INTRODUCTION TO THE STRUCTURE OF THE EARTH

Third Edition

Edgar W. Spencer

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PREFACE

The primary objective of this text is to provide a broad up-to-date review of the principles of structural geology and tectonics for use in introductory courses. Because the volume of literature in these fields is expanding so rapidly, only a representative sample of the outstanding work that has been done can be included.

Although the text has been rewritten with a focus on the principles of structural geology, coverage of tectonics and regional geology has been retained. Examples of features of regional scale are included with the discussions of various types of structural features. Pertinent aspects of tectonics are integrated with the coverage of stress in the lithosphere and with new chapters on deformation in subduction zones and continental collisions.

This text starts with a discussion of the earth model, the largest subdivisions of the crust, and a brief summary of plate tectonic theory. Against this background, the nature of stress and ideas about the way stresses come into existence in the lithosphere are examined. This leads to consideration of the strains we see in rock and the way strains may be measured and represented. Naturally produced stresses and strains are then compared with the results obtained through experimental studies. Laboratory experience brings out the pronounced differences between the brittle and ductile behavior of materials in the earth. The next two chapters deal with examples of brittle behavior (mainly fracturing) and ductile behavior (with examples taken from soft sediment, salt, and metamorphic rocks).

Because of their central importance in structural geology, faults and folds are treated in a series of chapters. Generally these chapters begin with description and classification followed by discussion of theoretical and experimental evidence bearing on the origin of the features. They conclude with discussion of the tectonic settings in which these features occur.

In the concluding chapters the relationships between features of regional size and the large orogenic belts of which they are a part are emphasized. These chapters provide a final overview of the tectonic settings in which most structural features are formed.

Many people helped in the completion of this book. I am especially grateful to my wife, Elizabeth Humphris Spencer, for preparing the new art program and for providing help and encouragement in the writing and editing of the manuscript. I am also deeply indebted to Margaret Thomas, Susan White, Peggy Riethmiller, and Barbara Thomas, who mastered the word processor, typed the manuscript, and helped assemble the bibliography, glossary, and permissions, and to Washington and Lee University for providing support for this project.

I want to thank the many authors and editors who allowed me to use their illustrations, and Patrick Hinely for his photographic work. Special thanks are due the critical readers, Thomas Anderson, Mark Cloos, Eric Erslev, David Gold, and Woody Hickcox, for the excellent job they did reducing the number of errors and for making the manuscript both more up-to-date and more readable.

Finally I wish to acknowledge and thank those teachers, friends, colleagues, and students who have taught me structural geology.

Edgar W. Spencer

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INTRODUCTION TO THE STRUCTURE OF THE EARTH

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STRUCTURAL GEOLOGY—DEFINITION AND SCOPE

Structural geology is the study of the architecture of the earth—especially of the earth's crust. It is concerned with the arrangement and internal form of rock masses and with their origin. Because the structure of the earth's crust is one of the central concerns of geology, structural geology is part of the core of the geology curriculum. Not only is structural geology a fascinating and challenging study in its own right, but knowledge of structure is essential in many other courses in geology. Although structural geologists share with sedimentologists and petrologists an interest in the internal fabric and features of rocks, their special concern is describing and understanding the origin of features caused by stresses acting in the earth's crust.

The features produced by stress in the earth's crust, referred to as *structural or diastrophic features,* range in scale from the submicroscopic alteration of lattice structure in crystals to the formation of mountain systems. Several distinctly different scales of investigation, each with its own methodology, are used to study these features. These scales may be classified as (1) microscopic, (2) mesoscopic, (3) macroscopic or regional, and (4) megascopic or tectonic. In investigations concerning the first three of these classes, description of natural exposures of deformed rocks, such as those illustrated in Fig. 1-1, is generally the initial step. Often, regional and tectonic studies in-

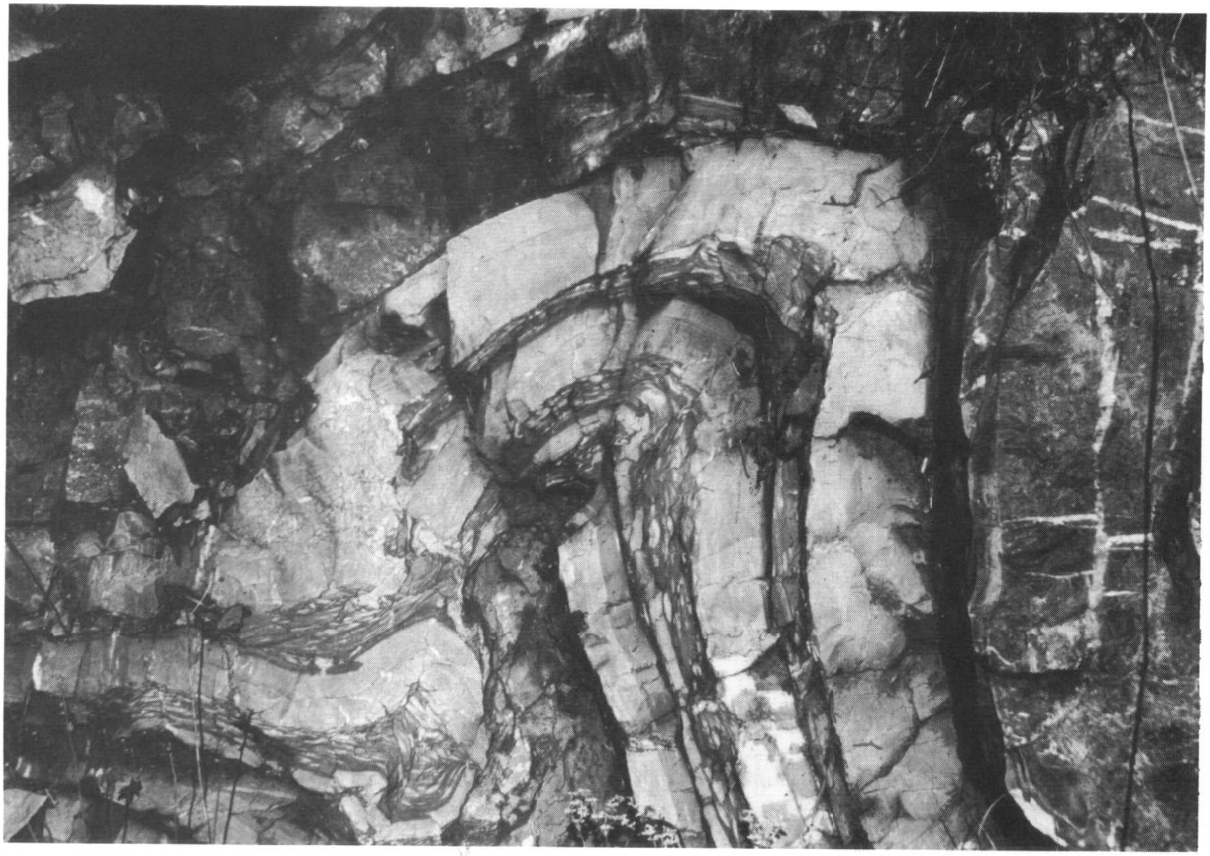

Figure 1-1 At one stage or another the work done by structural geologists involves analysis of outcrops such as the one seen here. More detailed work may consist of sampling rocks in settings like this followed by microscopic analysis. In regional studies the data collected from many such outcrops is combined to develop a regional picture of the rock structure.

volve not only structural analysis but also the synthesis of other studies, including those from such fields as stratigraphy, sedimentology, petrology, geophysics, and paleontology.

Cracks and offsets in crystals, twinning caused by mechanical deformation, recrystallization of minerals under stress, rotation or distortion of crystals, the development of partings, and alignments of crystallographic axes are examples of the types of features we study at the microscopic level (Fig. 1-2). Both electron and optical microscopes are used to examine such features. With these instruments we can compare, even at the atomic level, the texture and orientation of minerals found in naturally deformed rocks with those artificially produced in similar rocks deformed under carefully controlled laboratory conditions. In this way we are able to deduce the conditions responsible for the natural features found in the crust. The study of microscopic structures, which as a group compose the fabric of the rock, constitutes the field known as *petrofabrics*.

Mesoscopic-scale structural features are those ranging in size from a hand specimen to a large rock outcrop. These can be photographed, sketched, and measured with conventional tools, such as a compass and ruler or tape measure. At this scale both the measurements of the strike and dip of planes and the bearing and plunge of lines are important initial steps in our analyses. Representative types of

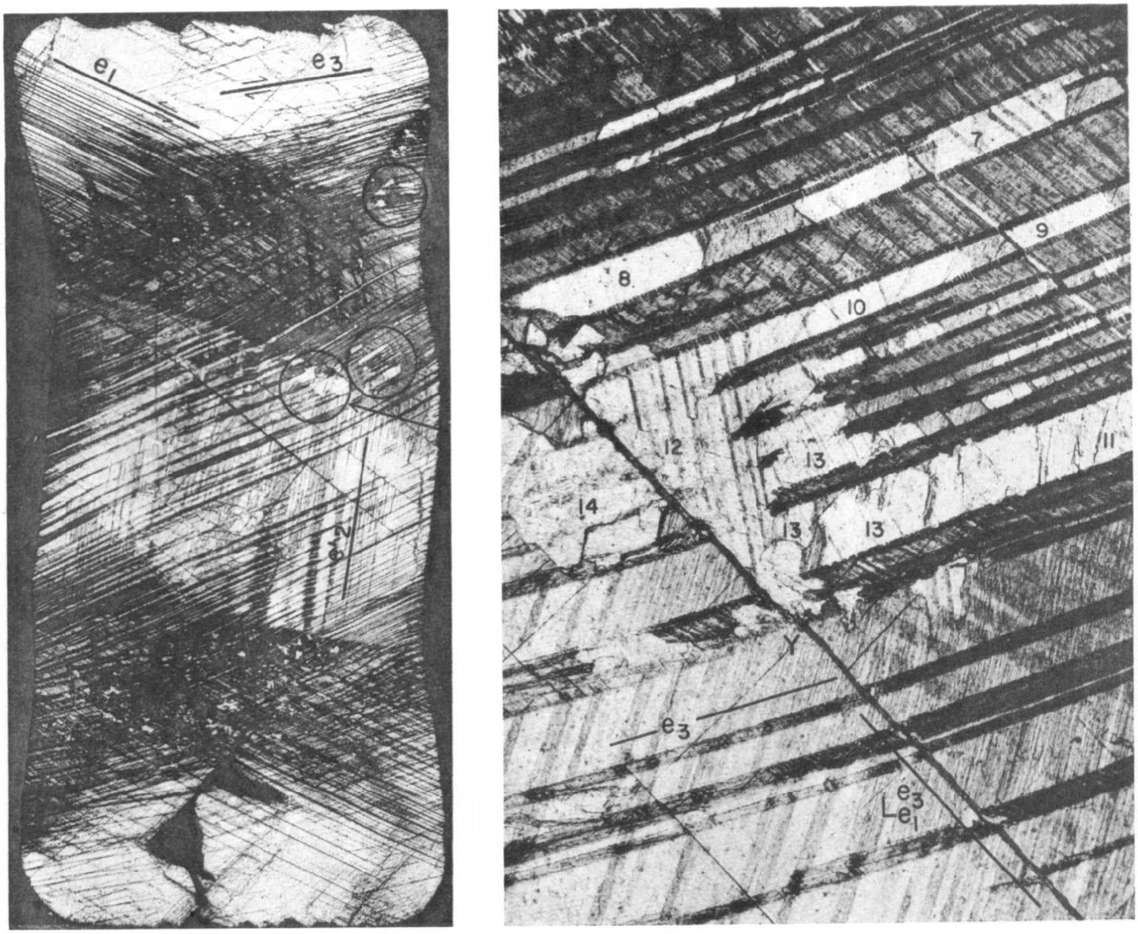

Figure 1-2 Thin sections of deformed rocks reveal the fine detail of the way individual grains have reacted to the applied forces. Naturally deformed rocks are often compared with those deformed experimentally under known conditions. A sample of calcite extended 20 percent is shown here. The sample at left is 17 mm wide. A ten times enlargement is shown at right. *(From Griggs, Paterson, Heard, and Turner, 1960.)*

structural features found at this scale are fractures, small faults, folds, the thickening and thinning of strata, sausage-shaped masses called *boudins,* and striations caused by scraping of one surface across another. Valuable information about the origin of these features is often obtained by comparing the microscopic-size features of rock samples with the mesoscopic-scale features of an outcrop from which they were collected. Model experiments and, more recently, computer modeling have helped us understand the origin of mesoscopic features.

At the regional scale, we expand our view, creating a synthesis by recording the data collected at outcrops onto aerial photographs, topographic maps, or other base maps to obtain regional geological and structural maps. The tools of preference for regional study become maps—geological, structure contour, isopach (contour maps showing the thickness of rock units), and tectonic. These provide information about the shape and regional extent of large folds, faults, fracture patterns, and other features of interest (Fig. 1-3).

As the size of the region being studied in-

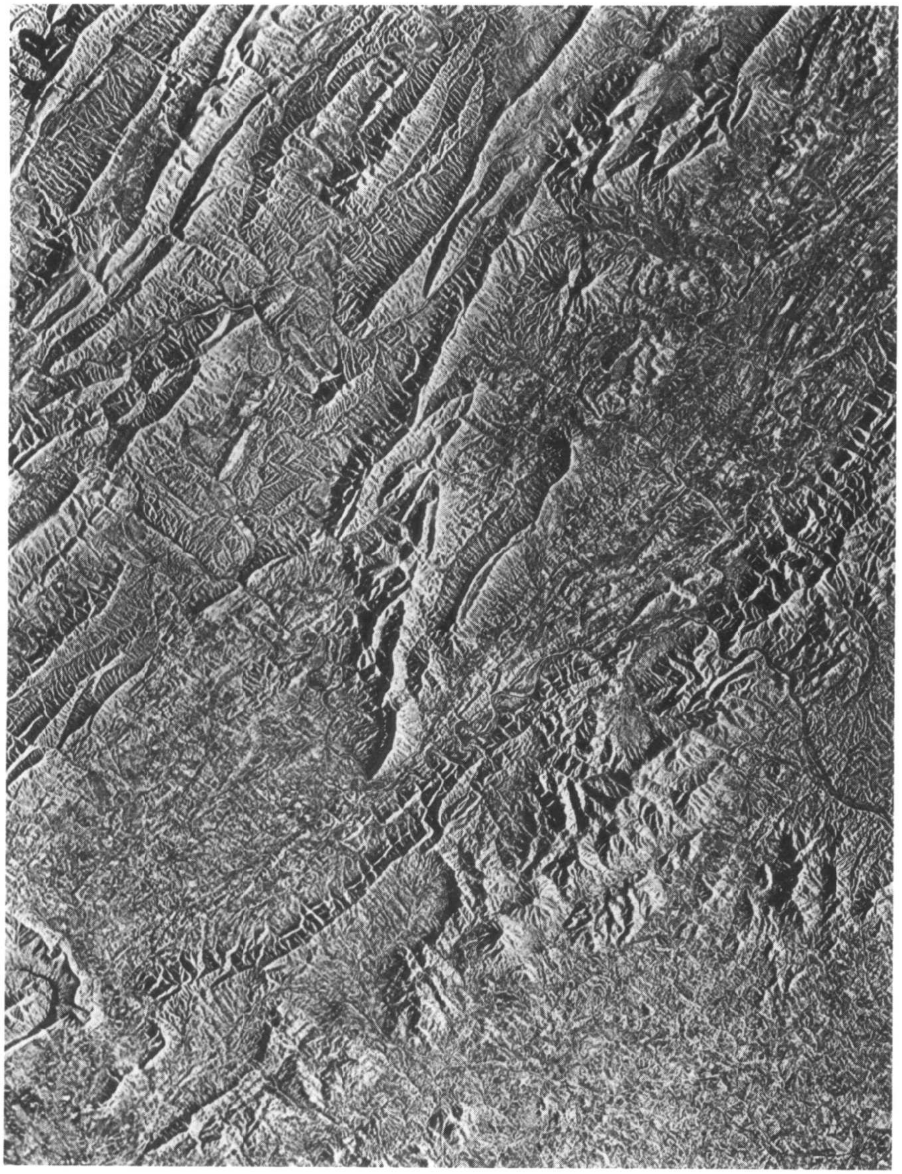

Figure 1-3a Side-looking radar image of a portion of the Blue Ridge and Valley and Ridge provinces in the Central Appalachian Mountains. Rock structure shows up because rocks that are resistant to weathering and erosion have been etched out. *(U.S. Geological Survey Image.)*

creases, what we commonly call regional structural geology merges with and becomes part of the overview field known as *tectonics*. Here our concern lies with the description, the origin, and the evolution of the largest features of the earth's crust, including mountain systems, oceanic ridges, and continental shields. Tectonics clearly involves aspects of many branches of earth science—especially geophysics, stratigraphy, and petrology, as well as structural geology.

Our ultimate goal is not only to describe features in the earth but to understand the physical processes which cause and govern the development of those features at all scales. Although we can understand some of these processes from field observations, structural geologists have increasingly turned to the methods of experimental physics and mathematical analysis to help clarify interpretations of observational data.

METHODS OF STRUCTURAL GEOLOGY

From the preceding discussion it is apparent that many quite different types of methodology are used in structural studies. These include (1) the collection of data concerning the shape and the geometry of rock bodies in the field, (2) compilation of surface and subsurface data on maps, (3) use of geophysical methods to obtain information about the subsurface, (4) use of the methods of petrofabrics to analyze rock textures and mechanisms of deformation that take place within as well as between minerals, (5) experimental methods involving use of high-temperature and pressure apparatuses, (6) mathematical theory and computer techniques used to analyze data and hypothetical situations in the behavior of the crust, and finally (7) synthesis of the data produced by the above methods of study.

Much of our knowledge of structural features is based on field observations of rock fabric and the relations of various structural features to one another. Such studies include geometrical analysis of bedding in sedimentary rocks; of foliations or layering in metamorphic rocks; of flow lines in igneous intrusions, fractures, cleavage, fold axes; and of axial surfaces in all types of rocks. The relations of these planar and linear elements to one another are often useful in establishing the history of events that have led to the present form of the rock bodies. Such analyses have proved fruitful in studying sedimentary and metamorphic rocks subjected to multiple deformations, even where conventional methods of geologic mapping have failed to resolve the complex geometrics of the rock bodies. Statistical methods and symmetry concepts—analytical techniques commonly used in petrofabric studies—have also proved useful in analyzing mesoscopic-size features.

Geologic mapping is one of the most important sources of structural data. Maps show the areal distribution of rock units and the attitude of contacts between units. The shape of these units at depth can be inferred from maps also. Maps in igneous and metamorphic terranes may show the geographic distribution of planar and linear structures in the rock. From this pattern, the larger structure of the rock body can be interpreted.

Subsurface structural methods include all the means by which the configuration of a rock body below the ground surface is obtained. These methods include the construction of cross sections and other projections at depth based on the geometry of the rock at the surface or actual control points obtained in wells or mine shafts and by use of geophysical methods. Among the most powerful of these tools are structure contour and isopach or thickness maps.

Geophysics is of great significance not only as a means of determining depth to stratigraphic horizons and their attitude in space but as our best source of information about the crust as a structural unit and about the deeper structure and composition of the interior of the earth. A large part of what we know about the structure

Figure 1-3b Aerial photographs such as this one of Little Dome anticline in Wyoming are used as a base for regional geological mapping. *(U.S. Geological Survey Photograph.)*

of ocean basins is derived from geophysical methods. These help us locate anomalous and thus potentially interesting areas for detailed study. The seismic methods, especially seismic reflection profiling, used in the exploration for traps suitable for the accumulation of oil and gas are one of our most powerful tools in studying the structural configuration of rock layers beneath the surface. In recent years a cooperative project, known as COCORP, Consortium for Continental Reflection Profiling, involving a number of universities as well as commercial organizations has conducted seismic reflection profiling along lines selected for their importance in answering scientific questions about subsurface structure. These lines have been run in many parts of the North American continent.

Petrofabric studies have been useful in establishing the changes of fabric that occur when rocks are deformed or metamorphosed. Such changes include the alignment of crystallographic axes in stress fields and recrystallization during and after deformation. Petrofabrics has proved particularly helpful in connection with experimental methods of studying rock deformation.

Experimental studies have been highly successful in demonstrating the behavior of rocks and minerals under various environmental conditions (especially varying temperature and pressure conditions). Small specimens of rock are deformed under carefully controlled conditions. The deformed specimens are then analyzed by petrofabric methods, and the geometric relationship between fabric and the known applied stresses is established. This method has provided an important basis for the dynamic approach to structural geology. Other experiments employing scale models and synthetic materials have been used to simulate structural features ranging from mesoscopic-scale folds to mountain systems. The dimensions of the large features of the earth's crust and the long periods of time over which geological processes operate make them difficult to treat experimentally. We can extrapolate the results of short-duration experiments, but it is important to remember that deformation in the crust may involve periods of millions of years.

Physical theories of stress, strain, and elasticity are used to gain a better understanding of the manner of rock yield and failure. The large number of variables involved in natural rock deformation makes theoretical analysis difficult, but such analyses have led to interesting conclusions concerning the mechanisms of folding and faulting. These methods are particularly valuable in combination with experiments and comparative field studies.

Synthesis involves bringing together information and integrating it into a coherent picture. The details of regional geology; the configuration of rock bodies and structural features beneath the ground surface; the conditions under which sediments, igneous rocks, and metamorphic rocks formed; and the timing of events are all important parts of the effort to reconstruct the structural evolution of the major features of the earth's crust. Plate tectonic theory provides a unifying concept that has integrated the results of varied types of investigations from all fields of geology. Since the early 1960s, plate theory has been more successful than any earlier theories in making much of what we know about the structure of the earth internally consistent.

USES OF STRUCTURAL GEOLOGY

Knowledge of the structure of the crust is important in all of the fields of applied geology. In exploration for oil and gas, the configuration of strata in the subsurface is one of the most important causes of traps in which oil or gas accumulates. Many such traps are formed by folds, along faults, or at angular unconformities. The shape of such traps is determined by use of cross sections constructed from surface geology, from various geophysical methods, and from the information obtained from drilled wells, Fig. 1-4. Data obtained from these

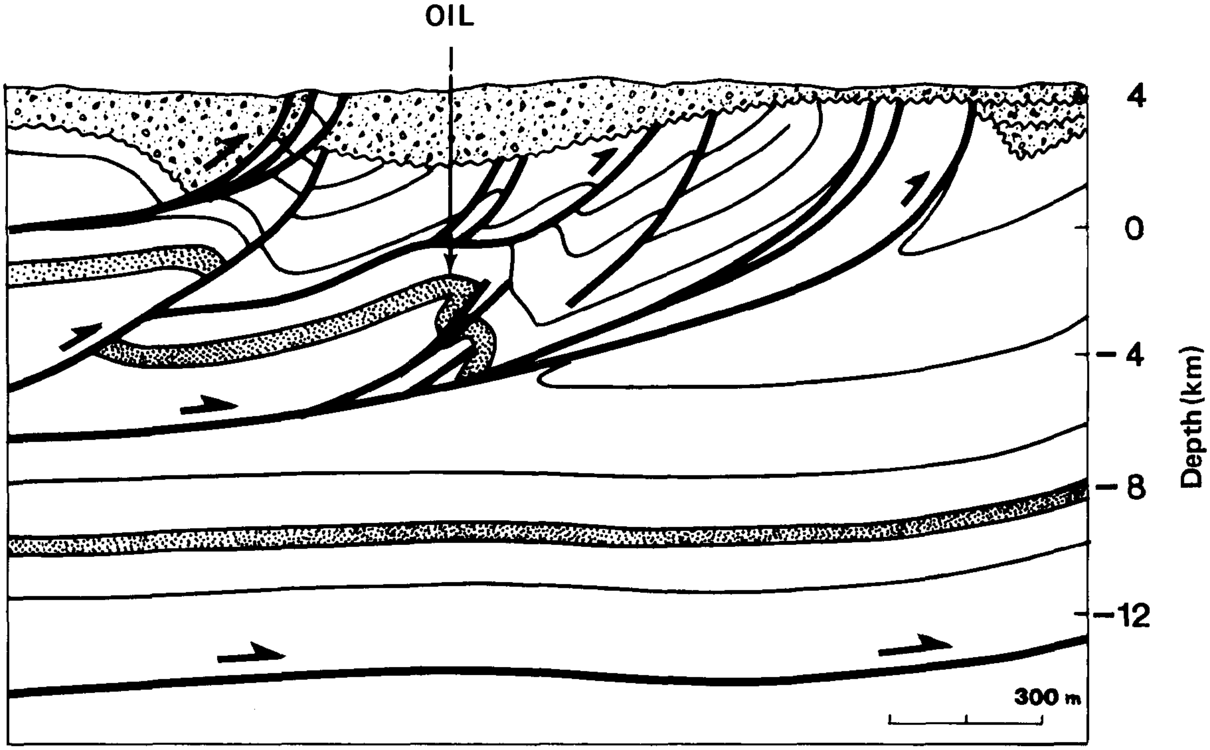

Figure 1-4 Both oil and gas in many of the world's largest fields have been trapped as a result of the structural configuration of the rock layers. Because oil and gas have low density, they float to the surface of water-saturated sediments. This upward movement continues until the fluid becomes trapped. This cross section is across a portion of the Wyoming fold and thrust belt showing the structure of the Painter field. Production is from the Nugget sandstone on an anticline above a branch off of the Absaroka thrust fault. *(After C. F. Lamb in Halbouty, 1980. Used by courtesy of the American Association of Petroleum Geologists.)*

sources are always interpreted in terms of our understanding of the principles of structural geology and especially the regional geology of the area where the exploration is taking place.

Most important structural traps exist at the scale of regional structural features. They are identified by constructing regional geologic and structural maps (e.g., structure contour or isopach maps). But, microscopic- and mesoscopic-scale structural features often play an important role in determining the porosity and permeability of the reservoir rocks. Porosity and permeability may be influenced or even controlled by such structural features as fractures or rock deformed in fault zones.

Structural knowledge is also of primary importance in the development of most mines and quarries. For example, structural knowledge is used to predict where and at what depths layers of coal will occur. Ore bodies may be localized by structural features. In many cases the metals have come up with magma or as hydrothermal solutions from magmas. The avenues of passage are commonly bedding planes, fractures, or fault zones. Knowing the geometry of these features is obviously essential in looking for the ore.

Structural features often determine the porosity and permeability of rock. For example, open fractures within a rock may increase its porosity and permeability many orders of magnitude. Thus, knowledge of rock structure is essential in studies related to the occurrence and movement of ground water. These studies are conducted both in exploration for groundwater supplies and in studies directed toward tracing actual or potential movement of pollution beneath the ground. The disposal of chemical and nuclear waste has prompted extensive studies to determine both the potential movement of such waste beneath the surface and the possibility of crustal movements that might disrupt such storage.

The possibility of movement of the bedrock is obviously an important consideration in the location of any major engineering structure. In the past, dams and nuclear reactors as well as many large buildings have been constructed on faults. Highways and reservoirs have been built where the bedrock structure makes the land prone to slump and sliding. In recent years, these problems have been more widely recognized and much more attention is being paid to the geology—both the structure and potential for movement—of such sites. The field of engineering geology has emerged as an important branch of applied geology, and it is one in which knowledge of rock structure is important.

Thus from a practical point of view, structural geology is used not only in exploration for oil, gas, ground water, and ore deposits but also in planning the extraction of coal and other valuable rocks, minerals, and fluids. Knowledge of structure is important in determining the stability of rocks at the surface and in the subsurface. Consequently it is indispensable in the field of engineering geology. When pursuing most other types of geological studies, it is necessary to understand how crustal movements have affected the position and orientation of rock outcrops. This understanding is especially important if the objective of the study is to reconstruct conditions (e.g., paleogeography) from some time in the past.

As seen from a purely scientific viewpoint, the objective of structural geology is to improve our understanding of the internal architecture of the crust, of how that form came into existence, and of how it has been modified.

CHAPTER 2

EARTH'S INTERIOR AND MAJOR CRUSTAL ELEMENTS

CHAPTER OUTLINE

INTRODUCTION

The character of the earth's interior and the processes functioning there are of fundamental importance to understanding the origin and development of the structural features we examine at the surface. The upper part of the mantle is important in all modern tectonic theories. Thus it is in the mantle that we seek the pro-