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STRUCTURAL GEOLOGY

Relation of Structural Geology to Geology

Geology has recently been defined as approximately synonymous with solid-earth sciences. Earth sciences are those sciences that deal with the earth; they include geology, geophysics, meteorology, and parts of oceanography. The geologist is concerned primarily with the solid part of the earth.

> The solid earth sciences are those that investigate the physical and chemical characteristics and processes of the earth and astrobodies; the origin, distribution, development, and utilization of earth materials and the land as a whole; and the interaction between the solid earth and the hydrosphere and atmosphere.[1]

Geology is such a large subject that it has inevitably been subdivided into many categories. But these subdivisions are arbitrary and many geo...

gists specialize in several of these fields. There are as many combinations as there are geologists. Moreover, some geologists overlap into other fields of science, such as physics, chemistry, and biology. Nevertheless, the many aspects of geology must be classified to the best of our ability.

Structural geology is the study of the architecture of rocks insofar as it has resulted from deformation. *Tectonics* and *tectonic geology* are terms that many consider to be synonymous with structural geology. To some, however, structural geology is concerned primarily with the geometry of the rocks, whereas tectonics deals with the forces and movements that produced the structure.[2] The movements that affect solid rocks result from forces within the earth, causing folds, joints, faults, and foliation. The movements of magma, because it is often intimately associated with the displacement of solid rocks, is also a subject that lies within the domain of structural geology. The deformation of the rocks of extraterrestrial bodies is also the concern of structural geology, as well as the effect of collisions between bodies in the solar system. The aim of structural geology is to determine and explain the architecture of rocks as observed in the field; laboratory investigations are supplementary means to attain this primary objective.

In field work the solution of structural problems is only one phase of broader investigations. It is futile to try to study the structure of folded and faulted sedimentary formations without a knowledge of *stratigraphy*, that phase of geology treating of the sequence in which formations have been deposited. *Sedimentation*, which deals with the deposition of stratified rocks, may offer much evidence on the tectonic events in areas adjacent to the basins in which the stratified rocks accumulate. *Paleontology*, which is the study of fossils, is indispensable to the structural geologist who works in rocks containing organic remains. *Petrology*, a subject that includes the systematic description of rocks and the study of their origin, sheds much light on the structural history of igneous, metamorphic, and sedimentary rocks. *Mineralogy*, which deals with the classification, atomic structure, and genesis of minerals is an integral part of geology, inasmuch as most rocks are composed of minerals. *Volcanology* is the study of volcanoes and volcanic rocks. A knowledge of *geomorphology*, the study of land forms, is particularly important to the structural geologist who investigates regions of recent tectonic activity, where the topography is a rather direct expression of the structure. Even in those areas where the tectonic evolution ceased long ago, geomorphology may furnish important clues to the structural geologist.

Some subjects employ methods and instruments that associate them more closely with other sciences, notably physics and chemistry. *Geophysics*, which involves the application of physics to geological problems, has been successfully employed in helping to solve many problems of direct concern to the structural geologist. It includes studies in seismology, gravity, electricity, and magnetism. *Seismology*, which deals with the propagation of elastic waves through rock, whether caused by earthquakes or artificial means, aids

in the solution of many structural problems. Moreover, it is the principal source of information on the nature of the interior of the earth, the source of tectonic energy. *Rock mechanics* deals with the physical properties of rocks and the significance of these properties in rock deformation and engineering projects. *Paleomagnetism* is the study of the ancient magnetic field of the earth and its tectonic significance. *Geochemistry* is concerned with the application of the principles of chemistry to geological problems. It overlaps many fields in geology, such as mineralogy, petrology, and weathering. *Geochronology* deals with the dating of geological events. For a century and a half the relative ages of geological formations was determined from an analysis of the fossils. In more recent years other means have been employed, such as tree rings and varved clay. But even more significant is *radiogenic dating*, which theoretically can determine in years the age of geological events.

Some terms refer to the application of scientific principles to specific domains. The science of geology evolved from observations made on the continents. Although the surface of the sea has been well known to man for many millennia, it is only recently that he has become concerned with the subsurface parts of the ocean. *Oceanography* is a large subject that involves many disciplines, notably biology, physics, chemistry, and geology. The structural geologist is especially concerned with the structure of the sea floor, as well as that of the underlying crust and mantle. The evolution of the sea floor is one of the most exciting subjects in modern geology. In recent years geologists have become involved in *lunar geology*, which involves especially mineralogy, petrology, structure, and geomorphology.

Objectives of Structural Geology

The structural geologist is concerned with three major problems: (1) What is the structure? (2) When did it develop? (3) Under what physical conditions did it form?[3]

In general, the first question must be answered first. It is essential to determine the shape and size of the rock bodies. Are they great flat-lying tabular masses covering scores of square miles? Or are they tabular masses that have been thrown into folds with a wavelength of several miles and an amplitude of thousands of feet? Or are they great cylindrical bodies thousands of feet in diameter and a mile or two deep?

Geological field work is indispensable to many such investigation and it is this fact that distinguishes most phases of geology from many of t other sciences. Because the correct location of outcrops is of the utmost imp tance, accurate maps are essential. For many regions topographic maps available, and by means of topography, drainage, and culture, a pre location is possible. Vertical aerial photographs are very useful in geolog field work. These photographs, made from directly above, are essent maps. In some respects they are superior to topographic maps because they not only portray all natural and artificial features with great accuracy, but they reveal, too, many features such as trees, forests, open fields, and fences that are not generally indicated on topographic maps. However, they lack contours; moreover, in mountainous regions, the scale is not constant. In regions for which suitable maps or aerial photographs are not available, it may be necessary for the geologist to prepare his own base map, usually by plane-table methods. A discussion of the technique of field methods is beyond the scope of this book, but is adequately discussed in several excellent texts.[4,5]

Successful geological field work consists of the accumulation of significant facts. At each outcrop the geologist records whatever data are pertinent to his problem, and, ideally, he should never have to visit an outcrop a second time. This is especially true in areas that are difficult of access, but even in accessible regions the work should be so planned that a second visit to an outcrop is unnecessary.

Geologic mapping, when properly done, demands skill and judgment. Such mapping requires keen observation and a knowledge of what data are significant. As the field work progresses and the larger geological picture begins to unfold, experience and judgment are essential if the geologist is to evaluate properly the vast number of facts gathered from thousands of outcrops. Above all, the field geologist must use the method of "working multiple hypotheses"[6] to deduce the geological structure. While the field work progresses, he should conceive as many interpretations as are consistent with the known facts. He should then formulate tests for these interpretations,[7] checking them by data already obtained, or checking them in the future by new data. Many of these interpretations will be abandoned, new ones will develop, and those finally accepted may bear little resemblance to hypotheses considered early during the field work.

Nothing is more naïve than to believe that a field geologist should gather only "facts," the interpretation of which is to be made at a later date. Because of his numerous tentative interpretations, the field geologist will know how to evaluate the facts; these hypotheses, moreover, will lead him to critical outcrops that might otherwise never have been visited. On the other hand, the field geologist should never let his temporary hypotheses become ruling theories, thus making him incapable of seeing contradictory facts.

Although much structural information in the past has been gathered from direct observation, either on the surface of the earth, in open pits, or in mines, a progressively greater proportion of our data is gleaned from the depths of the earth by indirect means. The petroleum geologists, in particular, have obtained vast amounts of structural data from the study of drill holes and from geophysical data. Subsurface geology[8] not only involves structural geology, but also paleontology, stratigraphy, sedimentation, and geophysical methods.

Aerial photographs[9] are not only of great value as base maps, but they often display unsuspected structural features. Moreover, geological maps, with a small amount of geological ground control, may be prepared from aerial photographs where the vegetative cover is slight and the geologic structure simple.* Spectacular aerial photographs have been obtained from orbiting satellites.[10] *Remote sensing* employs aerial photographic techniques that record gamma radiation and permit the taking of infrared and radar imagery photographs.[11] Geological maps of the moon, primarily structural in nature, have been prepared from telescopic and satellite photographs.[12] Special field techniques are necessary in studying the geology of the ocean floor[13,14] and the moon.[15]

A second objective of the structural geologist is to relate the structure to some chronology. One phase of this study is to determine the sequence in which the structural features developed. For example, he may find an anticline, a fault, and a dike. What are their relative ages? The anticline may be the oldest and the dike may be the youngest. It is also possible that the fault is the oldest and that the anticline is the youngest. There are also other possibilities. In some areas the sequence may be exceedingly complex.

The structural geologist is interested not only in the sequence of events in the area in which he is studying but he also wants to fit them into the geological history of the whole earth. This can be done by paleontological methods[16] or by radiogenic dating.[17]

A third objective of the structural geologist is to determine the physical processes that produced the observed structure. What was the temperature and pressure at the time the structural feature formed, and what was the stress distribution? It is desirable to answer these questions before we try to deduce the ultimate causes. Without knowing the stress distribution at the time the structural feature formed, it is difficult to decide whether a given fold was the result of contraction of the earth, subcrustal convection currents, or the forceful injection of magma.

Experimental geology provides significant data for the understanding of tectonic processes. The physical properties of many rocks have been investigated.[18] It is difficult to simulate natural conditions and consider all the variables involved, but much has already been accomplished by the use of ingeniously conceived apparatus.[19]

In another type of experiment, attempts have been made to reproduce geological structures in small models, or to observe the structures that result from the application of known forces. A classic example is the formation of folds when layers of suitable material are slowly compressed by a moving piston (see also p. 127). But the significance of many of these experiments is questionable because in many cases the investigator repeatedly changed either

* Many such maps of $7\frac{1}{2}$-minute quadrangles, on a scale of 1:24,000, were published by the U.S. Geol. Survey for some of the southwestern states between 1935 and 1965 as part of the "Miscellaneous Geological Investigations Maps."

the materials or the conditions of the experiment until he obtained the results he desired. It is possible, however, by the use of sound engineering principles, to construct small-scale models that will simulate natural conditions.[20,21]

Scope of this Book

Before it is possible to analyze the structure of entire mountain ranges, it is essential to have precise information on the many small separate areas that comprise each range. These small areas may cover 50 to 200 square miles, or they may be single mines or oil fields. This investigation of the structure of relatively local structure is the first and inevitable approach to the problem.[22]

Equally important, and perhaps in some ways more fascinating, is the synthesis or weaving together of the many facts obtained from local areas into a unified picture of the structure and tectonic history of the outer shell of the whole earth. Such studies are necessarily based in large part upon an intimate knowledge of the literature of structural geology because it is manifestly impossible for one man to investigate many areas in detail. But in order that he may more judiciously evaluate the reliability and importance of the published information, such an investigator must have made detailed studies of his own. One of the old classics in this field of synthesis is that by Ed. Suess, published in German and translated into French and English.[23] Excellent more recent books are those by Beloussov, Bucher, and Umgrove.[24,25,26] Others deal with the structure of the sea floor.[13,14]

Only *local structural* features will be considered at any length in this book. *Synthesis* of the structure of large areas are important and fascinating, but *they* are more advanced studies that cannot be comprehended until the *principles* of local structures are fully mastered. Moreover, to expand the text to include regional tectonics of the continents and oceans would occupy far more space than could possibly be made available in an elementary text. Fortunately, superb texts and tectonic maps are available for many areas.[27,28,29,30,31,32,33]

A study of geologic structures would be quite barren and fruitless if unaccompanied by a discussion of the forces involved. In the natural course of events, the structural geologist makes his observations first, then deduces the geological structure, and, finally, considers the nature of the causative forces. Normally, observation and description precede interpretation. It might seem logical, therefore, in a book such as this, to reserve a discussion of mechanics until the end. But it is far more satisfactory to treat each structural feature as a unit, describing it first and then considering the forces involved. It is essential, therefore, that a chapter on mechanical principles be given first in order that the origin of the various geological structures may be intelligently discussed.

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