SEVENTH EDITION

PHYSICAL GEOLOGY

Judson · Kauffman · Leet

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PRENTICE-HALL, INC.
Englewood Cliffs, New Jersey 07632

Library of Congress Cataloging-in-Publication Data

JUDSON, SHELDON.

Physical geology.

Leet's name appears first on the earlier editions.

Includes bibliographies and index.

1. Physical geology. I. Kauffman, Marvin Earl, date– . II. Leet, L. (Lewis Don), 1901-1974. III. Title.

QE28.2.J8 1987 551 86-25515

ISBN 0-13-669698-8

Editorial/production supervision: Virginia Huebner
Interior design: Christine Gehring-Wolf
Cover design: Linda Conway
Manufacturing buyer: Barbara Kittle
Page layout: Peggy Finnerty
Cover photograph: Massive sandstone cliffs in Zion Canyon, Utah. [Charlie Blecker.]

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-669698-8 01

Prentice-Hall International (UK) Limited, *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S.A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall of Southeast Asia Pte. Ltd., *Singapore*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

PREFACE

Since the first edition of this book appeared over three decades ago our understanding of the Earth has increased enormously. Plate tectonics and seafloor spreading have been invented and continental drift accepted. We have explored with space probes almost to the edge of the planetary system. And at home we have realized that the natural systems of Earth processes so vital to life can be disrupted by human intervention, both planned and unplanned. It has been indeed a heady period for students of the Earth.

Advances in knowledge have been impressive. But certainly they have built upon data, principles, and techniques developed over the decades, even the centuries that went before. This book, we hope, maintains a sensible balance between new and traditional knowledge.

The most immediately noticeable change in this edition compared with earlier ones is the use of color. The availability of full color has made many of the illustrations more effective and easier and more pleasing to 'read.' Furthermore, most of the diagrams have been redrawn and many redesigned or introduced for the first time.

We have added an opening quotation for each chapter, a quotation that we hope catches some of the spirit of the subject matter that follows. This is followed by a general overview of the chapter. We have retained the use of a closing outline to each chapter and have revised some of the chapter-end questions and have added a few new ones. For those who wish to pursue a subject further we have added new references in the Supplementary Readings.

We have added a number of boxes for the first time. Some of these concern technical material that might otherwise interrupt the flow of the main text. Others are brief vignettes about the Earth ranging in subject matter from water witching to dental cavities. We hope the student enjoys reading them as much as we did writing them.

The basic organization of the volume remains unchanged from the last edition. However, as a result of comments from students and colleagues we have extensively revised and rewritten Chapter 3 (Origin and Occurrence of Intrusive Igneous Rocks); Chapter 7 (Metamorphism and Metamorphic Rocks); Chapter 11 (Continents, Oceans, Plates, and Drift); Chapter 12 (Mass Movement); Chapter 19 (Useful Materials); and Chapter 20 (Planets, Moons, and Meteorites), and have made other, although less extensive, adjustments in the other chapters and in the Glossary.

The publisher is making available several pedagogical aids in support of this volume. These include an instructor's manual; a student's study guide; a set of overhead transparencies; a set of color slides; and a test item file on disks for IBM and Apple computers.

In preparing this edition we have had the benefit of comments from the users of the sixth edition. Beyond these we have been fortunate also in having very effective reviews from colleagues as this volume took shape. We are pleased and grateful to acknowledge the time and expertise of Dale A. Abbey, Monroe Community College (Rochester, N.Y.); Gary C. Allen, University of New Orleans; Andy R. Bobyarchick, University of North Carolina (Charlotte); Charles W. Byers, University of Wisconsin-Madison; Stanley Chernicoff, University of Washington; George R. Clark II, Kansas State University; Richard D. Conway, Shoreline Community College (Seattle); Robert B. Furlong, Wayne State University; Carol C. Gilchrist, University of New Orleans; Bryce M. Hand, Syracuse University; Jack H. Hyde, Tacoma Community College; M. Leroy Jensen, University of Utah; Clayton H. Johnson, University of Missouri-Columbia; John Klasik, California State Polytechnic University; William Krieger, York, Pa.; Thomas Moeglin, Southwest Missouri State University; Howard Mooers, University of Minnesota; Steven M. Richardson, Iowa State University; Benjamin H. Richard, Wright State University; Charles P. Thornton, Pennsylvania State University; Franklyn B. Van Houten, Princeton University; and Keith Young, University of Texas (Austin).

We remain indebted to many colleagues and organizations for the use of illustrative material and acknowledge their contributions where their material appears.

At Prentice-Hall, Holly Hodder has served as our editor and did so with efficiency, good humor and grace. Virginia Huebner and Christine Wolf saw the volume through the intricacies of production with unflappable patience and unerring accuracy. Lorraine Abramson, of Network Graphics has overseen the preparation of maps and diagrams each of which has benefited from her sensitive and professional eye.

Our many debts to the people, named and unnamed, who have helped us do not relieve us of the ultimate responsibility for shortcomings. They are ours.

SHELDON JUDSON
MARVIN E. KAUFFMAN

CONTENTS

CHAPTER■1

TIME AND A CHANGING EARTH

O earth, what changes hast thou seen!

Alfred, Lord Tennyson, from "In Memoriam."

OVERVIEW

This initial chapter provides a first look at *physical geology*. We introduce a few important concepts underlying much of what we shall discuss in some detail in later chapters.

First, Earth time is long—about 4.6 billion years—and like human history, it can be considered in either *relative* or *absolute* terms. This vast expanse of time has made it possible for very slow processes to effect very large changes in the Earth.

Second, we find that understanding present-day Earth processes provides the key to interpreting the *rock record*. This simple but powerful concept allows us to extrapolate from the present deep into the past. This past, this history, is recorded in the rocks: *igneous*, *sedimentary*, and *metamorphic*.

A third major concept is that of the *rock cycle*. This provides a useful model by which to arrange the different rock groups, the changes they undergo, and the processes that connect the various parts of the rock record. In turn, the rock cycle leads logically to a preliminary description of *plate tectonics*, *sea-floor spreading*, and *continental drift*. These last three processes have unified much of our thinking about the Earth as a dynamic, changing body and have become an effective elaboration of the rock cycle.

Fourth, we make the perhaps overly obvious point that geology has had, and will continue to have, practical applications to a wide range of human activities.

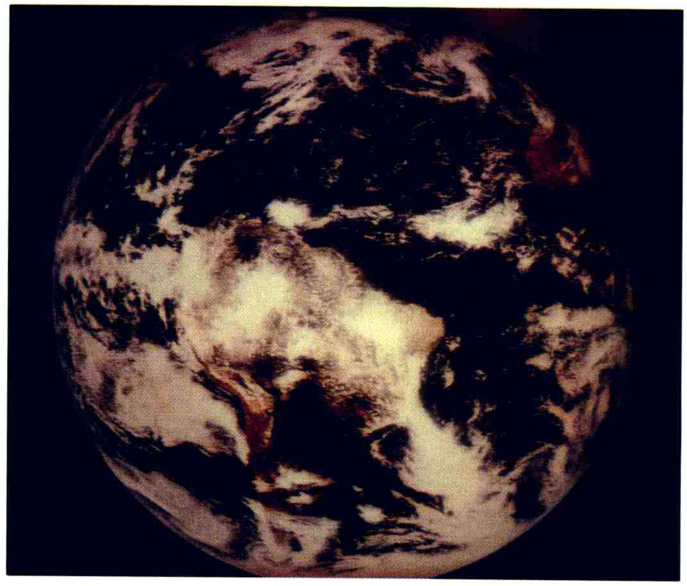
1.1 SOME INTRODUCTORY OBSERVATIONS

Geology (from the Greek for "earth" and "knowledge") is the science of the Earth, an organized body of knowledge about the globe on which we live—about the mountains, plains, and ocean deeps, about the history of life from amoeba to humanity, and about the succession of physical events that accompanied this orderly development of life (Figure 1.1).

Geology helps us unlock the mysteries of our environment. Geologists explore the Earth from the ocean floors to the mountain peaks to discover the origins of our continents and the encircling seas. They try to explain an immensely complex landscape shaped, for example, by the sudden violence of earthquake or volcano and, as importantly, by the gentler and slower processes of water in streams or underground or by the almost imperceptible changes of firm rock to pulverulent soil. They probe the action of glaciers that crawled over the land and then melted away hundreds of millions of years ago, and of some that even today cling to high valleys and cover most of Greenland and Antarctica, the remnants of a recent but presently receding glaciation.

Geologists search for the record of life from the earliest one-celled organisms of ancient seas to the complex plants and animals of the present. This story, from simple algae to seed-bearing trees and from primitive protozoa to highly organized mammals, is told against the ever-changing physical environment of the Earth.

Geologists are by no means earthbound, however. They have already applied their knowledge to the study of other



1.1 The Earth seen from the *Apollo 8* spacecraft during its journey to the Moon. Atmosphere partially obscures the Earth's surface. This atmosphere, however, makes possible not only life but oceans, rivers, glaciers, and winds. [NASA.]

bodies in our solar system (see Chapter 20). One can confidently predict that when observations of the planets and moons of other solar systems are possible, geologic principles will apply to their study as well (see Box 1.1.)

The Earth has not always been as we see it today, and it is changing (but slowly) before our eyes. The highest mountains are built of materials that once lay beneath the oceans. Fossil remains of animals that swarmed the seas millions of years ago are now dug from lofty crags. Every continent is partially covered with sediments that were once

BOX 1.1 What's in a Name?

The word *geology* derives from the Greek *geo*, "Earth," and *logos*, "discourse," and comes to us through the Latin. The present meaning of geology, "science of the Earth," came into use in the late eighteenth and early nineteenth centuries.

The medieval Latin word "geologia" was apparently used for the first time by Richard de Bury in the fourteenth century. To him, it meant the study of the law. If you were reading the Italian F. Sessa's 1687 volume *Geologia*, you would discover that the author was trying to demonstrate that the "influences" ascribed by the astrologers to the stars actually came from the Earth.

Students of the Earth 150 to 200 years ago might have known their subject either as geology or as *geognosy*. They were essentially the same subjects. Geognosy didn't catch on as a word; nor did *geonomy*, introduced a century ago as a synonym for geology.

Today we pretty well know what we mean when we use the term *geology*. True, some colleges and universities call the study of the Earth *geoscience* and others maintain that *Earth science* is a better term. Indeed, there are some differences in meaning among these terms. For our purposes here, we prefer the term *geology*, and follow a general definition coined by one of our colleagues:

ge·ol·o·gy, n. The study of the Earth and other solid bodies in space. Geology applies the techniques originally devised for Earth problems to deciphering the present attributes, history, and origin of any natural solid body.

laid down on the ocean floor, evidence of an intermittent rising and settling of the Earth's surface.

In this chapter we take a preliminary look at some of the important concepts in the study of our changing Earth. In subsequent chapters we shall discuss at greater length the subjects touched on here. Therefore you must read this chapter with the understanding that the assertions we make will be more fully explained at appropriate later points. This chapter is intended to provide a framework within which to organize your thinking about much of that more detailed material: It serves as a kind of map by which to chart our exploration of physical geology.

1.2 TIME

We now know that the Earth is about 4.6 billion years old—nearly a million times the age attributed to it in the seventeenth century. We are less certain about the age of the universe, of which our Earth is a part. But most current evidence suggests that the universe is more than three times the age of the Earth.

In the following paragraphs we briefly discuss some of the ways in which geologic time is divided and measured, deferring until Chapter 8 a more detailed consideration of the subject.

ABSOLUTE AND RELATIVE TIME

An initial and casual reaction to the notion of time is that we can mark it off without much difficulty, even though we recognize, as Thomas Mann wrote in *The Magic Mountain*, that

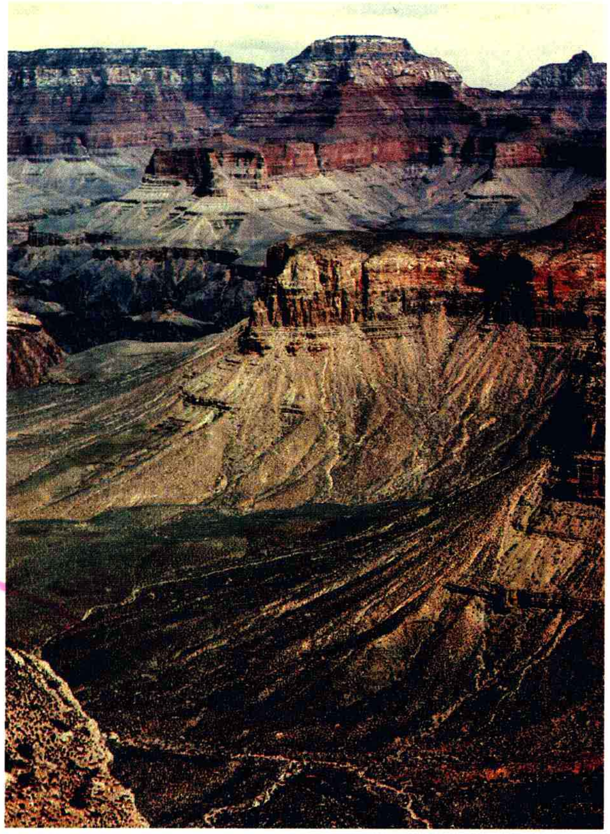
> time has no division to mark its passage, there is never a thunder-storm or blare of trumpets to announce the beginning of a new month or year. Even when a new century begins it is only we mortals who ring bells and fire off guns.[1]

Nevertheless, our modes—seconds, years, millennia, and the rest—are all we have to work with; consequently we can consider geologic time from two points of view: as relative or as absolute. **Relative time**—that is, whether one event in earth history came before or after another event—disregards years (Figure 1.2) On the other hand, whether a geologic event took place a few thousand years ago, a billion years ago, or at some date even farther back in earth history is reported in **absolute time** (Figure 1.3).

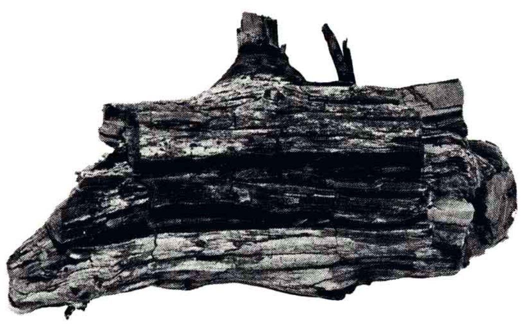
Relative and absolute time in Earth history have their counterparts in human history. In tracing the history of the Earth we may wish to know whether some event, such as a volcanic eruption, occurred before or after another event, such as a rise in sea level, and how these two events are related in time to a third event, perhaps a mountain-building episode. In human history, too, we try to determine the relative position of events in time. In studying United States history we find it important to know that the Revolutionary War preceded the Civil War and that the Canadian-American boundary was fixed sometime between these two events.

Sometimes events in both Earth history and human history can be established only in relative terms. Yet our record becomes increasingly precise as we fit more and more events into an actual chronological calendar: If we did not know the date of the United States–Canadian boundary treaty—if we knew only that it was signed between the two wars—we could place it between 1783 and 1861. (Recorded history, of course, provides us with the actual date, 1846.)

[1] Thomas Mann, *The Magic Mountain*, trans. H. T. Lowe-Porter, p. 225, Modern Library, Inc., New York, 1955.



1.2 These layers of rock in the walls of the Grand Canyon of the Colorado River in Arizona record relative time. Each layer is younger relative to the layers beneath and older relative to the layers above. [Neil Lundberg.]



1.3 This fragment of spruce log was part of a tree in a buried forest at Two Creeks, Wisconsin. Measurements of its content of radioactive carbon (carbon 14) give us an absolute age of the death of the tree as some 11,350 radiocarbon years ago. The fragment is about 20 cm long. [Willard Starks.]

Naturally, we should like to date geologic events with similar precision. But so far this has been impossible, and the accuracy we have achieved in dating human history—that is, written human history—will likely never be duplicated in geologic dating. Still, we can determine approximate dates for many geologic events, which are probably of the correct order of magnitude. We can say that dinosaurs became extinct about 63 million years ago and that about 11,000 years ago the last continental glacier began to recede from New England and the area bordering the Great Lakes.

Radioactivity Radioactive elements (those whose nuclei spontaneously emit particles to produce new elements, as discussed in Section 8.3) have provided the most effective means of measuring absolute time. The rate at which a given radioactive element decays is (so far as we have been able to determine) unaffected by changes in physical conditions or by time. So if we know the amount of original radioactive material (the **parent**) that remains, the rate of radioactive decay, and the amount of new elements (the **daughters**) that has formed, then we can calculate the time elapsed since radioactive decay began. Of course, the calculation is not quite so simple, as we discuss in Section 8.3. Nevertheless, from the time that the first radioactive-age determinations were made (in 1907) to now, we have learned enough about the techniques and pitfalls of radioactive dating to be confident about the thousands of dates now available, particularly those determined during the last two decades. A variety of elements has proved useful, with a time range from that of carbon 14, which can be used to date events that occurred a few hundred to a few tens of thousands of years ago, to that of an element such as uranium 238, which has the potential of dating events several times greater than the age of the Earth.

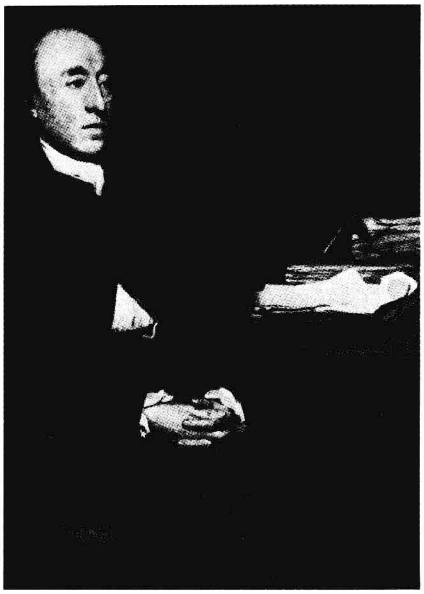
DIVISIONS OF GEOLOGIC TIME

The application of radioactive elements to the measurement of geologic time became useful only after geologists had already constructed a calendar of geologic events. This calendar, still in use, was based on the ages of rock units relative to each other. Such relative ages were determined by conclusions drawn from a number of phenomena, including the superposition of younger rocks on older rocks, the cutting of older rocks by more recently formed rocks, and the progressive evolutionary stages of plant and animal life, as represented by remains in some rocks. The methods are discussed in detail in Section 8.1. It suffices to say here that the arrangement of rock units and the Earth events they record in the geologic calendar, as determined before the twentieth century, have been confirmed by the absolute dates of later radioactive dating.

The rock units in their proper chronological order make up the **geologic column,** which is reproduced on the front endpaper of this book.

UNIFORMITARIANISM

Modern geology was born in 1785, when James Hutton (1726–1797), a Scottish medical man, gentleman farmer, and geologist (Figure 1.4), formulated the principle now known to geologists as the **doctrine of uniformitarianism.** This principle simply means that the physical processes operating in the present to modify the Earth's surface also operated in the geologic past—which is another way of saying that the laws of nature are unchanging. We are reasoning by analogy when we say that the record of the past was created



1.4 Many of the concepts of present-day geology stem from the eighteenth-century studies of James Hutton, a gentleman who is reported to have been less austere than he appears here.

by processes that are still operating today. True, the intensity of any process may—and does—change with time, but the basic process remains the same.

Here is an example. We know from observations that modern glaciers deposit a distinctive type of debris made up of rock fragments that range in size from submicroscopic particles to boulders weighing several tons. This debris is jumbled, and many of the large fragments are scratched and broken. We know of no agent other than glacier ice that produces such a deposit. Now suppose that in the New England hills or across the plains of Ohio or in the deep valleys of the Rocky Mountains we find deposits that in every way resemble glacial debris but find no glacier in the area. We can still assume that the debris was deposited by now-vanished glaciers. On the basis of evidence like this, geologists have worked out the concept of the great Ice Age (Chapter 15).

Such an example can be multiplied many times. For instance, most earth features and rocks exposed at the Earth's surface today are explained as the result of past processes similar to those of the present. We shall find that many conclusions of physical geology are based on the conviction that modern processes also operated in the past.

Armed with Hutton's concept of uniformitarianism, nineteenth-century geologists were able to explain Earth features on a logical basis. But the very logic of the explanation gave rise to a new concept for students of the Earth. Presumably, past processes operated at the same slow pace as do those of today. Consequently very long periods of time must have been available for those processes to accomplish their tasks. It was apparent that a great deal of time was needed for a river to cut its valley or for hundreds or thousands of feet of mud and sand to be deposited on an ocean bottom, and then harden into solid rock, and rise far above the level of the sea.

The concept of almost unlimited time in Earth history is thus a necessary outgrowth of the application of the principle that **the present is the key to the past.** For example, geologists know that mountains as high as the modern Rockies once towered over what are now the low uplands of northern Wisconsin, Michigan, and Minnesota. But only the roots of these mountains are left, the great peaks having long since disappeared. Geologists explain that the ancient mountains were destroyed by rain and running water, creeping glaciers and wind, and landslides and slowly moving rubble, and that these processes acted essentially as they do in our present-day world.

Now think of what this explanation means. We know from firsthand observation that streams, glaciers, and winds have some effect on the surface of the Earth. But how can such feeble forces level whole mountain ranges? Instinct and common sense tell us that they cannot. This is where the factor of time comes into the picture. True, the small, almost immeasurable amount of erosion that takes place in a human lifetime has little effect; yet when the erosion during one lifetime is multiplied by millions of lifetimes, mountains can be worn away. Time makes possible what seems impossible.

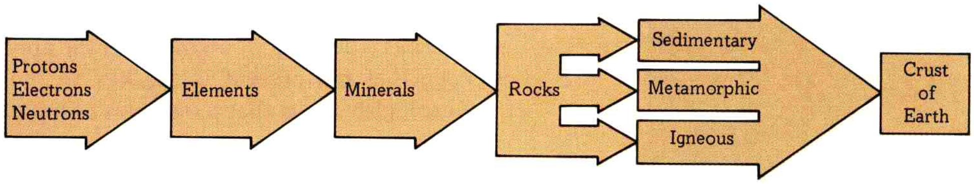
Before ending these observations on uniformitarianism, we should raise a warning flag already hinted at in the final sentence of the opening paragraph of our discussion. No process is "uniform" all over the world at any one time. Its rate and intensity can be—and usually are—different from place to place. Some areas erode faster than others; some are less prone to earthquakes than others. By the same token, rates and intensities may change with time. For example, a meteoritic impact is relatively rare today compared to the earliest history of the Earth, when impacts were not only extremely numerous but also, at least some of them, enormously large.

A final word: Some events are "catastrophic." These are rare and unlikely to be experienced in the average human lifetime. But we should view catastrophic events not as the result of a unique process, but rather as extreme end members of a familiar process. Thus a gigantic flood that happens once every 100 years or so appears unique when compared with an average annual flood. But the process of flooding obeys the same basic principles whether the event is large or small, catastrophic or benign.

1.3 EARTH MATERIALS AND THE ROCK CYCLE

Geology is based on the study of rocks. We seek to know their composition, their distribution, how they are formed and destroyed, and why they are lifted up into continental masses and depressed into ocean basins.

Rock is the most common material on Earth. We may recognize it as the gravel in a driveway, the boulders in a stream, or the cliffs along a ridge. It is the stuff that forms



1.5 Relation of particles, elements, minerals, rocks, and the crust of the Earth.

the crust of our earth. Close examination demonstrates that rock can be divided into three major groups based on mode of origin: **igneous, sedimentary,** and **metamorphic.**

When we look deeper, we find that a rock is merely an assemblage of minerals. These minerals are chemical compounds with definite compositional and physical characteristics. Over 2,000 different minerals have been described, but only a handful (a dozen, more or less) make up the great bulk of the rocks of the Earth's crust. Digging farther, as we do in Chapter 2, we recognize that minerals are composed of chemical elements that in turn are made up of differing arrangements of protons, electrons, and neutrons. Figure 1.5 is a convenient way of relating these various levels of matter.

THE THREE ROCK FAMILIES

In later chapters we will examine the three rock families—igneous, sedimentary, and metamorphic—in some detail. Here we will merely take an introductory look at them.

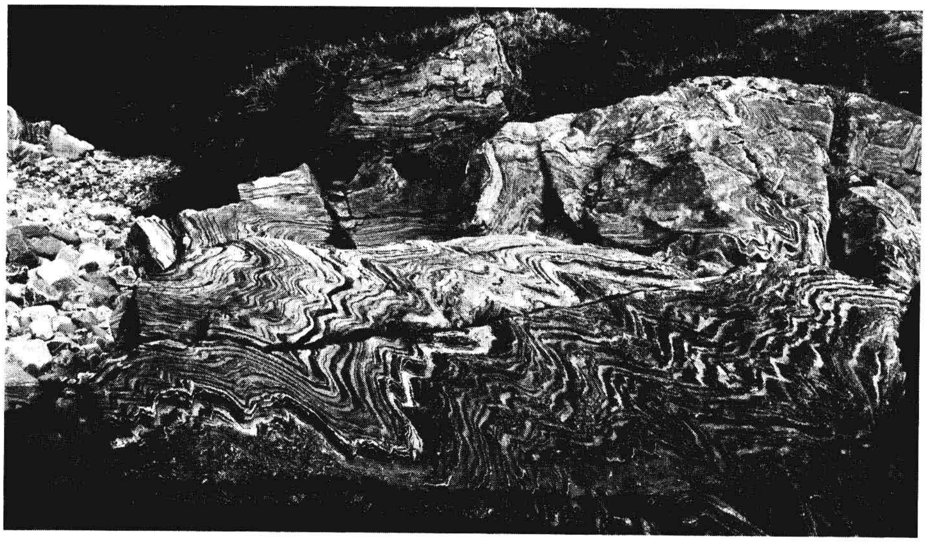
Igneous rocks, the ancestors of all other rocks, take their name from the Latin *ignis*, meaning "fire." They form when a hot molten mass cools. When this material lies beneath the surface, we call it a **magma.** Igneous rocks that form the magma are hidden from our view until erosion strips away the overlying rock. When the magma works its way to the surface it may explode violently to form layers of **ash and cinders,** or may erupt more quietly as a stream of molten material that we call **lava.** Both of these may combine to build a volcanic cone (Figure 1.6). The lava cools rapidly—in days or weeks—into firm, solid rock. By contrast, the molten mass at depth cools and solidifies very slowly over hundreds of thousands, even millions of years.

Most sedimentary (Latin *sedimentum*, "settling") rocks are made up of particles derived from the breakdown of preexisting rocks. Usually these particles are transported by gravity, water, wind, or ice to new locations, where they are deposited in new arrangements. For example, waves beating against a rocky shore may provide the sand grains and pebbles for a nearby beach. If these beach deposits were to harden, we should have sedimentary rock. As we will see later, however, a few sedimentary rocks form from the direct chemical precipitation of minerals. One of the most characteristic features of sedimentary rocks is the layering of the deposits that go to make them up (Figure 1.7).

Metamorphic rocks compose the third large family of rocks. Metamorphic (from the Greek words *meta*, "change," and *morphē*, "form") refers to the fact that the original rock has changed from its primary form to a new

1.6 Volcano Arenal in Costa Rica is a cone built up of layers of lava and associated beds of volcanic ash and cinders. The material was derived from molten rock, magma, deep beneath the surface. [Andrea Borgia.]

1.7 Layering is very characteristic of sedimentary rocks. Here in Pueblo County, Colorado, beds of limestone alternate with beds of shale. The shale beds are slightly recessed because they weather more rapidly than limestone in the fairly dry climate of the area. The limestone beds vary between 5 and 20 cm in thickness. [G. K. Gilbert, U.S. Geological Survey.]



1.8 These twisted bands of metamorphic rock in Aberdeenshire, Scotland, began as flat-lying layers of limey muds. They were then turned into the sedimentary rock limestone. Later they were subjected to high pressure and temperature and the resulting contorted beds are the metamorphic rock, marble. [Geological Survey of Great Britain.]

form. Earth pressures, heat, and chemically active fluids beneath the surface may all be involved in changing an originally sedimentary or igneous rock into a metamorphic rock (Figure 1.8).

THE ROCK CYCLE

We have suggested that there are definite relationships among sedimentary, igneous, and metamorphic rocks. With time and changing conditions, any one of the rock types may be changed into some other form. These relationships form a cycle, as shown in Figure 1.9, which is simply a way of tracing out the various paths that earth materials follow. The outer circle represents the complete cycle; the arrows within the circle represent shortcuts in the system that can be, and often are, taken. Notice that the igneous rocks are shown as having been formed from a magma and as providing one link in a continuous chain. From these parent rocks, through a variety of processes, all other rocks can be derived.

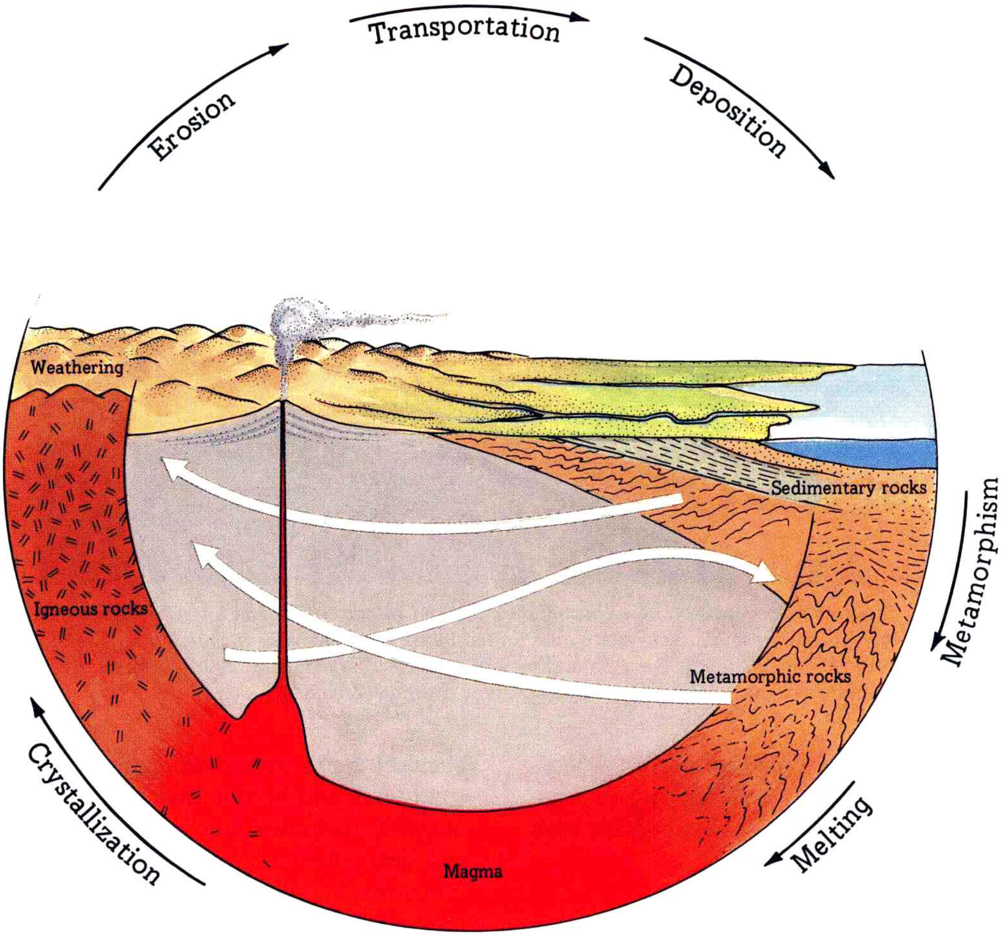
First, weathering attacks the solid rock, which either has been formed by the cooling of a lava flow at the surface or is an igneous rock that was formed deep beneath the Earth's surface and then was exposed by erosion. The products of weathering are the materials that will eventually go into the creation of new rocks—sedimentary, metamorphic, and even igneous. Landslides, running water, wind, and glacier ice all help to move the materials from one place to another. In the ideal cycle this material seeks the ocean floors, where layers of soft mud, sand, and gravel are consolidated into sedimentary rocks. If the cycle continues without interruption, these new rocks may in turn be deeply buried and subjected to pressures caused by overlying rocks, to heat, and to forces developed by earth movements. The sedimentary rocks may then change in response to these new conditions and become metamorphic rocks. If these metamorphic rocks undergo continued and increased pressure and heat, they may eventually lose their identity and melt into a magma. When this magma cools, we have an igneous rock again; we have come full circle.

But notice too that the complete rock cycle may be **interrupted.** An igneous rock, for example, may never be exposed at the surface and hence may never be converted to sediments by weathering. Instead, it may be subjected to pressure and heat and converted directly into a metamorphic rock without passing through the intermediate sedimentary stage. Other interruptions may take place if sediments or sedimentary rock or metamorphic rock are attacked by weathering before they continue to the next stage in the larger, complete cycle.

This concept of the rock cycle was probably first stated in the late eighteenth century by James Hutton, whom we have already mentioned.

> We are thus led to see a circulation in the matter of this globe, and a system of beautiful economy in the works of nature. This earth, like the body of an animal, is wasted at the same time that it is repaired. It has a state of growth and augmentation; it has another state, which is that of diminution and decay. This world is thus destroyed in one part, but it is renewed in another; and the operations by which this world is thus constantly renewed are as evident to the scientific eye, as are those in which it is necessarily destroyed.[2]

[2] James Hutton, *Theory of the Earth*, vol. 2, p. 562. Edinburgh, 1795. Hutton's theory of the earth was first presented as a series of lectures before the Royal Society of Edinburgh in 1785. These lectures were published in book form in 1795. Seven years later Hutton's concepts were given greater circulation in a more readable treatment, called *Illustrations of the Huttonian Theory*, by John Playfair.



1.9 The rock cycle shown diagrammatically. If uninterrupted, the cycle will continue clockwise around the outer margin of the diagram from magma to igneous rocks to sedimentary rocks to metamorphic rocks and back to magma. The path may be interrupted, however, and follow one of the arrows through the interior of the diagram.

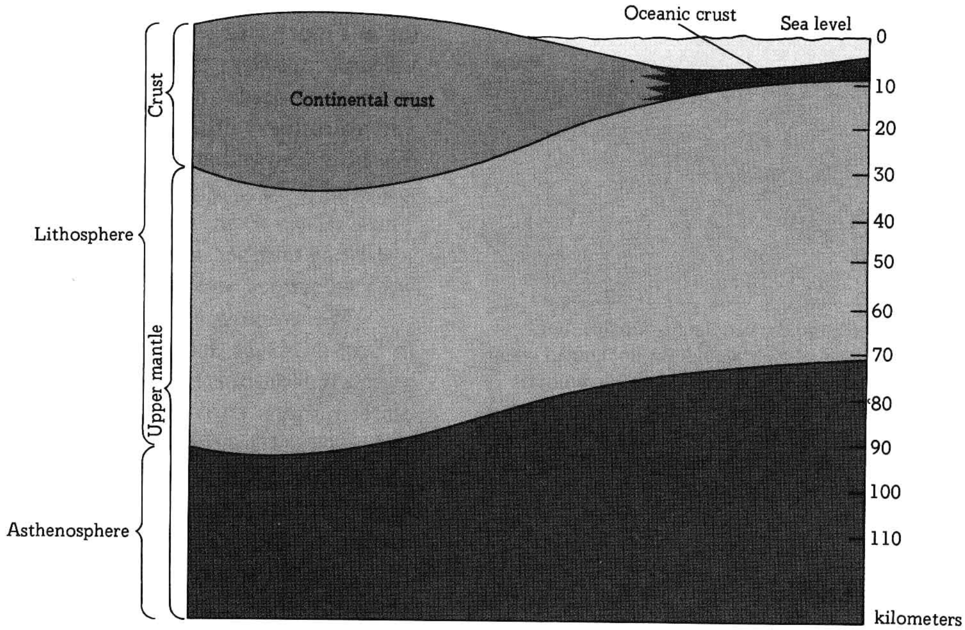
We can consider the rock cycle to be a kind of outline of physical geology, as a comparison of Figure 1.9 with the Contents of this book will show.

1.4
PLATE TECTONICS, SEA-FLOOR SPREADING, AND CONTINENTAL DRIFT

To generations of geologists it has been clear that the Earth is a dynamic, changing body. As we have pointed out, new rocks—sedimentary rocks—are made from the weathered debris of older rocks, and they can be crumpled, metamorphosed, and lifted into high mountain chains; or old rocks can be melted and the resulting magma cooled to form igneous rocks. Indeed, these changes can be traced in nature and pictured as we have in the rock cycle in Figure 1.9. But only recently have we been able to fit the rocks and their alterations into a worldwide, integrated system and to explain in a general way the origin of continents and ocean basins and of mountain ranges and continental plains, as well as the location of volcanoes and earthquake belts. Two of the processes involved are referred to as **plate tectonics** and **sea-floor spreading.** Although we shall later extensively discuss these processes—particularly in Chapter 11—we take a preliminary look at them here. They include the movement of several large plates that, fitted together, form the rigid rind of the Earth. This movement causes the growth as well as the closure of ocean basins and the creation of earthquakes, volcanoes, and mountain building along the plate boundaries. The movement also accounts for the shifting positions of continents over the last several hundred million years. The processes focus on the outer 200 km (kilometers) of the Earth, a subject to which we shall also return later. Meanwhile a brief sketch of what we know about this zone is presented below.

LITHOSPHERE, ASTHENOSPHERE, CRUST, AND MANTLE

The outer 50 to 100 km of the Earth is a rigid shell of rock called the **lithosphere** (from the Greek *lithos*, "rock," and "sphere"). Yet as observations from deep mines tell us, the temperature of the Earth increases by around 15°C (Celsius) with each kilometer of depth. So at a depth of



1.10 The relationships between the upper mantle and crust (continental and oceanic) and the lithosphere and asthenosphere. (See also Figure 10.28.)

about 70 km the temperature averages 1000°C, at which rock will slowly flow if pressure is applied. This "soft" zone, which is encountered at a depth from 70 to 100 km, is called the **asthenosphere** (Greek *asthenēs*, "weak"). As we shall see, its existence helps explain some of the Earth's major movements, both vertical and horizontal.

The lithosphere and asthenosphere are distinguished by temperature, but we can also divide the outer part of the Earth into shells on the basis of composition. We speak, therefore, of the skin of the Earth as the **crust** and of the bulk of the Earth beneath the crust as the **mantle.** A wide variety of rock types constitutes the Earth's crust, and we can make direct observations of most of the types. A discontinuous cover of sedimentary rocks, a few meters to a few kilometers thick, overlies igneous and metamorphic rocks. The crust beneath the continents is thicker (averaging about 35 km) than that beneath the oceans (about 5 km). A dark-colored, relatively heavy igneous rock called **basalt** dominates the crust beneath the oceans, and we quite naturally call it **oceanic crust.** Its density, about 3 g/cm^3 (grams per cubic centimeter), contrasts with the lighter-weight **continental crust,** with a density of about 2.6 g/cm^3. A large portion of the continental crust is composed of the igneous rock called **granite,** which not only is less dense than basalt but also is light gray to pink in color. Beneath the rocks of the crust at a depth of 5 to 50 km lies the mantle, made of rocks with a density of about 3.3 g/cm^3; the asthenosphere lies within the upper mantle (Figure 1.10).

VERTICAL MOVEMENTS AND ISOSTASY

Precise surveying shows that when a sufficiently large lake forms behind a dam, it will depress the Earth's crust slightly. We also know that when glaciers expanded during the Ice Age, their weight depressed large areas of the crust. Conversely, when the glaciers waned and disappeared, the land rose, recovering its earlier elevation; and even today some areas of Scandinavia and Canada are still rising in response to the melting of the last glaciers. Again, we know that surface elevations can be affected by changes in temperature in the zones beneath. For instance, the Midatlantic Ridge stands high in the Atlantic Ocean basin because of increased heat flow from below along this axis of rifting. As we will see in the following paragraphs, the ocean floor moves slowly away from this zone of high heat, and as it does, it cools and subsides to lower and lower elevations below sea level. The ancient geologic record provides other examples. Studies of thick sequences of sedimentary rocks show numerous situations in which thousands of meters of sediments accumulated in shallow marine environments. There is no way to explain a continuous pile of shallow-water sediments unless the basin in which they had accumulated was shallow from the beginning and kept sinking slowly as additional sediments were added.

In all these examples of **vertical movement** portions of the Earth's crust behave as if they were floating in a soft, slowly flowing zone. And that is what we believe happens. The crust and the uppermost mantle that lie above the asthenosphere have some strength. But they cannot resist the pull of gravity, and they respond to the addition or removal of a load. So if material such as water, ice, or sediments is added at the surface, that overloaded area (and the column of rigid rock beneath) sinks slightly into the asthenosphere; conversely, if a load is removed, an area of the crust floats upward. This floating balance of the crust is called **isostasy** (meaning "equal standing"; Figure 1.11). It explains why the thick, lightweight continental crust stands high in relation to the ocean basins underlain by thinner, heavier oceanic crust.