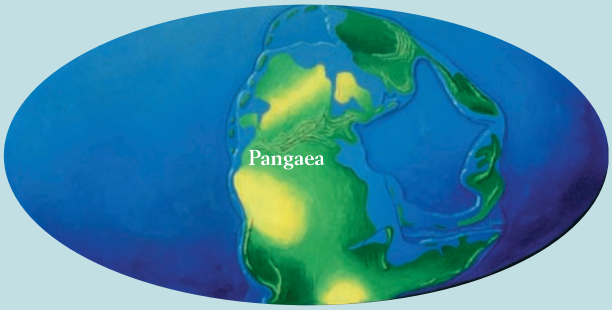
Pangaea is fragmenting

LATE CAMBRIAN



The Proterozoic supercontinent has fragmented

LATE PERMIAN



Gondwanaland is sutured to Euramerica to form Pangaea

EARTH SYSTEM HISTORY

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FOURTH EDITION

STEVEN M. STANLEY

University of Hawaii

JOHN A. LUCZAJ

University of Wisconsin–Green Bay

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ABOUT THE AUTHORS

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STEVEN M. STANLEY is a research professor in paleobiology at the University of Hawaii. His research includes such areas as functional morphology; macro evolution; effects of changing seawater chemistry on biomineralization, reef growth, and lime sediment production; and the role of climate change in mass extinctions. He received an AB from Princeton University in 1963 and a PhD from Yale University in 1968. Before moving to the University of Hawaii, he was on the faculty of the University of Rochester for two years and the faculty of Johns Hopkins University for thirty-six years.

Dr. Stanley has written three previous editions of *Earth System History* and a total of three editions of its predecessors, *Earth and Life Through Time* and *Exploring Earth and Life Through Time.* His other books include *Principles of Paleontology* (with David M. Raup), *Macroevolution: Pattern and Process*, *The New Evolutionary Timetable* (nominated for an American Book Award), *Extinction*, and *Children of the Ice Age: How a Global Catastrophe Allowed Humans to Evolve*. He has been elected to the National Academy of Sciences and the American Academy of Arts and Sciences and has received a Guggenheim Fellowship and numerous awards, including the Paleontological Society Medal, the James H. Shea Award of the National Association of Geoscience Teachers (for books authored), the Mary Clark Thompson Medal of the National Academy of Sciences, the Twenhofel Medal of the Society for Sedimentary Geology, and the Penrose Medal of the Geological Society of America.

Dr. Stanley has taught courses in earth history, paleontology, paleoecology, macroevolution, marine ecology, biodiversity, and Darwin and Darwinism.

JOHN A. LUCZAJ (Loủ-chai) is a field geologist interested in sedimentology, geochemistry, and hydrogeology, specializing in diagenesis in sedimentary systems. He has conducted research on hydrothermal dolomitization, fluid inclusions in minerals, groundwater geochemistry and aquifer recovery, geologic mapping, geomorphology, and Holocene cave deposits. One of his important contributions was the first successful dating of diagenetic dolomite using the uranium-lead method.

Dr. Luczaj received a BS in geology from the University of Wisconsin–Oshkosh in 1993, an MS in geology from the University of Kansas in 1995, and a PhD in geology from Johns Hopkins University in 2000. He worked as a USGS-NAGT summer trainee at the Hawaiian Volcano Observatory in 1993, as a visiting assistant professor at Towson University (1999–2000) and Western Michigan University (2000–2002), and as an environmental consultant from 2002 to 2005 before joining the faculty at the University of Wisconsin–Green Bay. He is currently chair of the geoscience unit in the Department of Natural and Applied Sciences at UW–Green Bay. In conjunction with the Wisconsin Geological and Natural History Survey, he completed a countywide bedrock geologic mapping project in 2011.

Dr. Luczaj teaches courses in physical geology, historical geology, sedimentology and stratigraphy, glacial geology, regional field geology, hydrogeology, and radioactivity. His current research focuses on the groundwater chemistry of confined aquifer systems in eastern Wisconsin and on the diagenesis of sedimentary rocks, including petroleum reservoirs. He has recently completed a review article on the geology of the Niagara escarpment in Wisconsin. He received the Vincent E. Nelson Award in 2001 from the American Association of Petroleum Geologists for his work on hydrothermal dolomitization.

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PREFACE

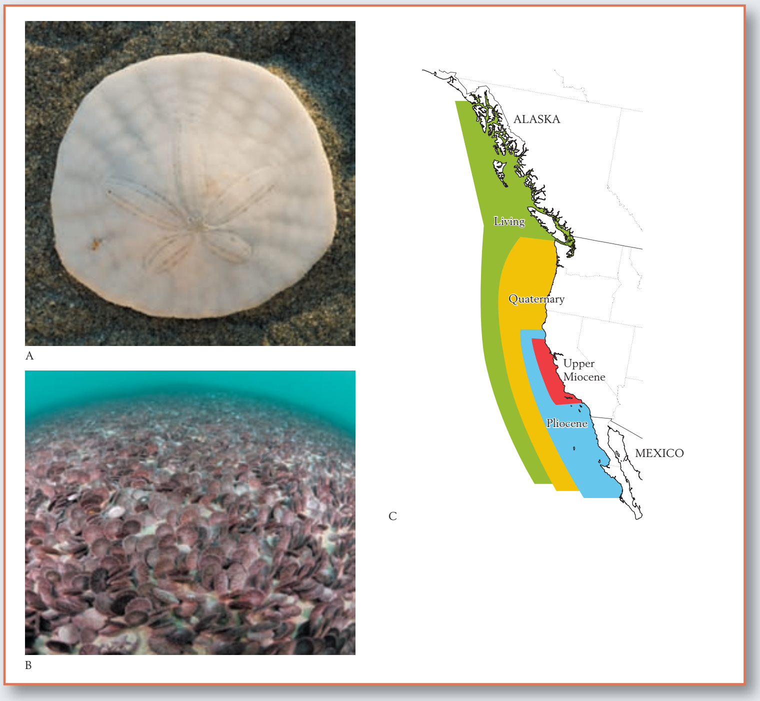
This edition benefits from the expertise of a new coauthor, Dr. John A. Luczaj, from the University of Wisconsin–Green Bay. John's added knowledge and experience in many areas of geology have brought a fresh view to many aspects of the textbook.

We coauthors share not only an intellectual passion for the history of our planet and its life, but also an aesthetic and romantic excitement about our subject, with its immense scale in time and space. Our goal is to instill similar enthusiasm in students.

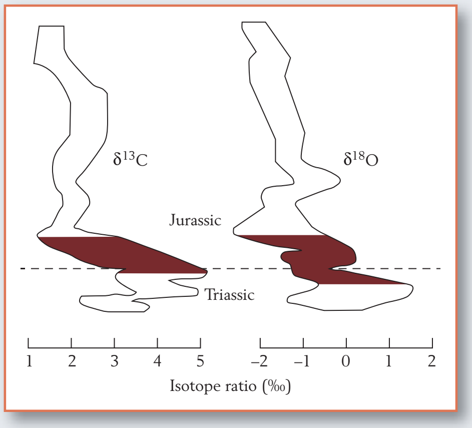
This edition, like those that preceded it, is founded on the basic principle that the physical and biological history of Earth are so thoroughly intertwined that they must be treated in an integrated fashion. Once again, Chapters 1–10 introduce the facts, processes, and concepts that are required for comprehension of Chapters 11–20, which present the narrative of changes in the Earth system since its inception. Each of these later chapters, focusing on a particular geological interval, begins with broad topics, such as the nature of the life that populated the planet and patterns of global paleogeography and climate change. Most of these chapters then narrow their focus to examine important regional events.

New Science

- New examples of punctuational evolutionary origins of distinctive taxa, such as freshwater jellyfish on the island of Palau and the marine sand dollar *Dendraster* along the coast of California (pp. 170–172; Figure 7-14).



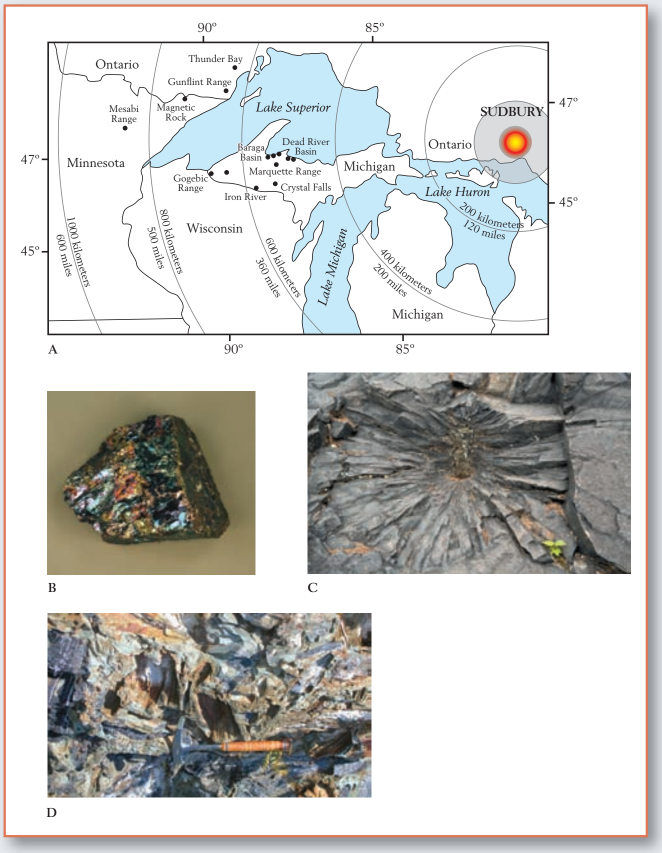
The geologically sudden origin of the asymmetric sand dollar *Dendraster* in a small region in association with the new life habit of standing upright on the seafloor and feeding on suspended organic matter. (A, Rich Reid/National Geographic/Getty Images; B, Derek Tarr, wildoceanphoto.com; C, After S. C. Beadle, Paleobiology 17:325–339, 1991.)



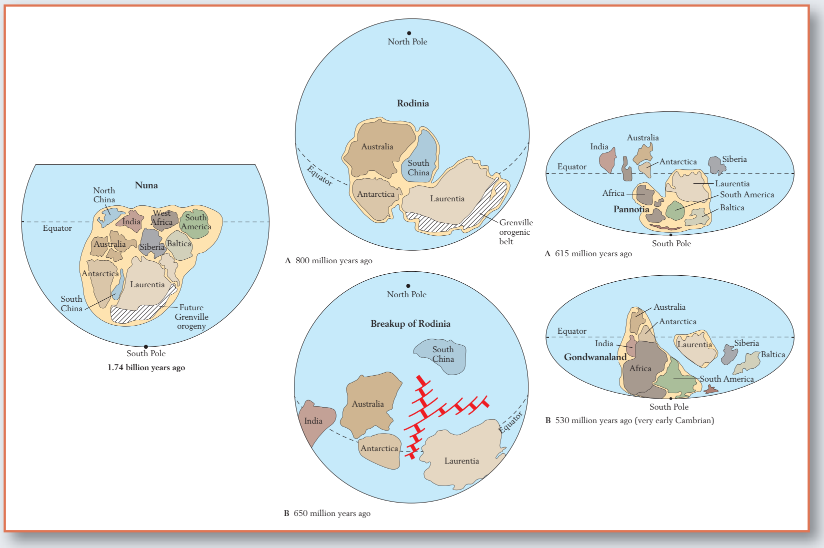
- Current views of all the major mass extinctions. New information is presented throughout much of the book (Chapters 10 and beyond) illustrating how isotope excursions that coincide with mass extinctions reflect global climate change (Chapter 10; Figure 10-19).

Parallel negative excursions for carbon and oxygen stable isotopes across the Triassic-Jurassic boundary, which indicate that intense climatic warming occurred. (After C. Korte, S. P. Hesselbo, H. C. Jenkyns, R. E. M. Rickaby, and C. Spotl, J. Geol. Soc. Lond. 166:431–445, 2009.)

- Updated Proterozoic history, including a discussion of the colossal Sudbury asteroid impact, which occurred in southern Canada 1.85 billion years ago and melted crustal rocks to produce massive metallic ore deposits (Chapter 12; Figure 12-19).

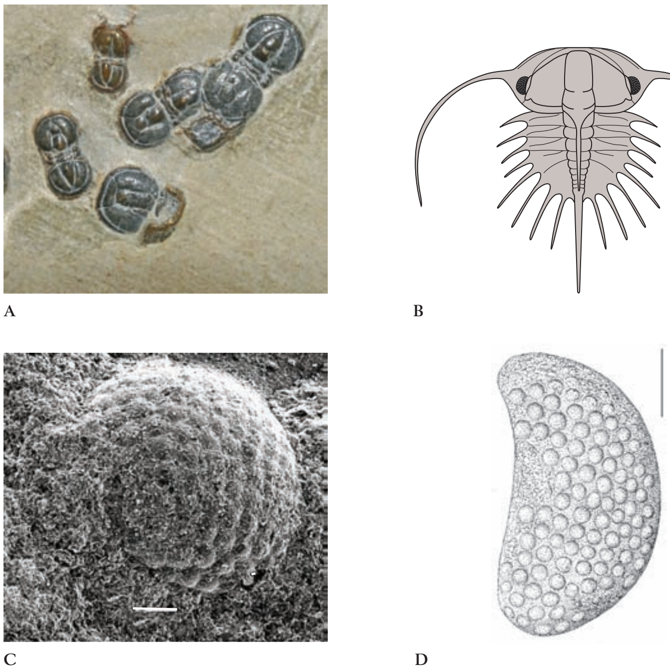


Copper ore, a shatter cone, and a megabreccia—all produced by the Sudbury impact. (A, Courtesy of William F. Cannon, U.S. Geological Survey; B, Courtesy of James St. John, Ohio State University at Newark; C, © Don Johnston/age fotostock/Alamy; D, Courtesy of Brian Allison.)



- A new evaluation of the snowball Earth hypothesis (Chapter 12).
- A discussion of four supercontinents that formed during the Proterozoic, with new illustrations (Figures 12-22, 12-24, and 12-25).

The latest reconstructions of the supercontinents Nuna, Rodinia, and Pannotia—and also Gondwanaland near its time of origin. (A, Courtesy of William F. Cannon, U.S. Geological Survey; B, Courtesy of James St. John, Ohio State University at Newark; C, © Don Johnston/age fotostock/Alamy; D, Courtesy of Brian Allison.) (After Z.-X. Li and D. A. D. Evans, Geology 39:39–42, 2011.) (After S. A. Pisarevsky, J. B. Murphy, P. A. Cawood, and A. S. Collins, Geol. Soc. Lond. Spec. Publ. 294:9–31, 2008.)

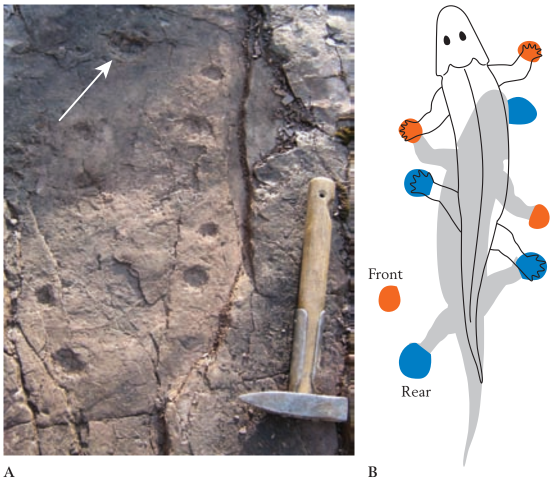


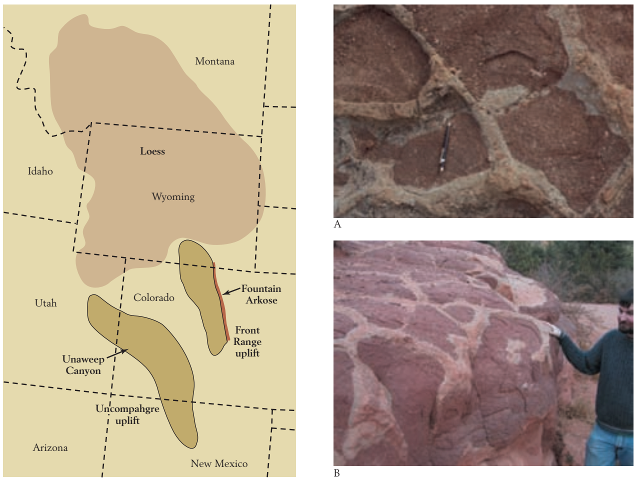
- New interpretations of the Burgess Shale fauna (Chapter 13) and other early Paleozoic life forms, including trilobites (Figure 13-3).

Very small Cambrian trilobites that are interpreted as having lived a planktonic life. (A, © Géry Parent; C and D, from B. Schoenemann, E. N. K. Clarkson, P. Ahlberg, and M. E. D. Alvarez, Palaeontology 53:695–701, 2010.)

- New evidence, in the form of trackways, that vertebrates had evolved legs and feet with toes and were walking on land long before they left a recognized skeletal fossil record (Figure 14-21).

Tracks in Poland showing that amphibians walked the earth in early Middle Devonian time, long before the existence of the oldest amphibians known from fossilized skeletons. (A, Grzegorz Niedźwiedzki.)





- New evidence that widespread glaciation occurred close to the equator in Late Carboniferous time (Figures 15-20 and 15-21).

Loess deposits and cracks that formed in frozen ground, both indicating that widespread Late Carboniferous glaciation occurred at low latitudes in what is now the American West. (After G. S. Soreghan, M. J. Soreghan, and M. A. Hamilton, Palaeogeogr. Palaeoclimatol. Palaeoecol. 268:234–259, 2008.) (Photos: Dustin E. Sweet, Texas Tech University.)

- New evidence on the cause of the terminal Permian mass extinction.
- New evidence supporting an interpretation of the Grand Canyon's history as extending back to at least the Late Cretaceous (Chapter 17).
- An up-to-date discussion of dinosaur biology in "The Rise of the Dinosaurs: Why Were They So Successful?" (Earth System Shift 16-1, Figure 8).

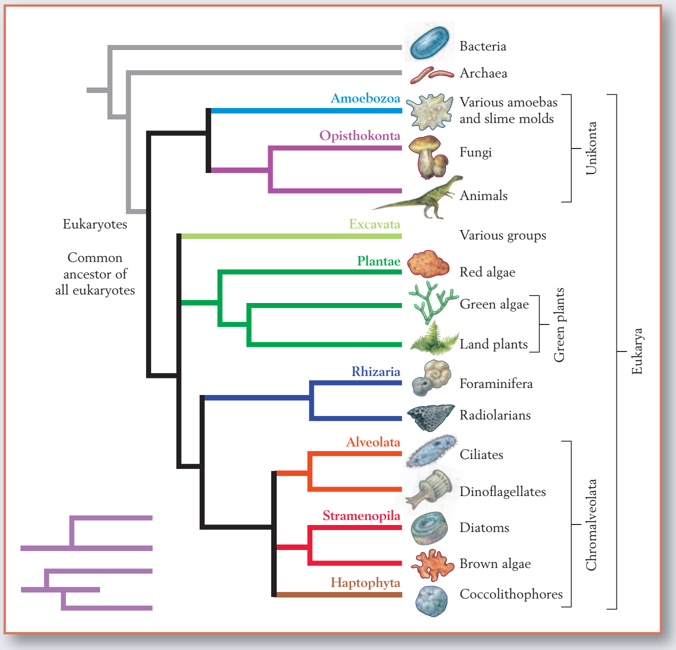
Color patterns of a gliding feathered dinosaur, reconstructed through the use of revolutionary new analytical techniques. (Julius T. Csotonyi/Science Source.)

- Updated interpretations of Cenozoic climate change (Chapters 19 and 20).
- The newest evidence on human evolution (Chapter 19).

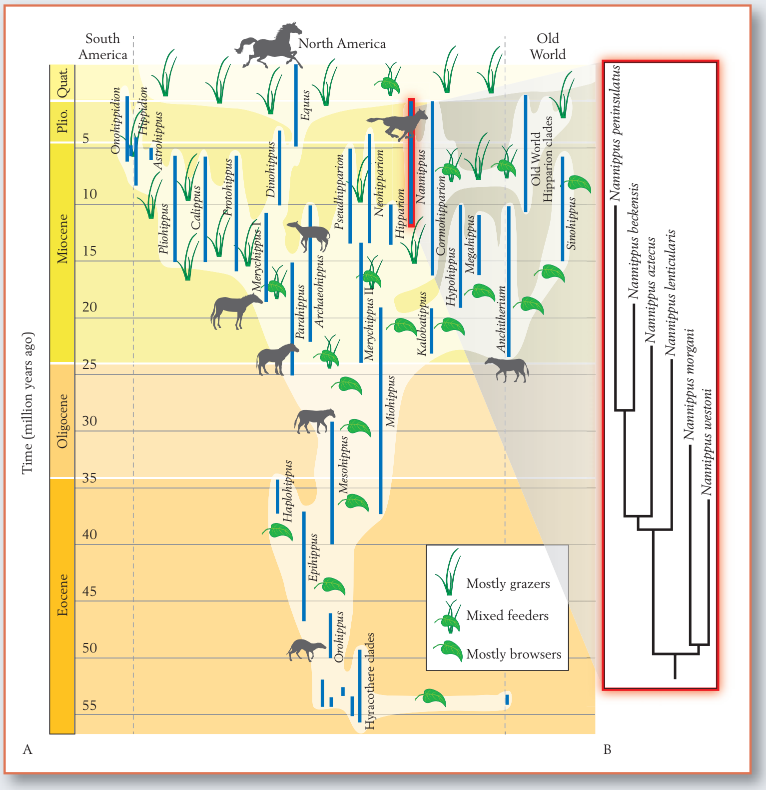
A cluster of needle-shaped colonial diatoms from Arctic Ocean sediments; these show, surprisingly, that sea ice was present in the Arctic as early as 46 million years ago. (Courtesy of Catherine E. Stickley, University of Tromsø)

Additional New Features

- Literally over a thousand updates and changes to figures, text, and captions.
- A completely revised and updated photo program.
- A revised geologic time scale, including the formal addition of the Quaternary Period.
- Expanded coverage of cross-cutting and relative age relationships, such as those evident in faults and xenoliths.
- New use of important scientific terms, such as "*Lagerstätte*" and "microbiolite," that have become widely used in the Earth history literature.
- Revised phylogeny and biodiversity sections in Chapter 3, including the modern picture of the general phylogeny and classification of life on Earth with corresponding new line art (Figure 3-6).



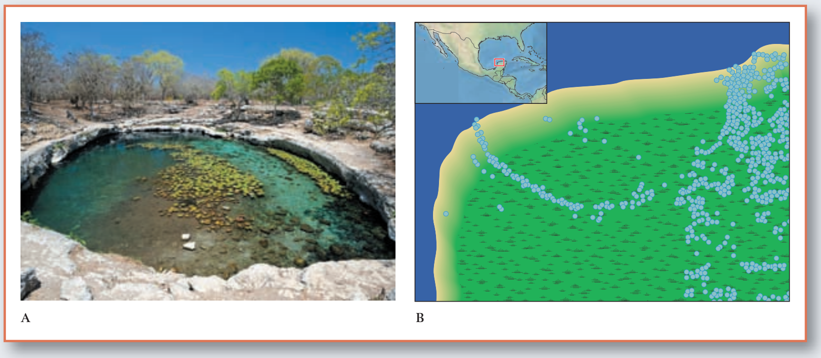
A highly revised tree of life with many new names for major taxonomic groups.



- Other new line art figures feature major groups of the Anthropoidea (monkeys, apes and humans) (Figure 3-7), the phylogeny of horses (Figure 3-11), and the phylogeny of plants (Figure 3-19).

The general phylogeny of horses, with a detailed species-level phylogeny for the genus *Nannippus* produced by cladistic analysis. (After B. J. MacFadden, Science 307:1728–1730, 2005, and K. C. Maguire and A. L. Stigall, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 267:175–184, 2008.)

- Other new and updated art, including Mississippi River delta lobes (Figures 5-17 and 5-18), stromatolite growth (Figure 5-30), maps of submarine fan locations (Figure 5-33), magnetic stratigraphy (Figure 6-4), zircon dating interpretations (Figure 6-9), several isotope curves (Figure 6-12; Figure 10-10; Figure 10-19; ESS 12-2, Figure 4; Figure 16-2; Figure 19-14), domes and basins (including a new geologic map of the Michigan basin [Figure 9-22]), cenotes in the Yucatán Peninsula (ESS 17-1, Figure 5), and more.



Cenotes, which are flooded sink holes in the Yucatán Peninsula, some of which dramatically outline the crater made by the asteroid impact that eliminated the dinosaurs. (A, Martin Engelmann/Getty Images; B, after P. K. H. Maguire et al., Geological Society of London Special Publication 140:177–193, 1998.)

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This robust resource helps students focus their study, review, and exam preparation time. What's more, instructors have access through the site to presentation resources, images, and an online gradebook that allows them to track student progress.

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Earth as a System

1

A lava channel flowing from the Hawaiian volcano Kilauea. This volcano has erupted 33 times since 1843. (G. Brad Lewis/Aurora Creative/Getty Images.)

Few people recognize, as they travel down a highway or hike along a mountain trail, that the rocks they see around them have rich and varied histories. Unless they are geologists, they probably have not been trained to identify a particular cliff as rock formed on a tidal flat that once fringed a primordial sea, to read in a hillside's ancient rocks the history of a primitive forest buried by a fiery volcanic eruption, or to decipher clues in lowland rocks telling of a lofty mountain chain that once stood where the land is now flat. Geologists can do these things because they have at their service a wide variety of information gathered over the two centuries during which the modern science of geology has existed. The goal of this book is to introduce enough of these geologic facts and principles to give you an understanding of the general history of our planet and its life. The chapters that follow describe how the physical world assumed its present form and where the inhabitants of the modern world came from. They also reveal the procedures through which geologists have assembled this information. Students of Earth's history inevitably discover that the perspective this knowledge provides changes their perception of themselves and of the land and life around them.

Knowledge of Earth's history can also have great practical value. Geologists have learned to locate subterranean reservoirs of petroleum and water, for example, by ascertaining where the porous rocks of these reservoirs tend to form in relation to other bodies of rock. Geologists have also helped to discover deposits of coal, metallic ores, and other natural resources buried within Earth. They have also shown that environmental conditions on our planet have been very different in past times, and that those conditions have sometimes changed very rapidly, not only over geologic time but even on the time scale of human history.

Exploring the Earth System

The rocks of Earth's outer regions constitute a vast archive that we can read and interpret in order to unravel the planet's long history. By studying Earth's history, we learn how our planet functions as a complex system. An understanding of that system will help us to address problems caused by changes that are now taking place in the world, or that will soon be occurring.

Earth is a special planet

Given the presence of trillions of planets circling sunlike stars in the universe, many scientists believe that life must exist in many places outside our solar system. Nonetheless, only a small percentage of all planets could support any form of life. Earth has special features that make it a livable planet. For example, Earth's distance from the sun and the size of the sun itself produce temperatures at Earth's surface that allow complex carbon compounds—the building blocks of life—to survive and enter into chemical reactions. In addition, Earth has a large enough mass to retain life-supporting fluids through gravitational attraction; thus it can be mantled by an ocean and an atmosphere, and it can hold water in lakes, rivers, and soil. At the same time, Earth is small enough that its gravity does not attract many giant asteroids from space, whose impacts can devastate life. In contrast, numerous massive meteorites have pelted Jupiter, whose mass is 318 times that of Earth.

The components of the Earth system are interrelated

The Earth system has both physicochemical and biological components. We can reconstruct many aspects of the planet's physical history, including the growth and destruction of mountains, the breakup and collision of continents, the flooding and reemergence of land areas, and the warming and cooling of climates. We can also trace the evolution of life from an early world inhabited largely by bacteria and similar forms of life through the origins of plants and animals in ancient seas to the invasion of the land, the rise and fall of dinosaurs, and ultimately the ascendancy of humans. We cannot understand either the physical or the biological history of Earth in isolation, however, because the two have been tightly intertwined: the physical environment has influenced life, and life, in turn, has influenced the physical environment. For example, as we will see in Chapter 4, climatic patterns control distributions of plants on land. At the same time, plant life affects climates. Forests warm regional climates by trapping heat, for instance, and plants also affect global climates by altering the chemistry of the atmosphere. The geologic record reveals that the histories of land plants and climates have shifted in concert for hundreds of millions of years. Many other factors, including continental movements and the rising and falling of seas, have influenced climates as well. The present state of Earth is a momentary condition that is the product of a long and complex history.

Armed with knowledge of Earth system history, we can more effectively address problems caused by changes that are now taking place in the world. Consider the shifting of coastlines as sea level rises or falls. The geologic record of the past few thousand years documents a global rise in sea level as huge glaciers have melted and released water into the ocean. The geologic record near the edge of the sea reveals how coastal marshes have shifted their positions as sea level has changed. These marshes are very important to humankind; they cleanse marginal marine waters and sustain forms of animal life that are valuable to us. Study of the geologic history of coastal marshes will help us to predict their fate as human activities warm Earth's climate and sea level continues to rise in the decades and centuries to come.

Aspects of the Earth system are fragile

The geologic record of the history of life also provides a unique perspective on the numerous extinctions of animals and plants that are now resulting from human activities. Humans are causing extinctions by destroying forests and other habitats, and our collective behavior also affects life profoundly in less direct ways. Human activities are causing average temperatures at Earth's surface to rise throughout the world. The geologic record of ancient life reveals how climatic change has affected life in the past—how some species have survived by migrating to favorable environments, for example, and how others that failed to migrate successfully have died out. To the surprise of many biologists, geologic evidence has revealed that many of the natural assemblages of species that populate the world today are not ancient associations of interdependent species. Instead, they are associations that have developed very recently (on a geologic scale of time) as climatic changes have caused many species to shift about independently of one another.

As we come to understand the speed and power of natural environmental change and the temporary nature of assemblages of species, we can begin to appreciate the fragility of the world we live in. More generally, having studied the past, we can make more intelligent choices as we contemplate the future of our changing planet.

Before we launch into our detailed examination of the history of Earth and its life, however, an introduction to some of the basic facts and unifying concepts of geology is in order. The first ten chapters lay this groundwork, and the chapters that follow trace out Earth system history.

The Principle of Actualism

Underpinning the science of geology today is the notion that the fundamental physical and chemical principles that humans observe operating today have operated throughout Earth's history. In fact, this concept, which geologists term **actualism**, is a basic tenet of science, and it applies on all time scales. Thus a physicist who performs a laboratory experiment on a given day assumes that an identical experiment the next day—or ten or a hundred years later—will yield the same result. Geologists hold this principle in particularly great esteem, however, because, as we will see, it was the widespread rejection of opposing views during the first half of the nineteenth century that signaled the beginning of the modern science of geology.

Geologists nonetheless recognize that Earth's processes have operated at different rates at different times. For example, our planet is rotating more slowly now than it did early in its history, and continents, on average, have grown larger over the course of geologic time.

Geologists conduct research based on actualism

How is actualism employed in geology? When we see ripples on the surface of an ancient rock composed of hardened sand (sandstone), for example, we assume that they formed in the same way that similar ripples develop today—under the influence of certain kinds of water movement or wind (Figure 1-1). Similarly, when we encounter ancient rocks that closely resemble those forming today from volcanic eruptions of molten rock in Hawaii, we assume that the ancient rocks are also of volcanic origin. Geologists cannot observe rocks twisting into contorted configurations like those seen in mountains, but they can witness the breaking, bending, and uplift of rocks during earthquakes, and they can calculate that the same immense forces that produce these effects can contort rocks deep within Earth and elevate them into mountains. The rates of horizontal and vertical ground motion can be observed using real-time GPS instruments that track the positions of specially placed markers called bench marks.

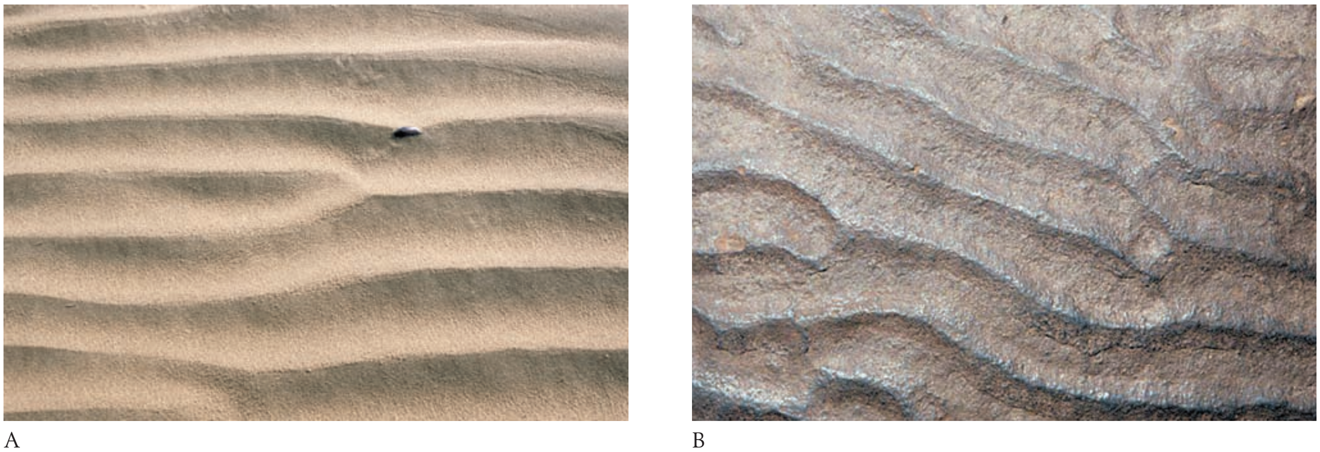


FIGURE 1-1 **Ripples in sediments and sedimentary rocks.** A. Wave ripples exposed along a modern beach at low tide. B. Similar wave ripples preserved in 200 million year old sandstone. (A, PearlBucknall/Alamy; B, The Natural History Museum/The Image Works.)

Although it is universally agreed that natural laws have not varied in the course of geologic time, not all kinds of events that occurred in the geologic past have been duplicated within the time span of human history. Most researchers believe, for example, that the impacts of very large asteroids (rocky or metallic objects smaller than a planet) explain certain past events, such as the extinction of the dinosaurs 66 million years ago. In Chapter 17 we will review evidence that the dinosaurs' reign on Earth ended when a massive asteroid—one perhaps 10 kilometers (6 miles) in diameter—plunged through the atmosphere and ocean and penetrated the seafloor along the coast of Mexico. It is easy to imagine that the consequences of such a huge impact would have wiped out many species around the world. Even so, because humans have never observed such an event, we must rely on theoretical considerations to surmise what actually happened. But we need not abandon basic physical or chemical principles to do so.

Geologists have also learned that certain types of rocks exist but cannot be observed in the process of forming today. In such cases, geologists usually make one of the following three assumptions:

1. The rocks in question formed under conditions that do not exist at the present time.

2. The conditions responsible for the formation of the rocks still exist, but at such great depths beneath Earth's surface that we cannot observe them.

3. The conditions responsible for the formation of the rocks still exist, but produce the rocks only over a long interval of geologic time.

Many iron ore deposits more than 1.8 billion years old, for example, are of types that cannot be found in the process of forming today. It is believed that when these deposits formed, chemical conditions on Earth differed from those of the present world and, furthermore, that the rocks underwent slow alteration after they were formed. The existence of these iron ore deposits does not negate the principle of actualism inasmuch as there is no evidence that natural laws were broken.

In an attempt to address some of these problems, geologists have learned to form certain kinds of rocks in the laboratory by simulating the conditions that prevail at great depths within Earth. They expose simple chemical components to temperatures and pressures many times greater than those at Earth's surface to replicate the textures and mineral content observed in natural rocks.

Actualism replaced catastrophism in the nineteenth century

Until the early nineteenth century, many natural scientists subscribed to the concept of **catastrophism**, which asserted that global floods caused by supernatural forces formed most of the rocks visible at Earth's surface. Late in the eighteenth century, Abraham Gottlob Werner, an influential German professor of mineralogy, promoted catastrophism with great success, claiming that most rocks had been formed by the precipitation of minerals from a vast sea that periodically flooded and retreated from Earth's surface. These ideas were largely speculative, and because they relied on unspecified supernatural forces, we now recognize that they were fundamentally unscientific.

Near the end of the eighteenth century, however, not long after Werner published his ideas, James Hutton, a Scottish gentleman farmer, established the foundations of actualism in his writings on the origins of rocks in Scotland. Hutton came to the conclusion that those rocks had formed as a result of the same processes that were currently operating at or near the surface of Earth—processes such as volcanic activity and the accumulation of grains of sand and clay under the influence of gravity.

Central to Hutton's view of Earth's history was vast geologic time. For the processes that were constantly shaping and reshaping the planet, he envisioned "no vestige of a beginning, no prospect of an end." Everyday processes, he proposed, had created and destroyed large bodies of rock, elevated and leveled mountains, and left remnants of their workings in an immense geologic record. Early in the nineteenth century, many geologists recognized that certain kinds of rocks formed from liquid rock that spewed from volcanoes, whereas others formed from sand or mud that settled on the bottoms of streams, lakes, or shallow seas. Nonetheless, some diehard catastrophists still attributed all the layered rocks on Earth to a series of catastrophes, the last of which they believed to have been survived by Noah and his ark.

After extensive debate, Hutton's ideas came to dominate the science of geology after Charles Lyell, an Englishman, popularized them in the 1830s in a three-volume book titled *Principles of Geology*. Lyell was a more effective writer than Hutton, and the world was more receptive to the new ideas when Lyell promoted them than in Hutton's day. Like Hutton, Lyell understood that volcanoes, floods, and earthquakes transform Earth. He argued that these events transform Earth in piecemeal fashion, and that they operate on local or regional scales, as do more subtle agents of change, such as the wearing away of old rocks and the accumulation of sand and mud to form new ones. In the eyes of Hutton and Lyell, Earth resembled an enormous machine that was always churning but retained its basic features.

Although from a modern perspective Lyell was basically correct in his arguments, he carried them too far in three respects:

1. Lyell argued that no events of a kind never seen by humans—even events that violated no laws of nature—had ever played an important geologic role. As illustrated by our current understanding of the asteroid impact that resulted in the dinosaurs' disappearance, we now recognize that Lyell's extreme view was incorrect. Even some gradual processes, such as the deposition of iron formations in ancient seas described earlier, are no longer operating on Earth.

2. Lyell argued that all geologic changes were gradual. In addition to the asteroid impact that killed off the dinosaurs, we now recognize numerous agents of geologic change that have operated with great suddenness. Some can reasonably be termed catastrophic, though not in the Wernerian sense of entailing supernatural forces and forming large bodies of rock throughout the world.

3. Lyell argued that the kinds of rocks that form our planet—and even the kinds of living things that occupy Earth's surface—had never basically changed. As he saw it, particular bodies of rock and particular species of plants and animals had come and gone, but no fundamentally new kinds of rocks or organisms had appeared. For example, Lyell believed that mammals had been present from Earth's beginning, whereas we now know that mammals have existed for only about 5 percent of our planet's history, and that for most of that time few were larger than a house cat. Similarly, Lyell believed that the processes that shape Earth had operated at the same general rates throughout geologic time, whereas we now know that many of these processes have sped up or slowed down greatly over the course of geologic time.

Lyell's extreme philosophy, often summarized by the phrase "the present is the key to the past," is commonly labeled **uniformitarianism**, although some geologists consider this word to be a synonym of *actualism*. Definitions aside, Lyell deserves his prominent place in the history of geology, even though he went too far in denying that Earth and its life have changed appreciably. You might say that Charles Lyell, along with James Hutton, gave us the concept of geologic time.

Over the course of decades, Lyell's rigid uniformitarian view gave way to the more expansive concept of actualism. Although early in the twentieth century some geologists still denied that catastrophic events have played a major role in Earth's history, that view has now all but disappeared.

The Nature and Origin of Rocks

Rocks consist of interlocking or bonded grains of matter, which are typically composed of single minerals. A **mineral** is a naturally occurring inorganic solid element or compound with a particular chemical composition or range of compositions and a characteristic internal structure. Quartz, which forms most grains of sand, is probably the most familiar and widely recognized mineral; the materials we call limestone, clay, and asbestos consist of other minerals. Most rocks in Earth's crust are formed of two or more minerals, but some common rocks, such as limestone, dolostone, quartz sandstone, quartzite, and marble, are each composed of just one mineral. Others, such as coal, pumice, and obsidian (a volcanic rock), do not contain true minerals but are considered rocks because of their mode of origin and relationships to other rocks.

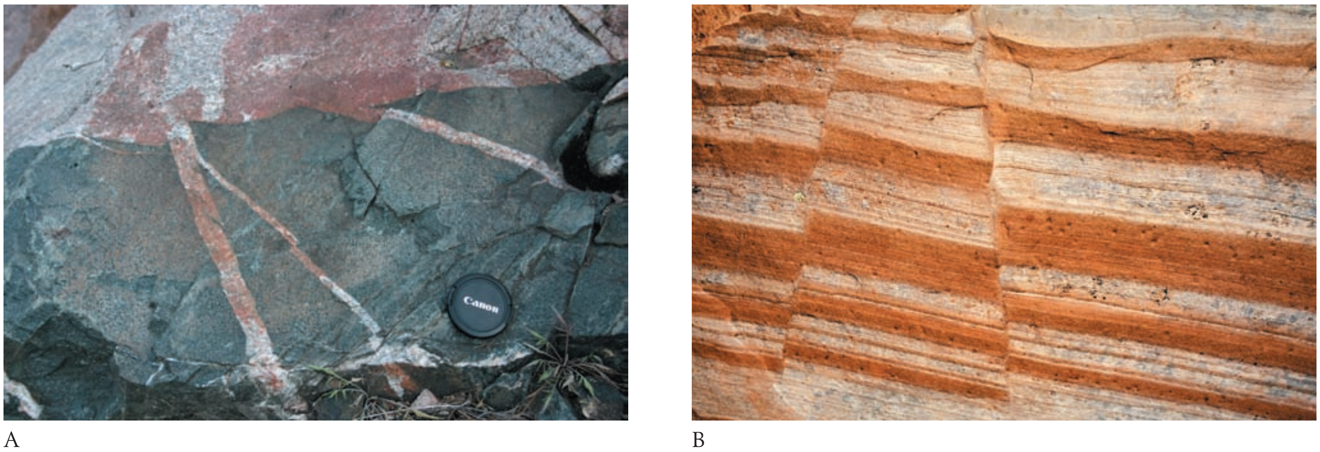
The interconnected set of rocks in Earth's crust that occurs beneath loose soil or sediment is known as **bedrock**. Bedrock surfaces that stand exposed and are readily accessible for study are generally referred to as **outcrops** or **exposures**. Scientists also have access to rocks that are not visible in outcrops. Well drilling and mining, for example, allow geologists to sample rocks that lie buried beneath Earth's surface.

Igneous, sedimentary, and metamorphic rocks can form from one another

On the basis of modes of origin, many of which can be seen operating today, early uniformitarian geologists, led by Hutton and Lyell, came to recognize three basic types of rocks: igneous, sedimentary, and metamorphic.

Igneous rocks are formed by the cooling of molten material to the point at which it hardens, or crystallizes (much as ice forms when water freezes). They are composed of bonded grains, each consisting of a particular mineral (Figure 1-2). The igneous rock most familiar to nongeologists is granite. The molten material, or **magma**, that becomes igneous rock comes from great depths within Earth, where temperatures are very high. This material may reach Earth's surface through cracks and fissures in the crust and then cool to form **extrusive**, or **volcanic**,

FIGURE 1-2 **Interlocking grains in granite.** The pink and white grains are two kinds of feldspar, the gray grains are quartz, and the black grains are mafic minerals. The smaller quartz grains are the size of grains of sand. (Sabena Jane Blackbird/Alamy.)


A

B

FIGURE 1-3 **Intrusive igneous rock and faults illustrate relative age relationships.** A. The pink material is granite that intruded into, and incorporated pieces of, the older rock surrounding it. These included pieces of the surrounding rock are known as xenoliths. The widest granite-filled crack is about 2–3 centimeters (an inch) wide. B. An outcrop of sedimentary rocks that have been cut by faulting. The field of view is about one meter (3 feet) wide. (A, John Luczaj, University of Wisconsin–Green Bay; B, Peter L. Kresan.)

igneous rock, or it may cool and harden within Earth to form **intrusive** igneous rock (Figure 1-3).

Even intrusive rocks that form deep within Earth can eventually be exposed at the surface if they are uplifted by Earth movements and overlying rocks are stripped away. **Weathering** is a collective term for the chemical and physical processes that break down rocks of any kind at Earth's surface. There are two types of weathering. *Physical* weathering entails the mechanical fragmentation of rock without chemical alteration. In *chemical* weathering, minerals in rock are altered to other minerals or dissolved away (Figure 1-4). Solid products are removed by **erosion**, the process that loosens pieces of rock and moves them downhill. After erosion sets these pieces of rock in motion, moving water, ice, or wind may transport them to a site where they accumulate as sediment. Water also carries some products of weathering away in solution.


FIGURE 1-4 **Pillar produced by weathering of granite in Joshua Tree National Park, California.** (Spring Images/Alamy.)

Sediment is material deposited on Earth's surface by water, ice, or air, or by gravitational transport down a slope. Grains of sediment accumulate in a variety of settings, ranging from the surfaces of desert dunes to river channels, lake bottoms, sandy beaches, and the floor of the deep sea. Grains that have accumulated as loose sediment can become bonded together to form solid **sedimentary rock** by either of two processes: the grains may become mutually attached by compression of the sediment after burial, or they may be glued together by precipitation of mineral cement from watery solutions that flow through the sediment. These two processes that turn loose sediment into solid rock are collectively termed **lithification**.

There are three principal kinds of rock-forming sediments:

1. **Detrital** (or clastic) **sediments**: Most sedimentary rocks are formed of the kind of sediment described above: debris generated by weathering of preexisting rocks. The most common grains produced in this way are particles of clay and sand. Tiny clay particles are formed by the chemical breakdown of certain minerals: they are chemical products of weathering. **Clay** is a flaky material that compacts to form the soft rock known as **shale**. Feldspars weather to clay. Because feldspars are the most abundant group of minerals in granite (see Figure 1-2) and are present in many other rocks on continents, clay is a major product of weathering at Earth's surface. Quartz grains also constitute a significant proportion of granite and other rocks. Weathering releases quartz grains from these rocks, generally without chemical alteration,

FIGURE 1-5 **Horizontal bedding of sedimentary rocks in the Grand Canyon.** The Kaibab Formation, preserved at the top of this sequence of rocks, forms the Kaibab Plateau and marks the horizon. (Martin M303/Shutterstock.)

which can accumulate to form sand and, eventually, sandstone. Such sand grains are globular, and they do not stick together well when compacted. Loose sand therefore becomes solid **sandstone** only when cement precipitates between adjacent grains, locking them together.

2. **Biogenic sediments**: Other sedimentary rocks consist of fragments of skeletons of once-living organisms. Many **limestones** are formed of such material, including bits of broken seashells. Cementation turns accumulations of this limey debris into solid rock.

3. **Chemical** (inorganic) **sediments**: Still other grains that form sedimentary rocks are precipitated chemically from water. The salt deposits that we mine for a variety of purposes form in this way when bodies of water evaporate in dry climates.

Sediments usually accumulate in discrete episodes, each of which forms a tabular layer known as a **stratum** (plural, **strata**) or **bed**. A breaking wave can create a stratum, for example, and so can the spreading waters of a flooding river. Even after lithification, a stratum tends to remain distinct from the one above it and the one below it because the grains of adjacent strata usually differ in size or composition. Because of such differences, the strata usually adhere to each other only weakly, and sedimentary rocks often break along these surfaces. As a result, many sedimentary rocks exposed at Earth's surface can be seen to have a steplike configuration when viewed from the side (Figure 1-5). **Stratification** and **bedding** are the synonymous words used to describe the arrangement of sedimentary rocks in discrete layers.

Metamorphic rocks are formed by the alteration, or **metamorphism**, of rocks within Earth under conditions of high temperature and pressure. By definition, metamorphism alters rocks without turning them to liquid. If the temperature becomes high enough to melt rock, and the molten rock later cools to form new solid rock, this new rock, by definition, is igneous rather than metamorphic. Some types of metamorphism result from the passage of watery fluids through rocks. Metamorphism produces minerals and textures that differ from those of the original rock and that are characteristically arrayed in parallel wavy layers (Figure 1-6). The two groups of rocks that form at high temperatures—igneous and metamorphic rocks—are commonly referred to as **crystalline rocks**.

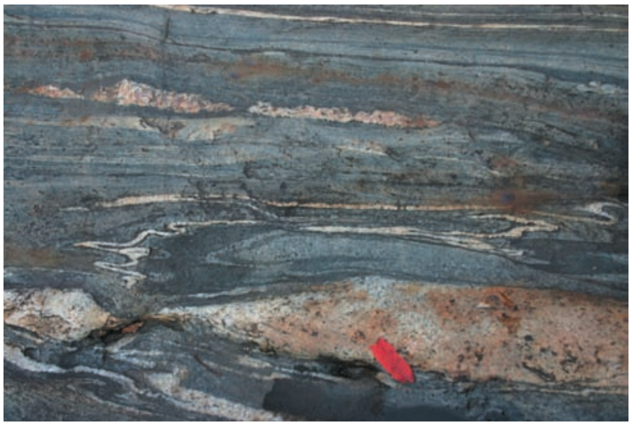


FIGURE 1-6 **Metamorphic rock.** The rock shown here is a coarse-grained type known as gneiss. While very hot and under great pressure deep within Earth, it was twisted like taffy. The dark bands in the foreground are several centimeters wide. (John Luczaj, University of Wisconsin–Green Bay.)

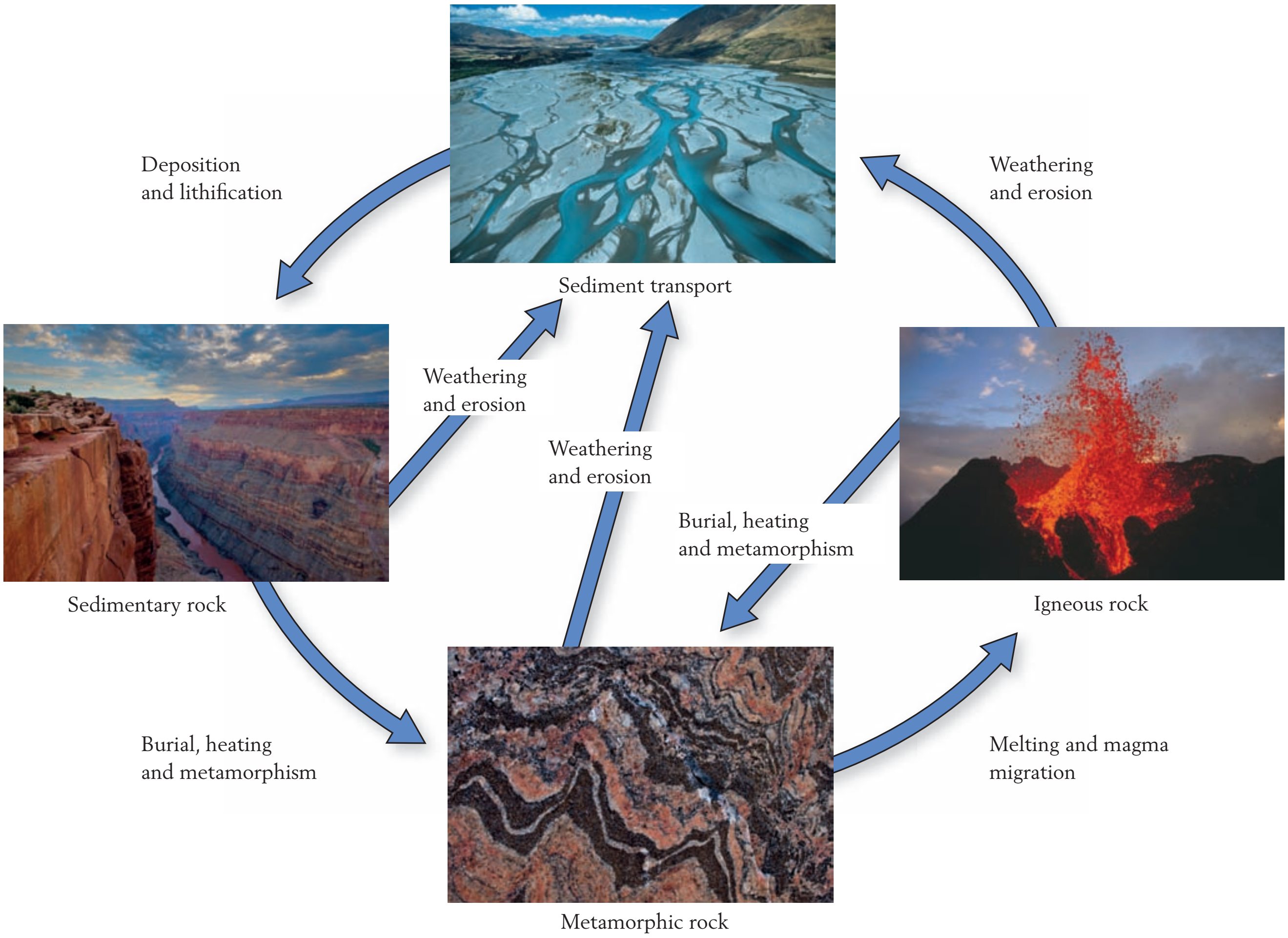


FIGURE 1-7 Transformations of one kind of rock into another kind of rock. Any of the three basic kinds of rock—igneous, sedimentary, or metamorphic—can be transformed into another rock of the same kind or either of the other two kinds through a variety of geologic processes. (Clockwise from top: Christian Février/naturepl.com/Nature Picture Library; age fotostock/SuperStock; Les Palenik/Shutterstock; Doug Meek/Shutterstock.)

Figure 1-7 summarizes the various possible relationships among igneous rocks, metamorphic rocks, and sedimentary rocks that are composed of debris from other rocks. Any body of rock can be transformed into another body of rock belonging to the same group (metamorphic, igneous, or sedimentary) or to either of the other two groups. In other words, any kind of rock can be metamorphosed, melted to produce magma, or weathered to produce sediment.

Bodies of rock are classified into formal units

Geologists also classify rocks into units called **formations**. Each formation consists of a discrete body of rock of a particular type that formed in a particular way—for example, a body of granite, of sandstone, or of alternating layers of sandstone and shale. Formations are represented by distinctive colors and patterns on geologic maps that depict their occurrence within particular geographic regions. A formation is formally named, usually for a geographic feature such as a town or river where it is well exposed.

The Kaibab Limestone is a typical formation. It forms the rim of a large portion of the Grand Canyon, and its upper surface forms much of the surface of the Kaibab Plateau, which borders the canyon and gives the formation its name (see Figure 1-5). The Kaibab Limestone is composed of fragments of shells and other skeletal debris. These and other distinctive features of the formation, including its color and the characteristic thickness of the beds within it, permit geologists to recognize the Kaibab wherever it occurs. Other limestones that occur below the Kaibab in the Grand Canyon region display different features.

Smaller rock units called **members** are recognized within some formations. Similarly, some formations are united to form larger units termed **groups**, and some groups, in turn, are combined into **supergroups**.

Steno's three principles concern sedimentary rocks

Because they form at Earth's surface, sedimentary rocks provide most of our information about the history of life and environments on Earth. It is therefore important that we understand their distribution and their age relationships. The study of stratified rocks and their relationships in time and space is known as **stratigraphy**.

In the seventeenth century, Nicolaus Steno, a Danish physician who lived in Florence, Italy, formulated three sensible axioms for interpreting stratified rocks. Steno's first principle, the principle of **superposition**, states that in an undisturbed sequence of strata, the oldest strata lie at the bottom and successively higher strata are progressively younger (Figure 1-8A). In other words, in an uninterrupted sequence of strata, each bed is younger than the one below it and older than the one above it. This is a simple consequence of the law of gravity, of course, as is Steno's second principle, the principle of original horizontality.

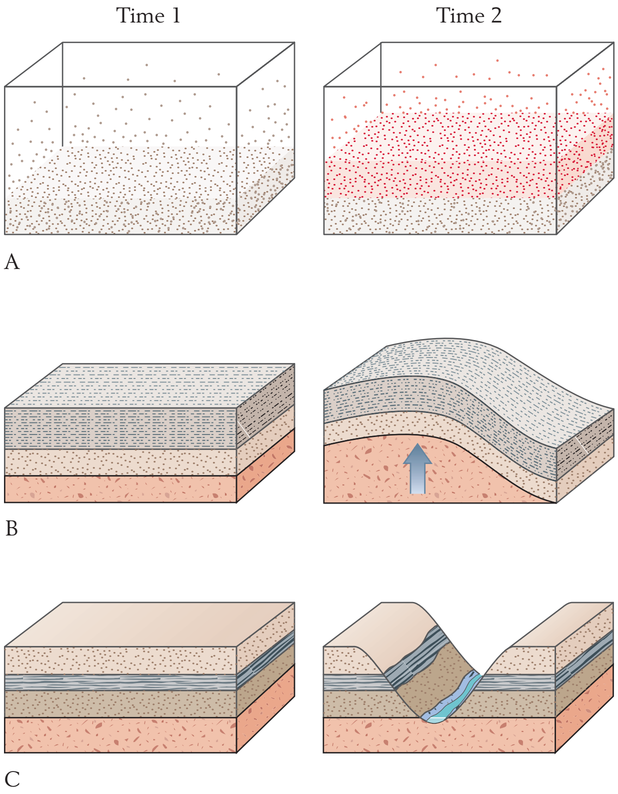


FIGURE 1-8 **Steno's three principles.** A. The principle of superposition: at time 2, sediment builds up on top of other sediment that was deposited earlier, at time 1. B. The principle of original horizontality: by time 2, strata that were horizontal at time 1, shortly after being deposited, have been uplifted and tilted. C. The principle of original continuity: by time 2, strata that were continuous at time 1 have been divided into two bodies of strata by a river that has cut through them.

The principle of **original horizontality** states that all strata are horizontal when they form. As it turns out, this principle requires some modification. We now recognize that some sediments, such as those of a sand dune, accumulate on sloping surfaces, forming strata that lie parallel to the surface on which they were deposited. Sediments seldom accumulate at an angle greater than 45° to the horizontal, however, because they slide down slopes that are steeper than that. Therefore, a reasonable restatement of Steno's second principle would be that almost all strata are initially more nearly horizontal than vertical. Thus we can conclude that any strongly sloping or folded stratum was tilted by external forces after it formed (Figure 1-8B).

Steno invoked his third principle, the principle of **original lateral continuity**, to explain the occurrence on opposite sides of a valley (or some other intervening feature of the landscape) of similar rocks that seem once to have been connected. Steno was, in effect, pointing out that strata are originally unbroken flat expanses, thinning laterally to a thickness of zero or abutting the walls of the natural basin in which they formed. The original continuity of a stratum can be broken by erosion, as when a river cuts downward to form a valley (Figure 1-8C).

The rock cycle relates all kinds of rocks to one another

After rocks form, they are subject to many kinds of change. Central to the uniformitarian view of Earth is the **rock cycle**: the endless pathway along which rocks of various kinds are changed into rocks of other kinds.

Three simple principles are useful for recognizing steps of the rock cycle. The principle of **intrusive relationships** states that intrusive igneous rock is always younger than the rock that it invades (referred to as **country rock**). The principle of **inclusions** states that when fragments of one body of rock are found within a second body of rock, the second body is always younger than the first. The second body may be a body of sedimentary rock in which the fragments have come from another body of rock (e.g., pebbles), or it may be a body of igneous rock that contains distinctive pieces of older country rock that magma engulfed before it cooled (see Figure 1-3A). Inclusions of country rock surrounded by igneous rock are called **xenoliths**. The principle of **cross-cutting relationships** states that any structure, such as a fault, that cuts through a sequence of preexisting rocks must be younger than the host rocks (see Figure 1-3B).

The rock cycle is actually a complex of many kinds of cycles in which components of any body of rock—whether igneous, sedimentary, or metamorphic—can become part of another body of rock of the same kind or either of the other two kinds. In other words, as partly illustrated by Figure 1-7, any rock may be (1) melted to form magma that later cools to form igneous rock,