Principles of Geology

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Preface

THIS book attempts to summarize some of the knowledge that geologists have won from the study of the earth. A subject so large must be treated very briefly if it is to be presented between the covers of a single book; we have chosen to concentrate on the analysis of processes that are at work upon and within the earth, rather than to present a catalog of descriptive facts and terms. We have felt, too, that the student is entitled to know something of the kind of evidence on which geologic conclusions are based, even though its presentation takes valuable pages that might be used to put forth more facts.

Some teachers will regret our brief treatment of many of the standard topics usually found in textbooks of physical geology. We can only hope that the loss will be balanced by the new material included covering many phases of the science in which rapid advances have been made in recent years, and more particularly by the emphasis on leading the student through approximately the same sequence of reasoning that was used in the historical development of the subject. We believe that the student may retain more of the basic principles on which geology is based if he knows how a geologic map is made, and if he is introduced to Werner's and Desmarest's divergent views on the origin of basalt, than if he is instructed too minutely on the purely technical terminology of landscape morphology or rock classification. It is our hope, too, that such a presentation carries with it an understanding of the intrinsic uncertainties of indirect evidence, upon which so much of geology depends.

Geology, as we know it, could hardly exist without the foundation of stratigraphy, which gave the dimension of time to the science. Accordingly, we have outlined a little of the development of stratigraphy instead of leaving it entirely for a later course in historical geology.

We are indebted for assistance in the preparation of this book to many persons, only a few of whom can be mentioned here. The contribution of Robert R. Compton goes far beyond that indicated on the title page; in addition to preparing the illustrations, he wrote one chapter of the book and acted as critic on all the others.

The staff of W. H. Freeman and Company gave its unfailing help and encouragement and relieved us of many bothersome details.

Special thanks are due our colleagues S. E. Clabaugh, John Shelton, George A. Thompson, Roger Revelle, Walter Munk, John C. Crowell, Arthur D. Howard, C. Melvin Swinney, Robert Sharp, D. I. Axelrod, W. C. Putnam, Cordell Durrell, George Tunell, M. N. Bramlette, and George Bellemin, who have read certain chapters and have generously aided us with constructive criticism and new ideas.

Specific credit for illustrative material is given in the captions for individual figures. More generally, we wish to acknowledge here the kindness of the U. S. Geological Survey, the Geological Survey of Canada, and the U. S. Air Force for opening photographic files to us. Individuals who also allowed us to make selections from large photographic collections include Eliot Blackwelder, Robert C. Frampton, Howard A. Coombs, John Shelton, and Arch Addington.

Miss Margaret Ellis and Mrs. Priscilla Feigan typed the manuscript and helped in other ways.

Finally, the three of us are greatly indebted to our families who patiently served as "guinea pigs" for our ideas and as good-humored critics of our literary eccentricities.

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1. *Introduction*

The Earth's Riddles

SINCE the dawn of civilization, men have been filled with curiosity about the earth on which they live. Why does a volcano erupt? What makes rain? What force causes the earthquake? What is the source of the water that bubbles up in a spring?

As man's curiosity led him to seek solutions to such riddles, he often found that he was faced with new ones even more baffling. How did sea shells become entombed in the rocks of high mountain ranges? Why does one stream have quicksand on one bank and solid rock on the other? What controls the beautiful geometric forms of snowflakes and other crystals? Why does one well yield water in abundance, whereas another dug to the same depth is dry?

It would be interesting to know how early man attempted to solve such riddles. By comparison, we of today have signposts along the way, for reasoning man has built up the method of investigation and the compilation of knowledge that is known as *geology*—the science of the earth.

To some of earth's riddles, geologists have won the final answers. To others, the suggested answers are still tentative; and to still others, only the faintest glimmerings of light that may ultimately illuminate the way to final solutions have, so far, been discovered. Progress in geology has not been at a uniform rate. There have been periods, following fundamental discoveries, when outbursts of fruitful activity quickly revolutionized some of geology's theories and methods. At other periods there has been little advance. At times geologists even followed the wrong trail, and progress in some branches of the science came to a dead end. Then more information and new skills were acquired until, finally, the accumulated dogmas were overthrown and a new start made.

The first roots of geologic knowledge are lost in antiquity. The early Greeks and some of the peoples of other early civilizations made progress in geologic study, but their ideas were largely based on untested speculations, and little has survived. The modern science known as geology is of comparatively recent origin—the word itself is less than 200 years old.

Despite its youth, however, geology has already done much to stimulate and unshackle the thinking of mankind. The demonstration that sea shells and other fossils* entombed in the rocks are but the remains of animals and plants that lived in the geologic past routed dogmas that had warped men's thinking for centuries. From the detailed study of the biological relationships of living and fossil organisms, coupled with geologic investigation of the sequence and changes of fossil assemblages with time, the doctrine of evolution emerged. This doctrine has profoundly influenced modern philosophical and scientific thought.

Evidence, well documented, that the landscapes about us are not static but are slowly changing, has not failed to stimulate the imagination of thinking men. The wheat farmer tilling the cold, wind-swept plains of Alberta is curious about the shells turned up by his plow, and becomes amazed when told that scientific comparison of these shells with living marine organisms shows that his farm was once the bottom of a warm, shallow sea.

Who can deny the thrill that comes with the realization that less than 20,000 years ago the site of Chicago lay under a sheet of ice such as enshrouds Antarctica today? Or that the green, well-watered hills of Scotland's Midland Valley were once the site of shifting sand dunes similar to those of the modern Sahara? Yet, preserved in the rocks and soils along Lake Michigan's shore and in sandstone quarries near the city of Glasgow are the proofs —as clearly recorded as are the deliberations of the Roman Senate preserved in the writings of Seneca and Cicero.

The science of geology has brought to mankind new conceptions of time, just as astronomy has revolutionized ideas of space. The rocks record events, some of which date back at least 1,800 million years, and throw into sharp perspective the short lapse of human history, as compared with that of the earth as a whole. There is a fascination in reading from the rocks the evidence on which we may reconstruct events of millions of years ago. It is this fascination that has led men to develop the science of geology—the attraction that will cause them to undertake deeper exploration of the earth's riddles.

Minerals, Wealth, and Politics

Man's interest in the minerals and rocks of the earth's crust ceased long ago to be that of mere curiosity. There are sound practical reasons for his inves-

* Fossils are the remains or imprints of animals and plants of the geologic past, naturally preserved by burial under sediments.

tigations. Our modern civilization makes many uses of the minerals and rocks that compose the earth's crust. Industry is almost wholly dependent on them. From minerals we obtain the iron, copper, aluminum, and other metals that make an industrial civilization possible. Our chief sources of power are the mineral fuels, coal and petroleum. In recent years, we have learned how to release stupendous amounts of energy from radioactive minerals.

Even our individual desires and needs are closely tied to the mineral industries. The bricks in our houses, the salt that seasons our food, the material that paves our highways, the gold and silver ornaments and precious stones with which we adorn ourselves—all have been won from mineral deposits in the earth's crust. Man's avid search for the gold and silver, the copper and gem stones that pleased his vanity and brought him security and wealth began early in the annals of civilization. With possession of the minerals, he sought to refine and improve them and to discover new uses to which they could be put. As a result, the arts and crafts in metal and stone were born; and these, in turn, expanded into the vast industries we know today.

On the international scene, the power and wealth of a nation is largely determined by its supplies of useful minerals, its authority over the areas that contain them, and its skill in discovering and utilizing them. In this age of political readjustment between nations, we know that the vast accumulation of petroleum in Iran and Arabia is a potent force in world politics. We shall be wiser in world affairs if we know how petroleum occurs, how it is discovered, and how its quantity may be estimated.

Without the economic urge to find and exploit the mineral wealth hidden in the earth, many of the great forward steps in geology would never have been made; for geology is the science of the mine and the quarry, of the oil field and the placer.

The Study of Geology

Although geology is a complex and varied subject, it is also a stimulating and interesting one. Relatively few of its problems are so simple that they can be solved directly by one method of approach. Many even require supplementary investigations with the techniques of other sciences. Geologists are constantly taking over from chemistry, biology, physics, and engineering new methods, data, and theories that can be adapted to their needs. Geologists, in turn, have contributed data and ideas to these bordering sciences. Progress in one science advances all the others.

Because of the complexity of its problems, geology has not advanced so far as has physics or mathematics. The geologist cannot move a volcano to the laboratory to observe the growth of its cone, nor can he spread a bed of coal on the laboratory table to watch for millions of years its development. Yet, these are the simpler phenomena of geology. Factors of size and time make experimental study of many geologic processes difficult and often impossible. It is not possible to put a lava flow in a calorimeter and measure its output of energy. Faced with these apparently insurmountable difficulties, geologists have had to devise ingenious, indirect methods for getting the answers to many of their questions. Despite these inherent difficulties in subject matter, however, geologists have been outstandingly successful in predicting where to drill for oil or other mineral deposits, and in arriving at verifiable solutions of complex scientific problems.

Geologists, if they would be successful, must develop resourcefulness and imagination. They must be able to make sound decisions on the basis of incomplete, and even partially conflicting, data. In deciding where to drill an oil well or where to develop a gold placer, the geologist must, in many instances, evaluate and coordinate several kinds of evidence. His fundamental guides, of course, are the data from geologic mapping and other geologic techniques. He may also need to consider results from geophysical exploration, data regarding production of other wells or placers, and miscellaneous additional evidence drawn from engineering, economics, chemistry, physics, and many other sources.

These very factors of complexity and diversity, together with the newness of the science, combine to make geology a vigorous, rapidly expanding field. A student who selects geology as his profession has a wide choice of what he will learn and do. For his first two years of training, he will study more chemistry, physics, and engineering than geology. A sound elementary knowledge of these basic sciences is essential for many advanced geology courses. The student will learn something of ordinary laboratory techniques, but will soon find that his main laboratory is not a building lined with bottle-filled shelves and machinery. The geologist's laboratory is the bold cliffs of high mountain peaks, the walls of deep canyons, and the slopes of desert ranges. A part of his education will be spent in strenuous hiking and climbing in some mountainous area, perhaps far from civilization, where he will map the rocks and their structures and collect other geological data. Such "field work" is essential to geological training.

Upon completion of his training, the geologist will find many opportunities open to him. He may work for an oil company and travel the earth in search of new petroleum deposits. He may direct exploration to find new bodies of ore in a mine. He may have the responsibility of estimating accurately the reserves of ore in the ground beneath a mining property or the amount of oil that can be recovered from a partially developed oil field. He may be called upon to decide which of several small mines is the best prospect for development and investment.

As an employee of a federal or state geological survey, the geologist may map rocks and mineral deposits, investigate conservation problems such as soil erosion and mineral depletion, or classify public lands as to their minerals, soils, water, and other natural resources.

Or the geologist may teach at a college or university, training future geologists, and at the same time, engaging in efforts to discover new principles or to unify and correlate old ones. Other opportunities for research are open in government work, in various research institutes, and in industrial laboratories.

In time of war, the geologist can serve by giving authentic information on problems of terrain, by discovering and assisting to develop critically short mineral supplies, and by selecting targets in enemy territory which, when demolished, will put an end to some vital industry of the enemy nation. He may sit at peace conferences and advise on the mineral resources of various nations and their resulting industrial potential.

There are also opportunities in commerce for the geologist. His geological knowledge can be used to good purpose in the development of a cement plant, or in the operation of a stone quarry, a brick yard, or a sand-and-gravel pit.

Whatever path the geologist takes, it is likely to lead to widespread travel, for the whole earth is the field for his investigations.

The Branches of Geology

Geology is such a large and varied field that only the briefest résumé of its subject matter can be outlined here. In general, this book emphasizes *physical geology* (also called *dynamical geology*). Physical geology is concerned with the physical processes that operate on and within the earth—the processes that have given the rocks of the earth's crust their composition and structure, and the forces that have shaped the landscapes we see on its surface. Many separate geologic sciences contribute to the broad field of physical geology. Among the more important are *mineralogy,* the science of minerals; *petrology,* the science of rocks; *geodesy,* which is concerned with measuring the form and size of the earth; *structural geology,* which seeks to interpret the structures to be seen in the rocks in terms of the dynamical forces that have produced them; and *geomorphology,* which deals with the origin of landscapes and with the changes that are constantly occurring in them.

Touched much more lightly in this book is the broad field of *historical geology*—the science that traces the evolution and development of the earth and of its animal and plant inhabitants with time. Historical geology is based, first of all, upon physical geology, but also draws extensively upon *paleontology,* the science that deals with the study of animals and plants of the geologic past, and on *stratigraphy,* the science that is concerned primarily with the order and sequence of the rocks that make up the earth's crust.

Another great field considered only briefly in this book is *economic geology*—the application of the science of geology to the uses of man, as illustrated in the finding and recovery of valuable mineral deposits from the rocks of the crust, the search for and recovery of oil and water from wells, or the study of the depletion of soils by erosion.

The subdivisions we have enumerated are not independent sciences. For example, physical geology could never have attained its present development without the concurrent progress in paleontology. In a broad view of geologic science practically every branch contributes in some measure to all the others.

2. *The Earth's Broad Pattern*

To BEGIN a study of the earth, we shall need to know something about its dimensions and form. How large is it? What is its shape? How high are its mountains, and how deep are its seas? What is the pattern of its rivers and ridges? And by what methods have men tried to find the answers to such questions?

The Plumb Bob

Some of the answers may be gained through observations made with the aid of an ordinary plumb bob. The plumb bob is one of the oldest and most useful instruments of civilization. The early Egyptians used it in recovering land boundaries after the annual floods of the Nile. Today, just as did our ancestors, we use plumb bobs in all surveying; in the construction of buildings, bridges, roads, and tunnels; in the making of all maps; and in measuring the size and shape of the earth.

The Earth's Gross Size and Shape

Early Measurements

The ancient Greeks noticed that the earth casts a round shadow upon the moon during eclipses. They also observed that the surface of any large body of water is curved, for only the upper part of a ship's mast is visible at a distance, and the ship appears to rise gradually out of the sea as it approaches. From these observations, the Greeks correctly inferred that the earth is, roughly, spherical. It is much easier for us to arrive at the same

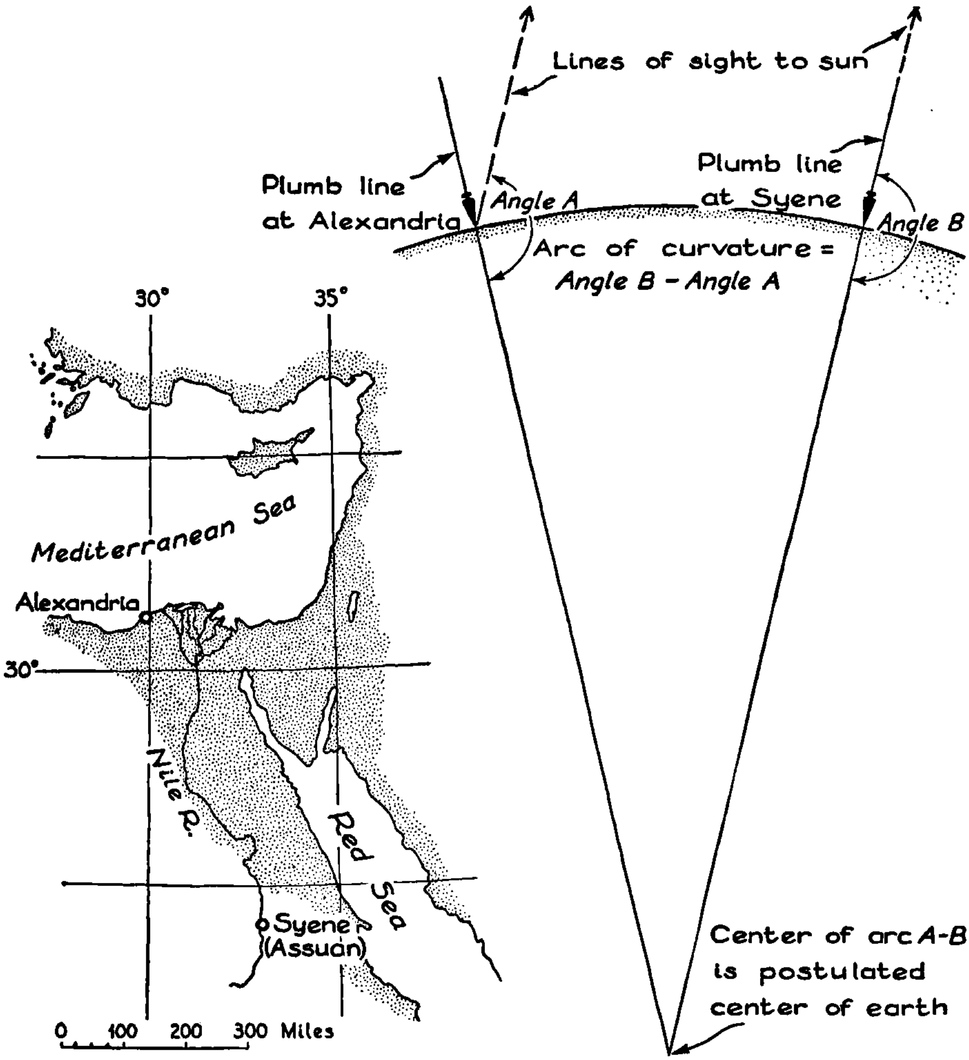

FIGURE 2-1. *Eratosthenes' method for measuring the size of the earth. Note that Syene does not lie due south of Alexandria, so that the distance between Syene and Alexandria was not measured along a meridian as he assumed. His result was therefore too large.*

conclusion today. In modern airplanes, we can circle the globe in a few days. The curvature of the earth can be seen plainly in photographs taken from stratosphere balloons and rockets.

A few of the early Greeks made even more penetrating interpretations. More than 2,000 years ago, Eratosthenes, a Greek geometer and astronomer, first measured the curvature of the earth's surface. Then, assuming the earth to be spherical, he computed its dimensions. Though measuring techniques have been greatly refined, his reasoning is still used in modern geodesy.

Eratosthenes learned that in southern Egypt, at Syene (now Assuan), the sun shines vertically down a well only at noon on the longest day of the year. On such a day, he measured the angle between the plumb line and the edge of the shadow cast by the sun at noon in a well at Alexandria (Fig. 2-1). Alexandria lies 5,000 stades (the ancient Egyptian stade equals about 600 feet) north of Syene. On the premises—

a. that the sun is so distant that its rays to Syene and Alexandria are parallel;
b. that Alexandria lies due north of Syene so that a plane through Alexandria, Syene, and the center of the earth also includes the noon sun;
c. that the plumb line points directly toward the center of the earth; and
d. that the earth is a sphere—

the angle between the plumb line and the shadow at Alexandria is equal to the arc of the earth's curvature between the two points (Fig. 2-1). On these assumptions, the circumference of the earth is given by solving the equation:

$$\text{Circumference} = \frac{360^\circ}{\text{Angle of sun's rays to vertical at Alexandria}} \times 5{,}000 \text{ stades}$$

Eratosthenes' earth was too large, but only 14 per cent larger than the figures now accepted. About a century later, Poseidonius, the Greek philosopher, applied the same method to another arc but was not so favored with compensating errors. The size of the earth deduced from his measurement was a quarter too small, and led to Columbus' error in mistaking America for India.

We shall see how, with refined modern measurements, the simple assumption that the earth is a sphere—which was satisfied by the early crude measurements—has had to be successively refined as succeeding measurements have become more and more accurate. It would, indeed, be difficult to find a better example of scientific method, and of successive changes in theory made necessary by improved observations, than is afforded by the history of investigation of the figure of the earth.

Modern Measurements

In the Seventeenth and Eighteenth centuries, as the expansion of navigation and the accurate surveying of land boundaries became more important, Eratosthenes' method came into wider use. Arcs of meridian (North-South lines), equivalent in length to one degree of geographic latitude or to some simple fraction thereof, were measured at many different localities. It was found that a degree of latitude is longer near the poles than at the equator. Or, stated in another way, if we hold to the assumption that the earth is a

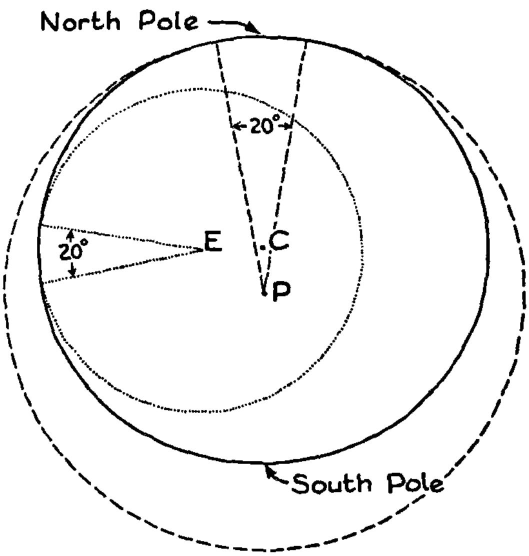

FIGURE 2-2. *Diagram showing how unequal circular arcs measured in different latitudes require an ellipsoidal figure for the earth.*

sphere, its radius, as determined by observations near the pole, is notably greater than that deduced from observations near the equator. This is shown greatly exaggerated in Figure 2-2. Here the dashed circle, with the center P, illustrates the size of the earth based on observations made near the pole. The dotted circle, with the letter E at its center, illustrates the size as determined from observations made near the equator. Note the discrepancy in size. These measurements indicate that the earth is not a perfect sphere. The inconsistency between the polar and equatorial measurements vanishes if we modify our assumption that the earth is a sphere and assume instead that it is slightly flattened at the poles—or, in technical words, that the earth is an ellipsoid. The solid line in Figure 2-2 is an ellipse with its center at C. This line fits the data from both the polar and the equatorial observations.

Thus, the simplest model of the earth that conforms with modern measurements is an oblate ellipsoid—the solid figure that is obtained by revolving an ellipse about its shorter axis. In the ellipse indicated by a solid line in Figure 2-2, the short axis would be a straight line connecting the North Pole with the South Pole. In the drawing, the flattening at the poles is greatly exaggerated, for the earth actually does not depart greatly from a sphere. The measurements now accepted and used internationally as the basis for official mapping, are:

Equatorial radius	6,378,388 meters	(3,963.5 miles)
Polar radius	6,356,912 meters	(3,950.2 miles)
Difference	21,476 meters	(13.3 miles)