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# Contents

*Acknowledgments* 

1 Plate Tectonics: A Revolution in Geology  

2 What the Earth Is Made Of  

3 The Rock Record and Geologic Time  

4 Earthquakes and the Inside of the Earth  

5 Volcanoes and Igneous Rocks  

6 Weathering and Erosion  

7 Sediments and Sedimentary Rocks  

8 Metamorphism and Rock Deformation  

9 The Hydrosphere and the Atmosphere  

10 The Record of Life on Earth  

11 Resources from the Earth  

12 Earth Systems and Cycles  

*Appendix 1: Units and Conversions*  

*Appendix 2: Elements and Their Symbols*  

*Appendix 3: Properties of Some Important Minerals*
Appendix 4: Symbols Commonly Used on Geologic Maps 311

Appendix 5: Some Great Earth Science Web Sites 313

Index 315
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A Note to the Reader

Welcome to the study of our home planet, Earth. In this book you will learn about the fascinating geologic processes that make the Earth the special place it is. You will find out how our understanding of this planet has changed dramatically over the past few decades as a result of new theories and new technologies for Earth observation. Yet we continue, as well, to build upon the scientific foundations laid by geologists of the past 200 years. Earth is a fascinating planet, and geology—the scientific study of the Earth—is a multifaceted discipline.

If you have purchased this book, you probably fall into one of three categories:

• you studied geology a number of years ago in college or university and want to update your understanding of the subject;

• you are currently studying geology in college or university and want to supplement your understanding of the material covered in lectures and labs;

• you have developed an interest in geology, perhaps through watching shows on public television or hearing about natural events such as earthquakes and volcanic eruptions, and you want to learn more about this fascinating science.

Whatever your background, I hope this book will meet your needs and that you will enjoy reading it and learning more about our planet in the process.

All of the chapters begin with a brief list of the main things you will be learning about. In most of the chapters you will find some text that is set apart like this:

The symbol indicates that this is something special that you might want to think about or an activity or experiment you might want to try for yourself.

Throughout the book you will find questions and answers, as well as a Self-Test at the end of each chapter. Use these to test your compre-
hension and retention of concepts and vocabulary as you read. The chapters of the book can be read independently of one another. However, each chapter assumes that you have learned the vocabulary and, in some cases, the concepts presented in the preceding chapters. In particular, the bold vocabulary terms are only introduced once; they are not redefined in each chapter in which they appear. For this reason, it will probably make the most sense for you to read the chapters in the order in which they are presented.

This book is mainly about physical geology, meaning that it focuses primarily on Earth materials (rocks, minerals, lavas, etc.) and processes (erosion, sedimentation, volcanism, etc.). However, it is difficult to separate physical geology from historical geology—the study of Earth history as preserved in the rock record and of organisms that lived long ago. There are two chapters (chapter 3 and chapter 10) in the book that focus specifically on historical geology. You will also discover that many other scientific disciplines—including astronomy, chemistry, biology, physics, oceanography, hydrology, and meteorology—contribute to our understanding of this complex planet we inhabit. I hope you will enjoy your exploration of planet Earth!
1 Plate Tectonics:  
A Revolution in Geology

This we know. The Earth does not belong to us; we belong to the Earth.

—attributed to Chief Seattle

It is my opinion that the Earth is very noble and admirable . . . and if it had continued an immense globe of crystal, wherein nothing had ever changed, I should have esteemed it a wretched lump of no benefit to the Universe.

—Galileo Galilei

OBJECTIVES

In this chapter you will learn

• what physical and historical geology are and the differences between them;

• how the theory of plate tectonics revolutionized geology;

• how scientists gathered evidence to support the theory of plate tectonics;

• how internal processes shape the surface of the Earth and make it a dynamic place to live.

1 UNDERSTANDING THE EARTH

Geology is the scientific study of the Earth. Geology is a young science; it has existed as a modern scientific discipline for just over 200 years. The study of the Earth is traditionally divided into two broad subject areas: physical geology and historical geology. Physical geology concerns the processes that operate at or beneath the surface of the Earth and the materials on which those processes operate. Some examples of geologic processes are mountain building, volcanic erup-
tions, river flooding, earthquakes, and the formation of ore deposits. Some examples of geologic materials are minerals, rocks, soils, lava, and water.

Historical geology concerns geologic events that occurred in the past. These events can be read from the rock record. Historical geologists try to answer questions such as when the oceans formed, why the dinosaurs died out, when the Rocky Mountains rose, and when the first trees appeared. Historical geology helps us establish a chronology of events in Earth history and gives us a context for understanding our present-day environment.

There are many more specialized areas of study within the traditional domains of physical and historical geology. For example, volcanologists study volcanoes and eruptions; seismologists study earthquakes; mineralogists study minerals and crystals; paleontologists study fossils and the history of life on the Earth; structural geologists study how rocks break and bend; economic geologists study the formation and occurrence of valuable ore deposits. This specialization is needed because geology encompasses such a broad range of topics.

Geologists are scientists who make a career out of the scientific study of the Earth. Yet to a certain extent we are all geologists. Everyone living on this planet relies on resources from the Earth: water, soil, building stones, metals, fossil fuels, gems, plastics (made from petroleum), ceramics (made from clay minerals), salt (the mineral halite), and many others. We are affected by geologic processes every single day we spend on the surface of this dynamic planet. By learning as much as we can about these processes, we can become better-informed, more responsible caretakers of our home planet.

Name three examples of geologic processes. Try to think of at least one example that was not mentioned in the text.

Answer: Examples in the text are mountain building, volcanic eruptions, river flooding, earthquakes, and the formation of ore deposits. Some other examples are groundwater movement, oil and coal formation, evaporation, and erosion. Can you think of any more?

Name three examples of geologic materials. Try to think of at least one example that was not mentioned in the text.

Answer: Examples in the text are minerals, rocks, lava, and water. Some other examples are soil, magma, glacial ice, and natural gas. Can you think of any more?
2 GEOLOGY THEN AND NOW: A SCIENTIFIC REVOLUTION

Even a science as young as geology can have a revolution, and that is what happened in the 1960s. At that time, a brand-new theory emerged and completely changed our understanding of geologic processes. The tools, the methods, and even the language of geology changed as a result of that scientific revolution. If you studied geology prior to the 1960s, you may remember some terms that are no longer in use today. Terms such as "eugeosyncline" and "miogeosyncline" were used to describe topographic features of the Earth's surface that geologists observed but could not explain. With the advent of the theory of plate tectonics, these features took on new meaning. Consequently, geologists began using new terms to describe them. This book will help you learn the vocabulary we use to describe our current understanding of the Earth.

This first chapter—and, indeed, much of the rest of this book—concerns the plate tectonic revolution and how it has informed and transformed our understanding of the Earth. But geology is currently undergoing another, more subtle revolution. This revolution is driven by the ability of scientists to observe and collect information about the Earth as a whole planet, using instruments mounted on satellites. This ability is quite new; remember that no one had ever seen a picture of the whole Earth until the 1960s, when the first photograph was taken of Earth from space.

Satellite images and data collected from outer space provide a scientific foundation for our study of the Earth as an integrated system. Earth system science, as this approach is called, is not new in philosophy, but its tools and techniques are very new. These tools are used in a wide range of applications, from weather forecasting to the monitoring of changes in sedimentation rates, measuring the flow of polar ice, locating mineral resources, documenting the extent of oil spills, tracking depletion of stratospheric ozone, and many others. Through Earth system science, geologists are contributing to our understanding of the Earth as a whole, how the Earth changes over time, and the impacts of human actions on the Earth system.

Name at least three applications of Earth system science.

Answer: Examples in the text are weather forecasting, monitoring changes in sedimentation rates, measuring the flow of polar ice, locating mineral resources, documenting the extent of oil spills, and tracking the depletion of stratospheric ozone. Can you think of any more?
3 GEOLOGY BEFORE PLATE TECTONICS.

During the 1800s, people favored the idea that the Earth, originally a molten mass, had been cooling and contracting for centuries. Scientists argued that mountain ranges full of folded rocks were expressions of the contraction and shrinkage of the Earth's interior (if the crust didn't contract as much as the interior, it would fold and crumple like the wrinkled skin of a dried prune). Contraction did appear to explain some features of the Earth's surface, but it could not explain the shapes and positions of the continents. Nor did it explain features like great rift valleys, clearly caused by stretching rather than by contraction.

At the beginning of the twentieth century, scientists discovered that the Earth's interior is heated by the decay of naturally occurring radioactive elements. This suggested that the Earth might not be cooling but rather heating up, and therefore expanding. A smaller Earth might once have been covered mostly by continents. As the Earth expanded, the continents would crack into fragments, and eventually the cracks would grow into oceans. The expanding Earth hypothesis did explain the apparent fit between the coastlines of Africa and South America, which look as if they have been ripped apart from each other. But there are other features that this hypothesis did not easily account for, such as folded mountain ranges formed by compression.

To get around the flaws in the expansion and contraction hypotheses, geologists began to search for other ways of explaining the shapes and positions of the continents, oceans, and mountain chains. By the middle of this century, all reasonable suggestions seemed to have been exhausted; the time was ripe for a totally new approach. This approach turned out to be plate tectonics—the theory that the continents are carried along on huge slabs, or plates, of the Earth's outermost layer. In some places the plates are slowly colliding, forming compressional features like huge mountain ranges. In other places the plates are moving apart, forming expansional features like great rift valleys. The theory of plate tectonics provided, for the first time, a coherent, unified explanation for all of these features of the Earth's surface.

What was wrong with the "contracting Earth" hypothesis?

**Answer:** It did not adequately explain the shapes and positions of the continents, nor did it explain features like great rift valleys, which appear to have been caused by stretching.

What was wrong with the "expanding Earth" hypothesis?
Answer: It did not adequately explain features such as folded mountain ranges formed by compression.

4 CONTINENTAL DRIFT AND THE STORY OF WEGENER

This chapter tells the story of how the theory of plate tectonics was conceived and developed and eventually came to be accepted. The modern part of the story began in the early 1900s with a German meteorologist named Alfred Wegener, who had some controversial ideas about the shapes and positions of the continents.

In 1910, Wegener began lecturing and writing scientific papers about continental drift. His continental drift hypothesis suggested that the continents have not always been in their present locations but instead have "drifted" and changed positions. Wegener's idea was that the continents had once been joined together in a single "supercontinent," which he called Pangaea (pronounced "pan-JEE-ah"), from Greek words meaning "all lands." He suggested that Pangaea had split into fragments like pieces of ice floating on a pond and that the continental fragments had slowly drifted to their present locations.

Wegener presented a great deal of evidence in support of the continental drift hypothesis. Nevertheless, his proposal created a storm of protest in the international scientific community. Part of the problem was that geologists simply could not envision how the continents could move around. Another part of the problem was that geologists had to be convinced that the evidence that the continents had once been joined was truly conclusive. Let's look at some of the evidence for continental drift, so you can judge for yourself. Notice that no single piece of evidence is conclusive on its own. It took several decades and the weight of all this evidence (and more) to finally convince geologists that continental drift really happens.

What was the name of the "supercontinent" proposed by Alfred Wegener?

Answer: Pangaea.

5 EVIDENCE FROM COASTLINES

Look at a map of the world. The Atlantic coastlines of Africa and South America seem to match, almost like puzzle pieces. The southern coast of Australia similarly seems to match part of the coast of Antarctica, and the same is true of some other continental coastlines. Is this apparent fit an acci-
dent, or does it support the hypothesis that the continents were once joined together?

To answer the question of whether continents were once joined, we must first recognize that the edge of the land—that is, the shoreline—usually isn't the true edge of the continent. To find the true edge of a continent, we need to locate the place where the rocks of the continent—mostly made of granite—meet the rocks of the ocean floor—mostly made of basalt. (You will learn more about these two important rock types in chapter 5.)

Along a noncliffed shoreline, such as the Atlantic coasts of North America, South America, and Africa, the land usually slopes very gently toward the sea (Figure 1.1). This gently sloping land is called the continental shelf. At the edge of the continental shelf there is a sharp drop-off to the steeper continental slope. At the bottom of the steep continental slope, the land begins to level off again; this is the continental rise, which marks the transition to the flat ocean floor, the abyssal plain. The actual place where the granitic rocks of the continent meet the basaltic rocks of the ocean floor is usually covered by sand, mud, and other loose rock particles. The actual shape of the shoreline depends on sea level, the presence or absence of cliffs, and the details of the topography of the continental shelf in any particular locality. Thus, the actual transition from continent to ocean may (or may not) be underwater.

So, how do we identify the true edge of a continent? Usually the edge of a continent is defined as being halfway down the steep continental slope. When we try to fit the continents together, we fit them along this line rather than along the present-day coastline. When we fit Africa and South America together in this way, the result is remarkable (Figure 1.2). In the "best-fit" position, the average gap or overlap between the two continents is only 90 kilometers (km) (about 56 miles)
Figure 1.2

[mi]). (Note that 1 kilometer ≈ 0.62 miles; see Appendix 1 for more about units, conversions, and abbreviations.) Furthermore, the most significant overlapping areas consist of rocks that were formed after the time when the continents are thought to have split apart. This strongly suggests that Africa and South America were once joined.

Sketch and neatly label a diagram showing the transition from continent to ocean. Show how the slope of the land changes, and label all of the topographic features. On your diagram, indicate the "true" edge of the continent.

Answer: Refer to Figure 1.1.

6 EVIDENCE FROM ROCKS

If Africa and South America were once joined, one would expect to find similar geologic features on both sides of the join. Such correlations provided some of the most compelling evidence presented by Wegener in support of the continental drift hypothesis. However, matching the geology of rocks on opposite sides of an ocean is more difficult than you might imagine. Rock-forming processes never cease. Some rocks formed before the continents were joined, some while they
were joined, others during the splitting of the continents, and still others after they separated. How can we tell which rocks are significant in trying to find a match between the continents?

A logical starting point is to see if the ages and orientations of similar rock types match up across the ocean. In Wegener's time, geologists did not have sophisticated tools for determining the exact age of a rock. But now we do have such tools, and we know that there are strong similarities in the ages of rocks across the oceans. The match is particularly good between rocks about 550 million years old and older in northeast Brazil and West Africa, but there is not a good match for younger rocks. This suggests that the two continents were joined together for some period of time prior to 550 million years ago, and they subsequently split apart.

We can also look for continuity of geologic features such as mountain chains. If we rejoin the continents as they would have been in the supercontinent Pangaea, mountain belts of similar ages seem to line up. For example, the oldest portions of the Appalachian Mountains, extending from the northeastern part of the United States through eastern Canada, match up with the Caledonides of Ireland, Britain, Greenland, and Scandinavia. A younger part of the Appalachians lines up with a mountain belt of similar age in Africa and Europe. These and other bedrock features that match up across the oceans are strong evidence that the continents were once joined together.

Another geologic feature that matches across continental joins is the deposits left by ancient ice sheets. These are similar to deposits left by recent glaciers in

![Figure 1.3](image)
Canada, Scandinavia, and the northern United States. In South America and Africa there are very thick glacial deposits. The deposits are the same age, and they match almost exactly when the continents are "moved back together." As glacial ice moves, it cuts grooves and scratches in underlying rocks and produces folds and wrinkles in soft sediments. Such features provide evidence of the direction the ice was moving during the glaciation. When Africa and South America are moved back together, the grooves and scratches show that the ice was radiating outward from the center of a former ice sheet (Figure 1.3). It's hard to imagine how such similar glacial features could have been created if the continents had not once been joined together. Africa and South America must also have had similar climates during this period, colder than their present-day climates. This suggests that they were not in their present equatorial locations. In fact, the southern portion of Pangaea was most likely close to what was then the South Pole.

How can the ages of rocks provide evidence that two continents—now separated from each other by an ocean—were once joined?

Answer: If the continents were once joined, we would expect to find rocks of similar type and age on either side of the ocean. There are strong similarities in rocks about 550 million years old and older in northeast Brazil and West Africa. This suggests that the two continents were joined together for some period of time prior to 550 million years ago.

7 EVIDENCE FROM FOSSILS

If Africa and South America were joined at one time, with the same climate and matching geologic features, then they also should have hosted similar plants and animals. To check this, Wegener turned to the fossil record. This revealed that there were communities of plants and animals that appear to have evolved together until the time of the splitting apart of Pangaea, after which they evolved separately.

Wegener pointed to specific fossils found in matching areas across the oceans. One example he used was an ancient fern, *Glossopteris*, whose fossilized remains have been found in southern Africa, South America, Australia, India, and Antarctica. Could the seeds of this plant have been carried from one location to another across the oceans? Probably not. The seeds of *Glossopteris* were large and heavy, and could not have been carried very far by wind or water currents. This fern flourished in a cold climate; it would not have thrived in the warm present-day climates of the continents where its fossil remains are found. This, too, suggests that the continents once had similar, colder climates.