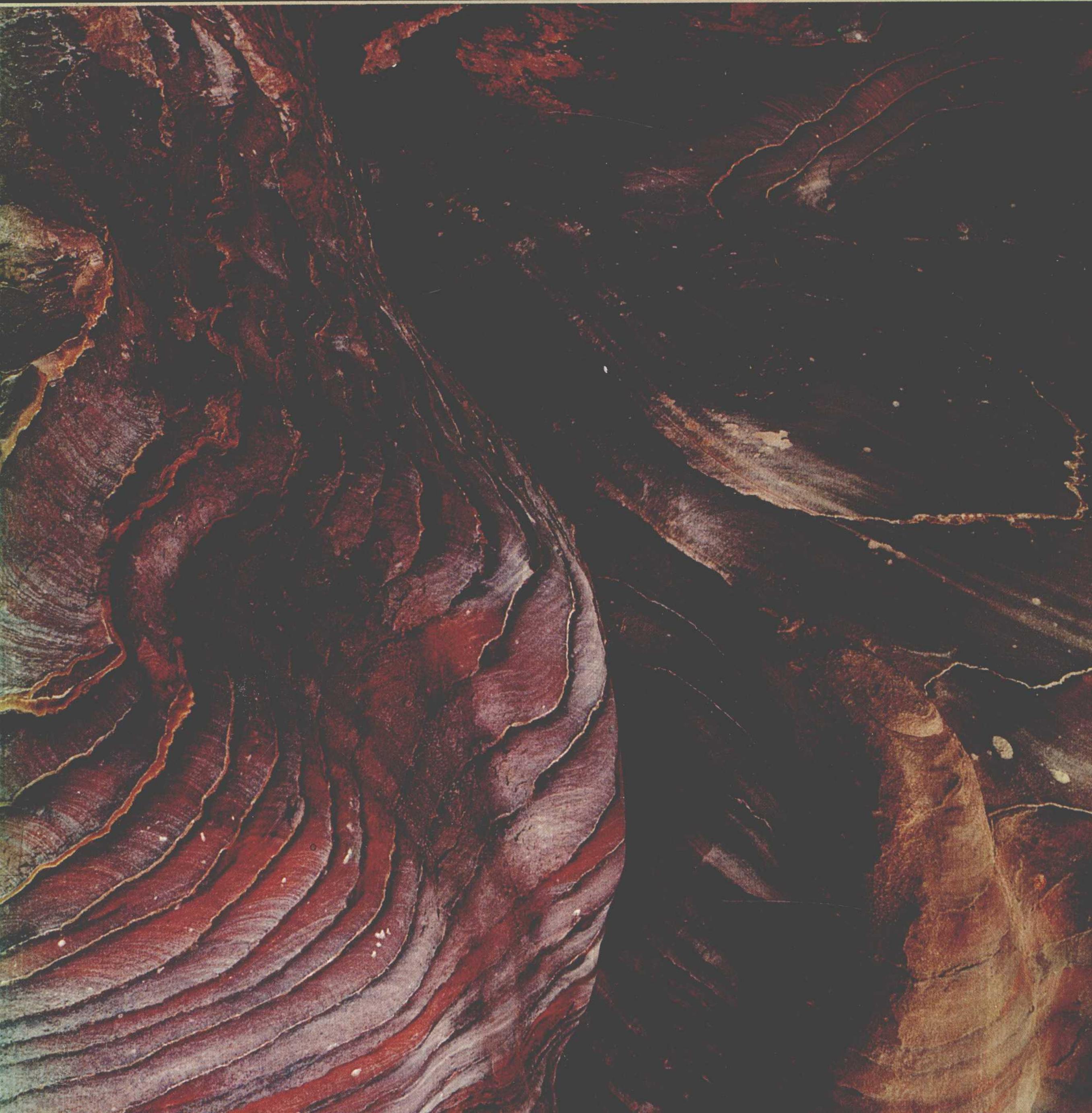
ROBINSON

BASIC PHYSICAL GEOLOGY



EDWIN SIMONS ROBINSON
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

BASIC PHYSICAL GEOLOGY

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to Evan, Lindsay, and Valarie

Cover photo: Sandstone laminations near Petra in Jordan. Iron oxides impart the red and brown coloring (Carl Purcell/Photo Researchers).

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PREFACE

This textbook is concerned with how the earth works and how it is put together. It is an introduction to dynamic geologic processes, minerals and rocks, and the structure and landscape of the earth. The level of presentation is intended for the serious college student, including those majoring in engineering, geology, and other physical sciences. The writing style is for the nineteen- or twenty-year-old student who wants to become involved with the discussions throughout the book.

The opening section, Introduction to the Earth, gives an overview of the main features of the earth and briefly introduces the topics of physical geology. Most of these topics are shown to be interdependent. Chapter 1 provides enough information about all of these topics so that they can be studied separately in later chapters with an understanding of how each one is part of a unified science.

The following chapters are grouped into four sections beginning with The Earth's Size, Shape, and Interior Zones. This section looks at the entire planet, its topography and gravity, its earthquakes and deep interior zones, and the concept of plate tectonics that describes the opening of oceans and the movement of continents over the face of the globe. This is the "big picture" of how the earth works. By presenting a thorough development of the idea of plate tectonics in these early chapters, instead of near the end of the book, this concept can be used effectively as a unifying theme for many of the topics presented in the remaining chapters. The next section, The Rocks of the Earth, examines the earth's interior in more detail. It describes minerals and rocks, and what they reveal about conditions inside the earth. First minerals are discussed, then each of the major rock groups, and finally how these rocks are molded into structures on a grand scale by mountain-building processes. This is followed by The Face of the Earth, a section that concentrates on the landscape and processes acting on or close to the earth's surface. Compared with the previous sections, the discussion here shifts much more toward a world we can feel and touch. This is a world of rivers, glaciers, waves, and wind that all help to carve and to shape the scenery of the land surface. The final section, Other Planets, describes the solar system. It is also a review of what we have learned about the earth, since this is the knowledge we use to determine the extent to which other planets are similar to the earth, or differ from it.

Chapters and topics in the book are arranged to give a comprehensive survey of the earth first, followed by intensive study of earth materials and structure, and finishing with a careful examination of near surface features and processes that perhaps are the most familiar to us. This is a sequence that I have used successfully in the classroom for more than a decade. However, opinions about how the topics of physical geology should be arranged in a book are diverse. Some professors and students may find advantages in following the sequence presented in this book. Others may prefer to study the chapters and sections in some other sequence. Chapter 1 provides a student with enough background to understand most of the material in any subsequent chapter without reference to other chapters. This background allows considerable flexibility for rearranging the sequence of chapters and sections in keeping with individual tastes and practices.

Each chapter in the book presents all of the kinds of information that make up one of the fields of specialization found in the modern community of professional geologists. The two exceptions are Chapters 1 and 5, which present topics with which almost all geologists are familiar. Otherwise, for instance, Chapter 3 discusses most of the things a seismologist should know about whereas Chapter 7 concentrates on the areas of interest to the igneous petrologist. Perhaps this is the most natural way to organize information in a book because it happens to be the way that we geologists have divided that information among ourselves.

This philosophy has also influenced the arrangement of chapters. For example, the chapters on igneous and metamorphic rocks follow one another immediately after the chapter on mineralogy because of the common interests of igneous and metamorphic petrologists in the crystal chemistry of high pressure and temperature environments. These subjects are followed by the chapter on sedimentary rocks, which consist of fragments of igenous and metamorphic rocks as well as older sedimentary rocks. The features of sedimentary rocks motivated geologists to look more carefully at a multitude of surface processes. Therefore, a natural sequence is to discuss these processes in the chapters following the description of sedimentary rocks.

Insofar as possible the information in each chapter is arranged in the sequence of look, describe, and then analyze. This sequence reflects the natural inclination of most of us to become curious enough about many of the things we see to want to learn more about them. But this is certainly not our only motivation to study the earth. There are many practical reasons related to the search for oil, gas, valuable ores, and other commodities of economic importance. Information about them is distributed throughout the book. Various aspects about the search for oil are included in Chapters 2 to 4, 9, and 10. Topics pertaining to ores are found in Chapters 3, 6 to 8, 10, and 12. Other practical information about water resources, industrialization, and urban development is included in Chapters 11 to 15. These applied aspects of geology have more meaning and interest to many students if they learn something of the sources of information for these topics. Therefore, most chapters of the book have descriptions of how geologists conduct field surveys and laboratory experiments.

Much of the book consists of relatively straightforward descriptive material. However, some analytical topics require the student to read and to ponder carefully. Although no college-level science background is required, rudimentary knowledge of chemistry, algebra, and trigonometry is assumed. The book uniformly presents the world from the viewpoint of a geologist. But the geologist needs to use some chemical formulas and mathematical expressions to describe certain relationships. These formulas and expressions are used in various parts of the book where they are appropriate to the discussion.

While writing this book I had numerous discussions with the members of the faculty of the Department of Geological Sciences of Virginia Polytechnic Institute and State University. These discussions have led to a clearer and more complete coverage of the various topics. In particular, I acknowledge with appreciation the efforts of Richard K. Bambach, M. Charles Gilbert, David A. Hewitt, J. Frederick Reed, and Paul H. Ribbe who critically read parts of the manuscript during its initial stages of preparation. Gerald V. Gibbs and Karen Geisinger prepared unique computer drawn crystal structure diagrams. During various stages of revision the entire manuscript was read critically by W. Gary Hooks of the University of Alabama, Winthrop D. Means of the State University of New York–Albany, Hamilton Johnson of Tulane University, J. Allan Cain of the University of Rhode Island, Joseph Lintz of the University of Nevada, Leonard M. Young of Northeast Louisiana University, Gunnar Kullerud of Perdue University, and Rolfe C. Erickson of Sonoma State University in California. Many of their suggestions have been incorporated into the final manuscript. Donald H. Deneck, geology editor at Wiley, provided much of the encouragement and guidance that went into the completion of this project. My wife Valarie helped with various parts of the manuscript and gave me the needed push to get the job done.

Edwin S. Robinson

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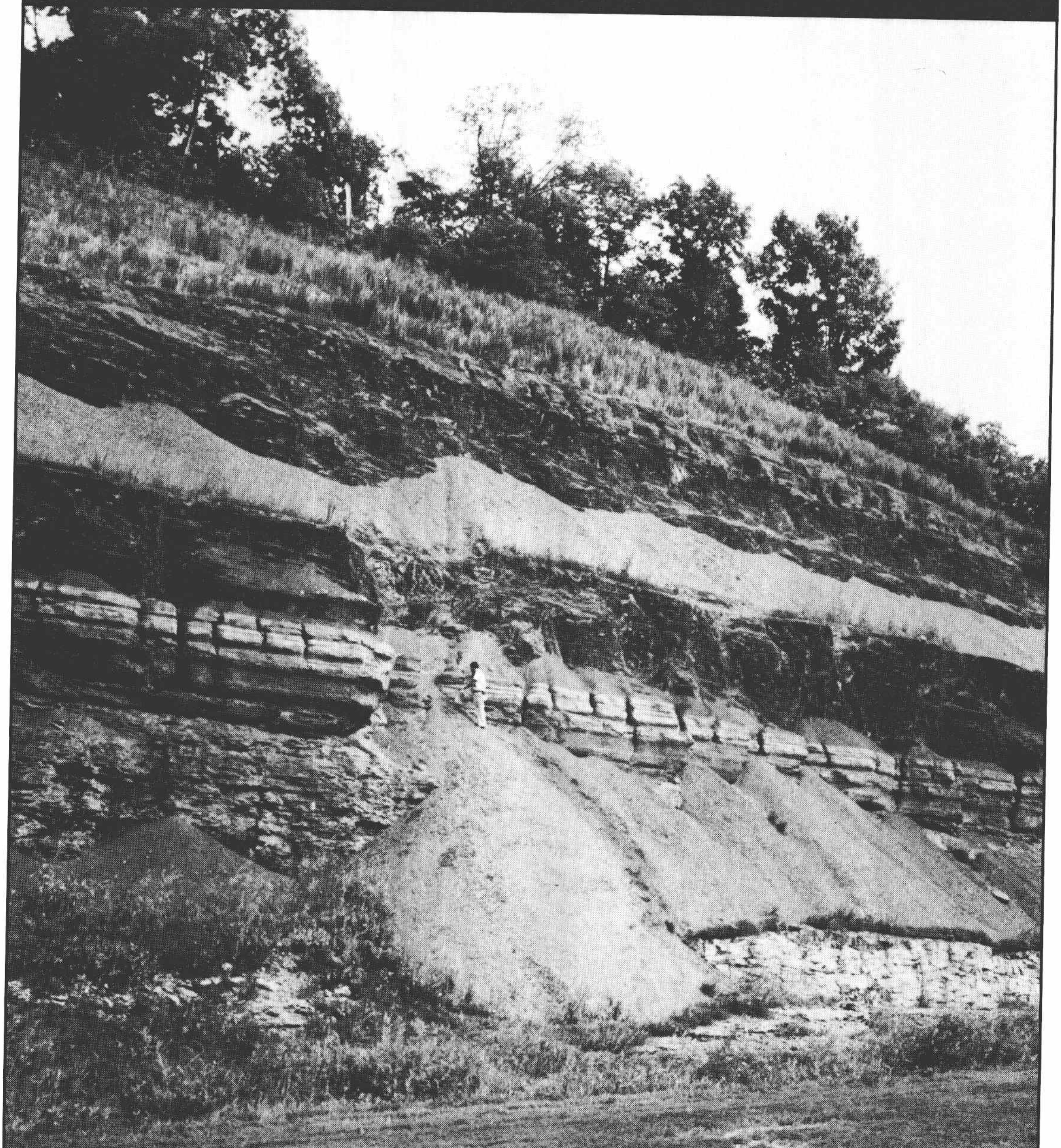
SECTION ONE
INTRODUCTION TO THE EARTH



1

ROCKS AND TIME

Why Study Geology?
The Form of the Earth
Minerals and Rocks
  Minerals
  Igneous Rocks
  Sedimentary Rocks
  Metamorphic Rocks
  Weathered Rock
  Geologic Maps
  Geologic Cross Sections and Columns
Uniformitarianism and Geologic Processes
  Principle of Uniformitarianism
  Volcanic, Plutonic, and Metamorphic Processes
  Erosion and Sedimentation
  Tectonic Processes
Earth History and Geologic Time
  Superposition and Crosscutting Relationships
  Stratigraphic Correlation
  Subdivisions of Geologic Time
  Controversy about Geologic Time
  Radiometric Dating of Rocks
  Calibration of the Geologic Time Scale
The Perspective of Geologic Time

WHY STUDY GEOLOGY?

The world we inhabit is a planet of fascinating complexity. To make sense of this complexity we must describe and explain as objectively as possible the materials, features, and processes that can be observed in our surroundings. The landscape of the earth, the nature and distribution of earth materials, and conditions in the earth's interior are the subjects of principal interest in the science of physical geology.

Much has been learned about the earth in our search for natural resources. All of the petroleum and coal and other natural fuels are discovered in the rocks of the earth. So are the ores from which metals are extracted, the raw materials for concrete, stone, asphalt, and other building supplies, and important sources of fresh water. These precious commodities are not easy to find. There have been many unsuccessful searches and some accidental discoveries of important deposits. In the long history of prospecting winners and losers alike have contributed basic information about how natural resources are associated with various kinds of rock in the earth. From their efforts we have gained a knowledge of geology that we now use to plan much of the exploration for industrial raw materials.

The valleys and plains, rivers and bays, and other features of the landscape have had a profound influence on our culture and civilization. In many important ways these features determine how our communities and transportation routes develop. But the landscape is continually changing, slowly in some places, and elsewhere with unexpected suddenness. Erosion and floods, landslides, earthquakes, and other geologic processes alter the land surface. Knowledge of these natural phenomena and the extent to which they can be predicted is important in the many land-use and building activities of our modern industrialized society. Geologists work with civil engineers in planning flood control, harbor stabilization, soil conservation, and water resource development projects. The strength and durability of rock and soil must be considered when planning the construction of dams, tunnels, and highways. Through these many activities we continue to learn about the nature of the earth.

Advances in our understanding of the earth have resulted from general intellectual interest as well as from attempts to contend with specific problems related to community and industrial development. Some individuals, motivated purely by curiosity, have formulated important geological principles. But whatever the intellectual or practical reason for a particular geological study, it often yields more and different information than was initially expected. Some knowledge of physical geology can help most of us to ask more intelligent questions, to separate fact from fancy in the arguments and exhortations to which we are persistently subjected, and perhaps to find a few answers.

Knowledge of the earth comes from observations made on or near the surface. Ideas about the deeper interior, which is hidden from view, are inferences based upon these surface observations. The different kinds of information pertaining to physical geology can be grouped into topics which are the separate subjects of the chapters in this book. To a certain extent these topics can be studied independently of one another. But there is a degree of interdependence. Some facts about rocks, processes, and geologic time are introduced in this first chapter to provide a background for the more thorough discussions in the chapters that follow.

THE FORM OF THE EARTH

The earth is a nearly spherical planet approximately 12,740 km (7916 mi) in diameter. Its solid surface is formed into **continental platforms** and **ocean basins.** The continental platforms, making up about 30 percent of the surface, stand at an average elevation of 670 m (2200 ft) above sea level. Here we find vast plains and plateaus, rolling countryside of hills and valleys, and high mountain ranges. The highest peak is Mt. Everest reaching 8848 m (29,028 ft) above sea level.

The varied continental landscape has been shaped by several processes. Streams erode sediment from some places and deposit it elsewhere. Glaciers spread slowly over parts of the land, scraping the surface, and later melt away leaving scattered deposits of rock debris. Winds shift the lose sand and dust over the landscape. Other processes originating inside the earth produce volcanoes, earthquakes, and slow warping of rock layers, all of which leave imprints on the landscape. The irregular surface of the continents is constantly changing.

The ocean basins occupy about 70 percent of the surface of the earth. Water overfills these basins, spreading in shallow seas on the margins of the continental platforms so that about three-quarters of the earth's surface is submerged. The floor of the ocean basins is at an average depth below sea level of 3900 m (12,800 ft). The landscape of the ocean floor displays broad, nearly flat abyssal plains, rolling hills, oceanic ridges as rugged as continental mountains, and deep trenches.

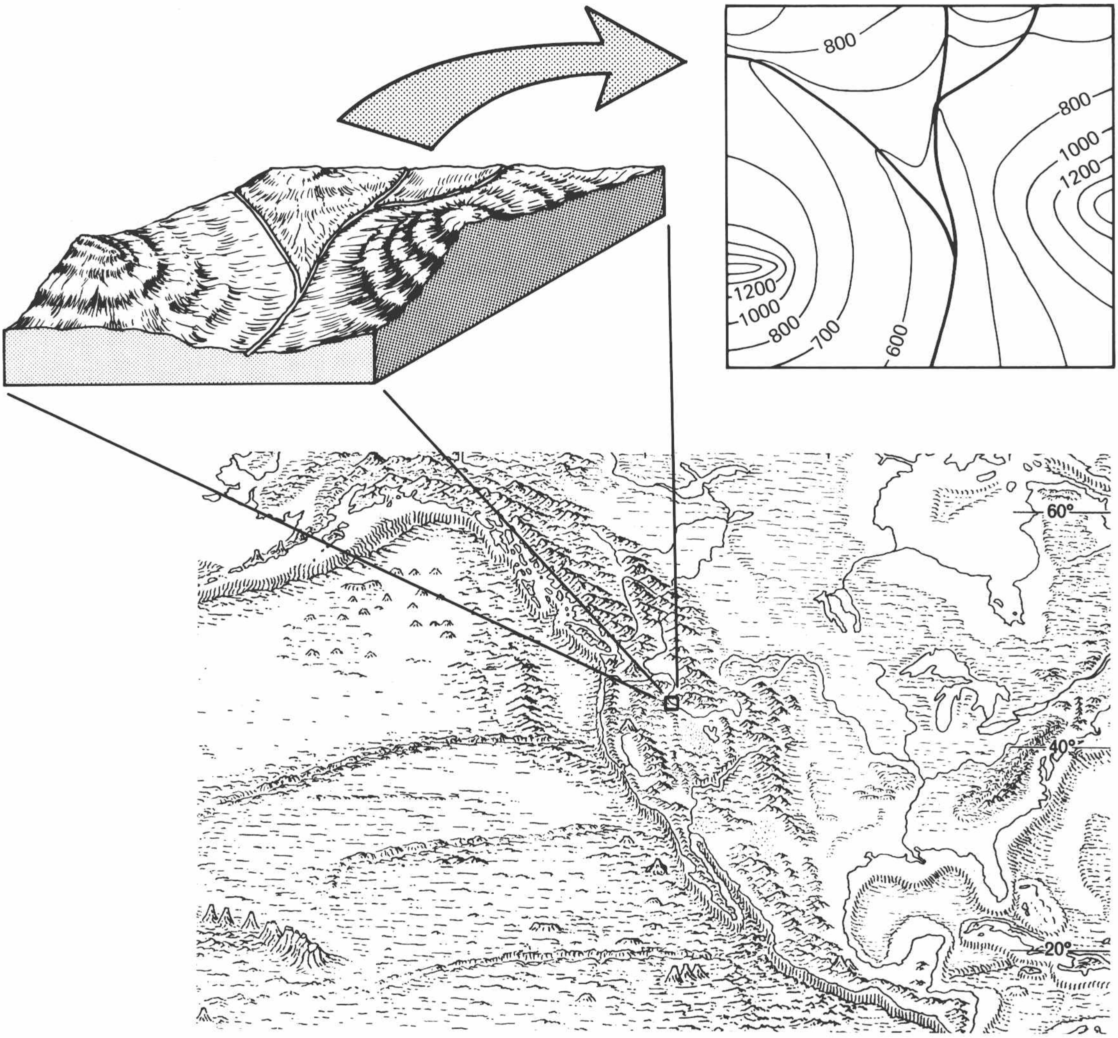


Figure 1-1 Artistic representation of the land surface over North America and the bordering ocean floor (after B. C. Heezen and M. Tharp and other sources), and more detailed representation of the land surface over a small area by means of topographic contour lines, which are lines connecting points of equal elevation above sea level.

The ocean bottom is 11,035 m (36,204 ft) beneath the surface of the sea in the Marianas Trench of the Pacific Ocean Basin. The character of the ocean floor is indeed as varied, but distinctly different, from the continental landscape.

We use topographic maps to represent the form of the earth's surface. This can be accomplished by artistic shading designed to exaggerate certain features. The landforms are depicted in this way in Figure 1-1*A*. For a more quantitative and detailed display, topographic contour maps are used. The example in Figure 1-1*B* illustrates how **contour**

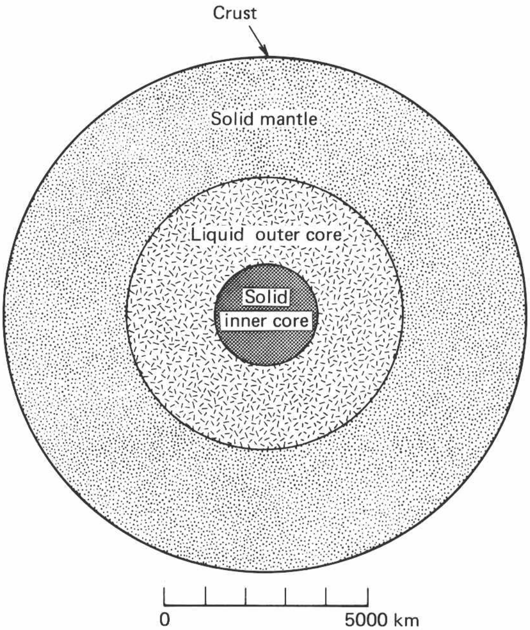


Figure 1-2 Principal interior zones of the earth.

lines, which connect all points of equal elevation, indicate the shape of the land. A topographic profile reveals the variation of the surface elevation along some particular line of direction.

The interior of the earth consists of concentric zones that are illustrated in Figure 1-2. We know this principally from studies of earthquake vibrations which travel at different speeds through these zones. The outermost part is called the **crust.** It consists of rock with a density lower than 3 gm/cm^3 (the **density** of a specimen of rock is found by dividing its mass by its volume). The earth's crust extends to depths of between 30 km and 60 km beneath the continents, and from 5 km to 10 km beneath the ocean basins. Below the crust is the solid **mantle** of the earth. Rock density in this zone is about 3.3 gm/cm^3 just below the crust, and increases to almost 6 gm/cm^3 near its base at 2900 km. Extending from this depth to the center is the **core** where density increases from almost 10 gm/cm^3 to more than 12 gm/cm^3. The outer part of the core reaching to 5100 km is inferred to be liquid from the nature of the vibrations that pass through it. The inner part of the core is believed to be solid.

MINERALS AND ROCKS

The continental platforms and the ocean floor are covered largely by a layer of **regolith** formed from soil, gravel, sand, clay, and other loose rock fragments. Solid **bedrock** exists everywhere beneath the regolith and is exposed in **outcrops** from place to place. Outcrops are abundant in mountainous areas and some arid regions. In some places great thicknesses of bedrock are exposed. But in other areas that are covered by a blanket of regolith ranging in thickness from less than a few meters to more than 100 m, samples of bedrock must be obtained by drilling and from a few small and widely separated outcrops. In recent decades bedrock specimens have been collected from the ocean basins by deep-sea drilling and shipboard dredging operations. By these techniques geologists have collected specimens from almost every region of the world, so that we can study the variety and composition of bedrock that exists near the earth's surface.

From a careful examination of representative samples and the appearance of outcrops and drill cores, it is possible to classify the varieties of bedrock into three general groups. These include **igneous** rocks, **sedimentary** rocks, and **metamorphic** rocks. The distinguishing properties of these different kinds of rock can usually be seen in hand specimens or by examination of polished surfaces and thin sections under a microscope (Figures 1-4 through 1-6). A thin section is made by mounting a chip of rock on a glass slide and grinding it away until only a paper-thin translucent layer remains. All of these rocks consist of grains of different minerals.

Minerals

The word **mineral** has been used in different ways. Coal, petroleum, building stone, ores, and other such commodities are commonly referred to as mineral resources. But for certain scientific purposes where a more restricted and specific definition is needed, we consider a mineral to be a naturally occurring inorganic substance with a definite chemical composition and geometrical arrangement of atoms. According to this definition we can recognize more than 2000 distinctive kinds of minerals. Only a few of these are abundant, and most are very rare.

One of the abundant minerals in the earth's crust is **quartz,** which has the chemical composition SiO_2. It is the principal constituent used in the manufacture of glass. In many places the sand along beaches is principally quartz grains. A crystal of quartz showing well-formed faces and a diagram of the internal arrangement of silicon and oxygen atoms illustrate (Figure 1-3) the geometrical properties of this mineral.

Figure 1-3 A cluster of quartz crystals, and a model showing how the silicon and oxygen atoms are geometrically arranged.

Quartz belongs to a group of minerals in which silicon and oxygen are important constituents. These are known as the **silicate** minerals, and they account for more than 98 percent of the mass and volume of the earth's crust. Oxygen and silicon alone make up about 75 percent of the weight and 93 percent of the volume of the crust. A few other elements including aluminum and iron are also important. Because we do not have the technical capability to separate economically these metallic elements from the other constituents, the silicate minerals are not useful as ores. They are used to a certain extent, however, in the manufacture of ceramics and building supplies.

Some minerals can be processed to extract metals. These minerals are recognized as ores where they have become concentrated in zones which can be mined. An example of an ore mineral is **galena** (PbS), a silvery metallic-appearing mineral that is the principal source of lead. It is a member of the sulfide mineral group in which metallic elements are combined with sulfur. The sulfide minerals occur in rare but economically important concentrations of ore in the earth's crust. There are many other important groups of ore minerals.

Minerals are useful indicators of conditions in the earth's interior. The temperature and pressure environment as well as the available chemical elements influence the kinds of minerals which can be synthesized in the earth. **Diamond** is a mineral variety of carbon that is produced under high pressure. Rare bits of diamond formed in the mantle are brought to the earth's surface by volcanic eruption processes. Another mineral variety of carbon is **graphite** which is used in pencils. It is produced under low pressure in the crust, and the atoms of carbon are grouped in a geometrical arrangement completely different from that of diamond.

Igneous Rocks

From time to time melting occurs in parts of the upper mantle and perhaps in deeper parts of the crust. We see evidence of this in the lavas erupted from volcanoes. The rock that is formed directly from solidification by cooling such molten material is defined as **igneous** rock. As this rock-forming liquid cools, some minerals crystallize before others, but eventually all of the elements present become incorporated into the solid rock.

The abundant igneous rocks in the earth's crust consist almost entirely of silicate mineral grains. When we examine a specimen of this kind of rock, we find a mass of irregular grains of individual minerals interlocked with one another. Different varieties of igneous rock are distinguished by the size of the grains and the kinds of minerals present.

As lavas spill from volcanoes onto the earth's surface, they cool and solidify rapidly. There is too little time for large mineral grains to develop. As a result the rocks formed from these lavas consist of grains so small that they can be seen only under a microscope. The most abundant of these fine-grained igneous rocks is **basalt,** a dark-colored rock. In some places where basaltic lavas from a succession of eruptions have spread one upon another over the countryside, we now find layers of basalt. Some features of this kind of rock are illustrated in Figure 1-4. Basalt is a silicate rock completely lacking in quartz.

Some igneous rocks are coarse grained,

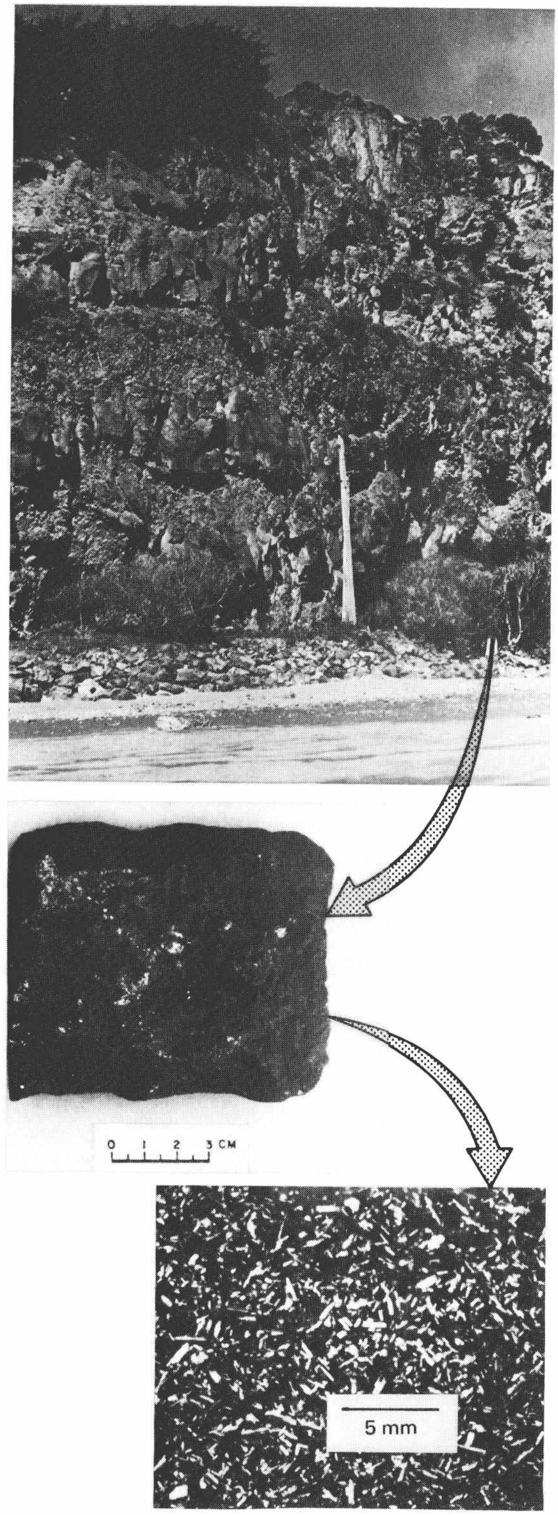


Figure 1-4 Basalt layers are exposed in this cliff near Christchurch, New Zealand. A thin section prepared from a specimen of this rock reveals microscopic interlocking mineral grains.

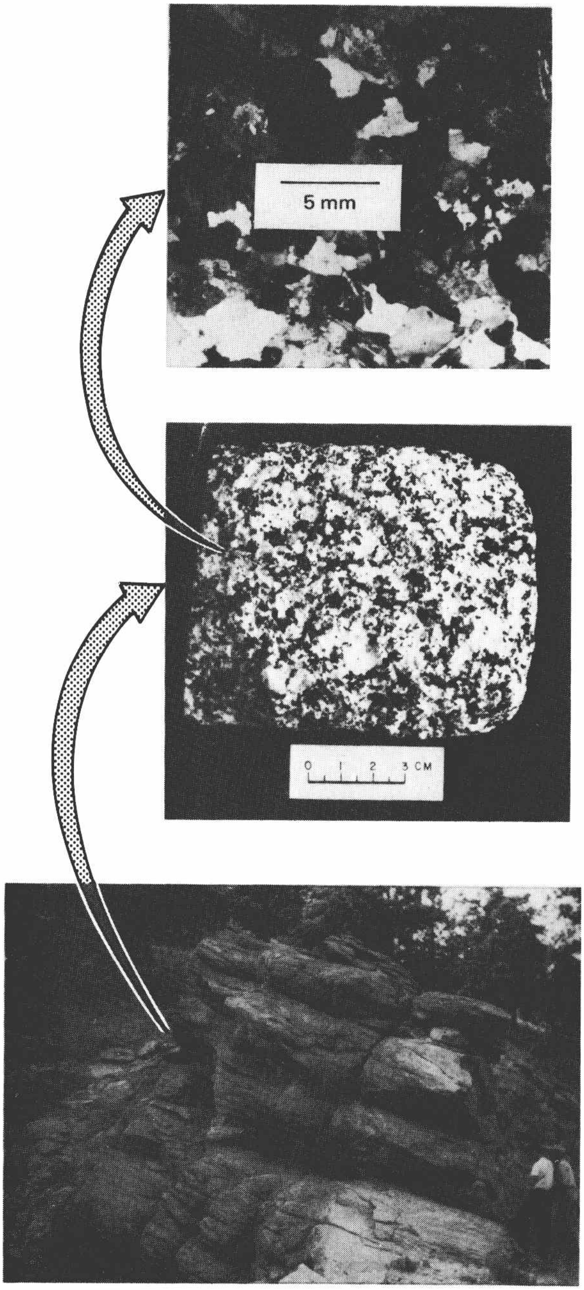


Figure 1-5 Granite is exposed in this outcrop near Boulder, Colorado. The different mineral grains can be seen in the specimen of this rock. The thin section reveals more clearly how the mineral grains are fitted together.

and the individual mineral constituents can be seen without magnification. Growth of these large crystals requires slow cooling and crystallization of a rock-forming fluid. Although no one has actually observed the synthesis of such rocks, it is clear that solidification must take place beneath the earth's surface. The most abundant coarse-grained igneous rock found near the earth's surface is **granite,** which consists of quartz and other silicate minerals. Figure 1-5 displays some characteristics of this variety of rock. The assorted light- and dark-colored grains give it an attractive appearance which for many centuries has enhanced its value as a building stone. Granite is widely distributed in large, somewhat irregular masses in the upper part of the earth's crust.

Sedimentary Rocks

Sediment is accumulating in many places on the earth's surface. Sand collects along beaches, pebbles and cobbles are washed along by streams, silt and clay accumulate on the deltas of large rivers, and the shells of a myriad of organisms collect on the sea bottom. Water percolates through the small openings between these grains of sediment dissolving some substances while others precipitate. Slowly these fragments are compressed under the weight of overlying sediment. Precipitates form on their surfaces binding them together more firmly. Eventually a solid mass of **sedimentary** rock is formed.

Exposures of sedimentary rock usually reveal a more or less distinct layering. In a series of layers you may be able to distinguish different kinds of sedimentary rock according to the composition and size of the constituent fragments. Some important examples are illustrated in Figure 1-6. Features indicative of the environment in which the sediment accumulated, such as a rippled surface reminiscent of a shallow sea floor, are commonly preserved in individual layers.

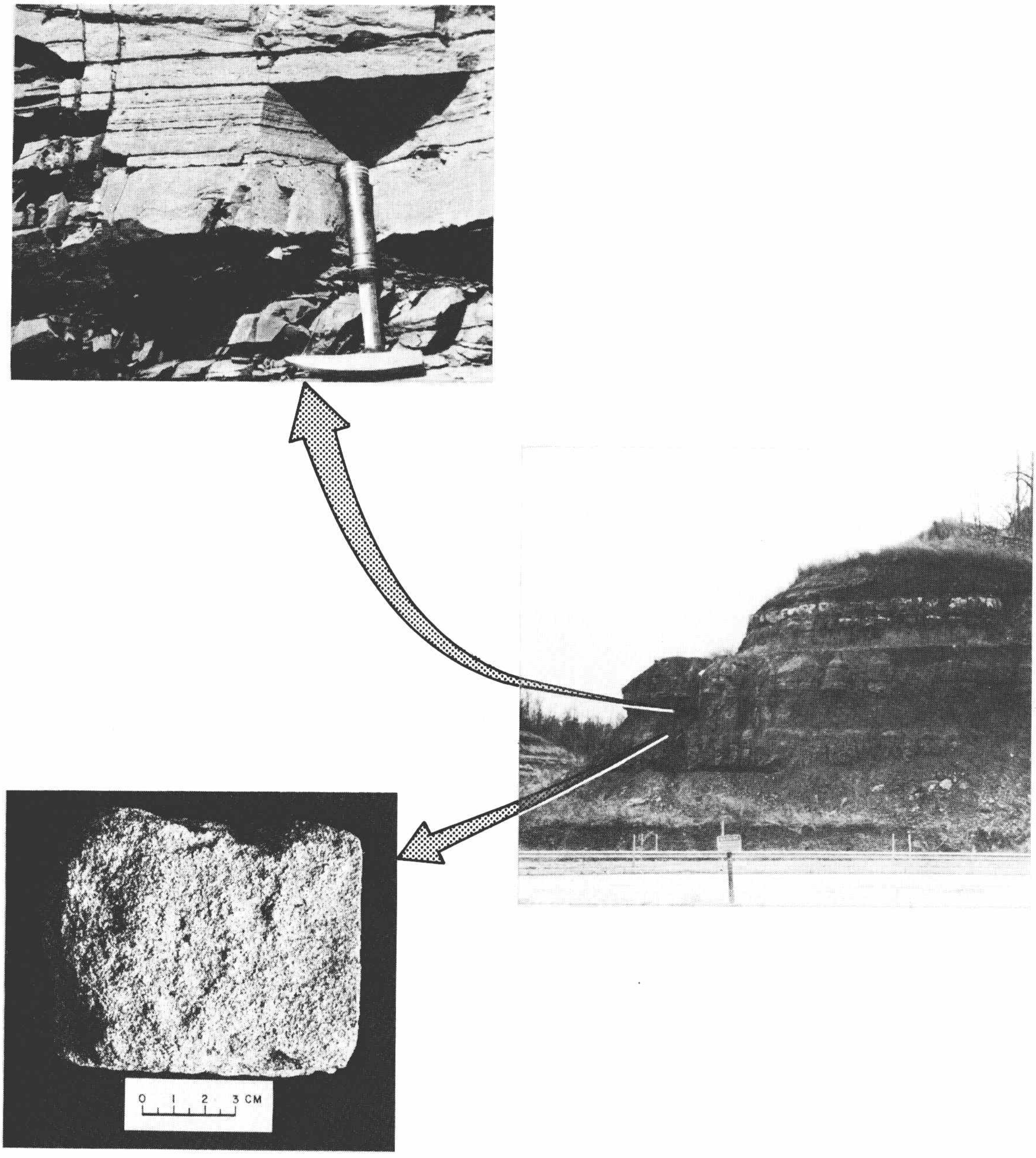


Figure 1-6 Alternating layers of sandstone and shale are exposed near Parkersburg, West Virginia. Constituent grains in the sandstone and thin laminations in the shale can be seen on closer examination.

The most abundant kind of sedimentary rock is **shale.** It is formed mostly from microscopic silt and clay particles. Shale layers consist of thin laminations and may split easily along closely spaced surfaces. Depending upon the content of organic material, iron oxides, and small amounts of other elements, shales display a variety of colors including black, purple, red, brown, green, and gray. It is not a durable rock, and little of value has yet to be extracted from it. This may change with the development of an economical process for removing petroleum now locked in the interstices of some shales that are rich in organic constituents. In this event vast accumulations of oil shale in western North America may become an important natural resource.

Sandstone is another common type of sedimentary rock. The constituent particles are visible without magnification, but they are mostly smaller than 2 mm in diameter. They are usually cemented together by calcium carbonate or silica and minor amounts of iron oxides which may impart a red, brown, or yellow color to the rock. Some kinds of sandstone are very durable and have been widely used for building stone.

Shell fragments and particles of calcium carbonate from decomposed shells are the basic constituents of **limestone,** another abundant sedimentary rock. Varieties of limestone with only small amounts of certain impurities are the source of lime used in cement. Beds of durable limestone are also quarried for building stone.

Metamorphic Rocks

Once formed, rocks may again be subjected to conditions that drastically alter their character. Some of the original constituents decompose or partially melt, and new and different minerals are produced. **Metamorphic** rocks are formed by these kinds of transformations which usually involve an increase in either or both pressure and temperature. They can be made from igneous, sedimentary, or other more ancient metamorphic parent rocks.

Metamorphism of a rock involves some recrystallization of the original minerals. Sometimes the same kinds of minerals are reformed into new interlocking grains. **Marble** is the metamorphic rock formed by recrystallization of limestone. By raising the temperature and pressure on the limestone, new interlocking grains of **calcite,** a calcium carbonate mineral, can be produced from the original calcite grains that made up the former shell fragments. In other kinds of metamorphic rock some or all of the original silicate minerals become altered to different mineral varieties. Depending upon the extent of recrystallization, it may or may not be possible to recognize the kind of rock that existed prior to metamorphism.

Some varieties of metamorphic rock display a distinct zoning of different minerals. The coarse-grained rock illustrated in Figure 1-7, which we call **gneiss,** consists of layered zones of alternating light- and dark-colored minerals. **Slate** is a very fine-grained metamorphic rock which is easily split along very smooth parallel surfaces because of the alignment and zonation of minerals. This property has traditionally made slate useful for chalkboards and roofing tile.

Weathered Rock

When bedrock is exposed at the earth's surface, it reacts chemically with the atmosphere and the water that seeps into cracks and interstices. Some of the constituent silicate minerals decompose, iron and aluminum may become oxidized, and clays form. The appearance and durability of the rock is changed. In some places the effects of weathering form a coating only a few millimeters thick. Elsewhere the weathered rock may reach depths of several tens of meters.