EDGAR W. SPENCER

Introduction to the Structure of the EARTH

SECOND EDITION

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This book is dedicated to the memory of two outstanding teachers

Arie Poldervaart

Walter Bucher

Preface

The objective of this book is to provide broad, up-to-date coverage of the principles of structural geology and tectonics suitable for use in an introductory course in these subjects. The book is organized into three parts. Part One deals with the traditional subject matter of structural geology, the description of structural features, and the theoretical and mechanical explanations of their origin. Part Two is devoted to a discussion of tectonics and regional structural geology, especially as it has come to be viewed in terms of plate-tectonic theory within the last decade. A discussion of the regional structural geology of the Appalachians, the Alpine-Himalayan system, and the Cordilleran system is included in order to broaden the student's conception of the relation of structural principles to regional and tectonic problems and to illustrate the relation of structural geology to other branches of geology and geophysics. The third part, the appendixes, provides a brief survey of the methods, particularly the geometric projections, used by structural geologists, an introduction to map and cross-section preparation, and stress analysis.

It has been my pleasure and good fortune to have been associated as a student, colleague, and friend with a number of outstanding geologists, and I am grateful for the help and encouragement these friends have given me. I am especially indebted to my former teachers Walter Bucher, Arie Poldervaart, Marshall Kay, and Marcellus Stow, who first stimulated my interest in the problems of structural geology. I also wish to express my appreciation to F. Aldaya, S. Warren Carey, J. M. Fontboté, Manuel Julivert, H. P. Laubscher, Arnold Lillie, Alberto Marcos, and Rudolf Trümpy for introducing me to the geology of other parts of the world.

I am indebted to my students, who helped me turn a critical eye on the first edition of this book, and to the reviewers, especially Woody Hickcox and Kevin Coppersmith, who helped me improve earlier drafts of the manuscript for this edition. I wish to acknowledge with thanks the many reprints, photographs, and line drawings which have been made available to me for use in the preparation of this book, and the help of Elizabeth Brewbaker, Dorothy Tolley, Peggy Riethmiller, Virginia Gillen, and Anne Barger who helped me prepare the manuscript. A special note of gratitude is due Dennis Slifer, Edward Backus, and my wife, Elizabeth, for preparation of many of the new illustrations in this edition.

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PRINCIPLES

Introduction

Knowledge of *structural geology* is central to our understanding of the earth either as a whole or in its myriad parts. The scope of the field is vast, ranging from the broadest framework of the earth's interior and the major crustal elements to the fine detail of rock fabric. It includes description of the geometry and spatial relationships of rock bodies on the one hand and the processes by which these relationships come into existence on the other.

Structural geology deals with the techniques used to obtain structural data in the field and to produce representations of that data suitable for analysis and interpretation. Development of an understanding of the physical processes or principles which govern the development of structural features is also of primary importance. Many of the underlying principles have been derived primarily from field observations, but increasingly, structural geologists are turning to methods of experimental physics and mathematical analysis for a more complete explanation of the observational data. Structural geology is a basic ingredient of regional geology, and description of regional structural relations is an important part of the field. In a sense, regional structure constitutes much of the basic data of tectonics.

Many of the most exciting developments in science during the last decade have occurred in the field of tectonics. The emergence of seafloor spreading and plate tectonics as an explanation for continental drift has captured the imagination of most earth scientists and has provided the most powerful unifying concept yet developed in viewing the origin and evolution of large-scale structural features. The purpose of this book is to examine each of these major aspects of the field of structural geology.*

Structural geology as a discipline is closely related to many other fields of earth science. The study of petrofabrics links structure to mineralogy and petrology. The form and internal fabric of undeformed sedimentary rocks showing features developed during

* See the Glossary at the end of the chapter.

deposition and consolidation of sediment is a concern of both sedimentologists and structural geologists. Many geophysical methods are used primarily to delineate subsurface structure, and other geophysical studies are used to reveal large crustal structures and point to their origin. And finally, structure and stratigraphy are intimately related in regional mapping and in development of the geologic evolution of the earth. Knowledge of earth structure is also vital in the applied fields of geology, such as ground-water hydrology and engineering, petroleum, and mining geology, where it is of critical importance to learn the subsurface configuration of rock bodies as well as to know their surface distribution. Many petroleum traps are structural features, and the geologist must know the structural setting of stratigraphic traps such as pinch-outs, unconformities, and reefs in order to locate and develop production intelligently. The evaluation of shape, size, and depth of an ore body or an economically important rock body determine the feasibility of mining it. Knowledge of the existence of a fault which displaces the ore or coal may well mean the difference between financial success and failure. Many of the failures of large engineering structures can be directly attributed to imperfect evaluation of the structure of the foundation rock. Dams have been built on active faults, tunnels have failed for lack of adequate knowledge of subsurface structure, and many large buildings and highways have been damaged because their foundation rock contained structural flaws.

Methods of Structural Geology

Methods as varied as the subject are used to obtain structural knowledge. Geologic mapping is by far the main source of structural data. Maps show the areal distribution of rock units, and the attitude of contacts between units and the form of the units at depth can be made from them. Maps in igneous and metamorphic terranes may show the geographic distribution of planar and linear structures in the rock. The larger scale structure of the rock body can be interpreted from this pattern.

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 by drilling, geophysical methods, or in mine shafts. 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 very large part of what we know about the structure of ocean basins is derived from geophysical methods. Geophysical methods help us locate anomalous and thus potentially interesting areas for detailed study.

Much structural knowledge is based on field observations of rock fabric and the relations of the various elements of the rock structure to one another. Such studies include geometrical analysis of joints, rock cleavages, foliations in metamorphic rocks, flow lines in igneous intrusions, bedding surfaces, fold axes and axial surfaces, or the relations of any of these planar and linear elements to one another. Such analyses have proved fruitful in metamorphic rocks and in regions subjected to multiple deformations where conventional methods of geologic mapping have failed to resolve the more complex geometries of the rock bodies. Some techniques of analysis have been carried over from petrofabric studies, employing statistical methods and symmetry concepts.

Petrofabric studies have been useful in establishing the changes of fabric when rocks are deformed or metamorphosed, such as the alignment of crystallographic axes in stress fields and the effects of recrystallization during and after deformation. Petrofabrics has proved particularly significant in connection with experimental methods of studying rock deformation.

Experimental studies have been highly successful in demonstrating the behavior of rocks and minerals when deformed under various environmental conditions (especially varying temperature and pressure conditions). The deformed specimens are analyzed by petrofabric methods, and the geometric relationship between fabric and the known applied stresses is established. This has provided an important basis for dynamic structural geology. Other experiments employing scale models and synthetic materials have been used to simulate large-scale structural features ranging from small-scale folds to mountain systems.

Mathematical theories of stress, strain, and elasticity have been applied to try to gain a better understanding of the manner of rock yield and failure. The large number of variables involved in natural rock deformation make rigid theoretical analysis difficult, but interesting conclusions have been reached through theory concerning the mechanisms of folding and faulting. These methods are particularly valuable in combination with experiments and comparative field studies.

Synthesis implies the bringing together of information and integrating it into a coherent picture. As such, synthesis is important as a method of structural analysis. This bringing together of the details of regional geology, subsurface configuration, lithology, and age is an important part of the reconstruction or synthesis of structural evolution which has led to so many major discoveries both for the exploration geologist and for the theorist. The concepts of geosynclines, continental drift, sea-floor spreading, plate tectonics, and orogeny are products of this approach.

GLOSSARY*

Diastrophism: The process or processes by which the crust of the earth is deformed, producing continents and ocean basins, plateaus and mountains, flexures and folds of strata, and faults. Also the results of these processes.

Dynamic structural geology: The study of the relationship between structural features (strains) and the stress conditions under which they form.

Kinematic structural geology: The study of the rock fabric of deformed rock based primarily on the movement pattern necessary to produce the observed strain and independent of the stresses responsible.

Petrofabrics: The study of rock fabric, involving analysis of the component parts of a rock—the fragments, crystal grains, and their sizes, shapes, arrangement, orientations in space, relations to one another, internal structure, and the movements and process which played a part in the formation of the fabric.

Structural feature: A feature produced in rock by movements after deposition, and commonly after consolidation, of the rock.

Structural geology: The study of the structural features of rocks, the geographical distribution of the features, and their causes.

Tectonics: The study of the broader structural features of the earth and their causes.

REFERENCES

Badgley, P. C., 1965, Structural and tectonic principles: New York, Harper & Row.

Bailey, E. B., 1935, Tectonic essays: Oxford, Clarendon.

Beloussov, V. V., 1962, Basic problems in geotectonics (J. C. Maxwell, ed. English edit.): New York, McGraw-Hill.

* Refer to Am. Geol. Inst. © 1972, Glossary of geology and related sciences.

Billings, M. P., 1972, Structural geology, 3d ed.: Englewood Cliffs, N.J., Prentice-Hall.
Bucher, W. H., 1933, The deformation of the earth's crust: Princeton, N.J., Princeton Univ.
Cloos, Hans, 1936, Einfuhrung in die geologie: Berlin, Gebruder Borntraeger.
Daly, R. A., 1940, Strength and structure of the earth: Englewood Cliffs, N.J., Prentice-Hall.
DeSaussure, Horace, 1796, Voyages dans Les Alpes, v. IV: Neuchâtel.
De Sitter, L. U., 1964, Structural geology, 2d ed.: New York, McGraw-Hill.
Eardley, A. J., 1951, Structural geology of North America, 2d ed.: New York, Harper & Row.
Fairburn, H. W., 1942, Structural petrology of deformed rocks: Cambridge, Mass., Addison-Wesley.
Geikie, James, 1940, Structural and field geology, 5th ed.: Edinburgh, Oliver & Boyd.
Goguel, Jean, 1965, Tectonics, 2d ed.: San Francisco, Freeman.
Griggs, D. T., and **Handin, John,** eds., 1960, Rock deformation: Geol. Soc. America Mem. 79.
Hills, E. S., 1953, Outlines of structural geology, 3d ed.: London, Methuen.
——— 1963, Elements of structural geology: New York, Wiley.
Irvine, T. N., ed., 1965, The world rift system: Geol. Survey Canada Paper 66-14, Dept. Mines and Technical Surveys, Ottawa.
Jeffreys, H., 1970, The earth, 5th ed.: London, Cambridge.
Kay, G. M., 1951, North American geosynclines: Geol. Soc. America Mem. 48.
Lotze, Franz, 1956, Geotektonisches symposium en ehren von Hans Stille: Stuttgart, Kommissions—Verlag von Ferdinand Enke.
Nevin, C. M., 1942, Principles of structural geology, 3d ed.: New York, Wiley.
Poldervaart, Arie, ed., 1953, The crust of the earth: Geol. Soc. America Spec. Paper 62.
Ramsay, J. G., 1967, Folding and fracturing of rocks: New York, McGraw-Hill.
Sander, B., 1930, Gefugekunde der Gesteine: Vienna, Springer.
——— 1948, Einfuhrung in die Gefugekunde der Geologischen Korper, pt. I: Vienna, Springer.
Schmidt, Walter, 1932, Tektonik und Verformungslehre: Berlin, Borntraeger.
Sonder, R. A., 1956, Mechanik der Erde: Stuttgart, E. Schweizerbartsche Verlags.
Stočes, Bohuslave, and **White, C. H.,** 1935, Structural geology: London, Macmillan.
Turner, F. J., and **Weiss, L. E.,** 1963, Structural analysis of metamorphic tectonites: New York, McGraw-Hill.
Umbgrove, J. H. F., 1947, The pulse of the earth, 2d ed.: The Hague, Nijhoff.
Whitten, E. H. Timothy, 1966, Structural geology of folded rocks: Chicago, Rand McNally.
Willis, Bailey, 1923, Geologic structures: New York, McGraw-Hill.
——— and **Willis, Robin,** 1934, Geologic structures, 3d ed.: New York, McGraw-Hill.

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Nontectonic Structural Features

Distinguishing between deformed and undeformed rocks is of basic importance in structural geology. This distinction is not always obvious. All rocks possess a primary external geometrical form, and the constituents of the rock have an initial size, packing, or spatial arrangement, referred to as *texture* or *fabric*, which arise as a result of the special conditions of sedimentation or crystallization. The initial fabric may have distinctive features or forms called *primary structural features* formed during deposition of sediment or crystallization of melt.

Both the external form and internal fabric undergo changes as sediment becomes lithified. These changes include compaction, cementation, sometimes crystallization, dehydration, and desiccation. All these processes take place in the earth's gravity field, and the rock is subject to the stresses which arise as a result of gravity. The initial form and fabric may be distorted or change volume—in a very real sense the initial rock is strained or deformed. But the important distinction for us is one between changes that occur as a normal result of lithification on the one hand and strains imposed on the rock as a result of abnormal applied stresses on the other. Features produced as a result of strains imposed on sediment or rock during or after consolidation by external stress fields are called *secondary structural features*.

In summary, different fabrics and structural features in rock bodies arise under different conditions:

1. Primary structural features formed during sedimentation or crystallization.

2. Features formed in the rock during lithification and subject to no applied forces other than gravity.

3. Secondary structural features formed during lithification as a result of externally applied forces in addition to gravity.

4. Secondary structural features formed after lithification and as a result of external forces (both gravity and other forces).

It is often very difficult to make these basic distinctions. The last three classes involve strain of the initial form and fabric, although that strain arises under different circumstances.

NONDIASTROPHIC STRAINS

The term *diastrophism* carries a genetic connotation. Thus it is implied that nondiastrophic strains are formed by forces other than those associated with uplift and deformation of mountains or continental drift. The remaining significant forces are gravity and such forces as may arise from internal changes in the material. Many types of structural features form in this way. For example:

1. Features due to differential compaction of sediment.
2. Folds developed as a result of compaction over irregular topography.
3. Features formed as water-saturated sediment is dewatered.
4. Folds and faults associated with slumps, flowage phenomena, and sliding of subaqueous masses.
5. Fractures formed as a result of volume changes caused by drying of sediment, dehydration, crystallization, and thermal effects.

PRIMARY SEDIMENTARY STRUCTURES

Field geologists encounter a great variety of textures, fabrics, and structures in rocks, some of which form during deposition or during emplacement and crystallization of igneous rocks and others which result from postdepositional or postcrystallization deformation. Often it is difficult to distinguish these later, secondary structural features from the earlier, primary features. This is particularly true when a distinction is to be drawn between syndepositional and postdepositional deformation in soft sediment. Secondary structural features may form at any time after deposition, including the stage during which the sediment is unconsolidated.

Study of primary sedimentary structural features is important because it is through our understanding of the primary form and attitude of strata that we are able to perceive that they are deformed and are able to measure the amount of that deformation. In addition, we rely on primary features to determine which side of a sedimentary layer was originally the top.

Stratification

No feature of sedimentary rocks is more universal than stratification. This feature arises through slight variations in any of the physical or chemical characteristics of sediment that occur essentially normal to the bedding. Stratification arises as a result of differences between layers in (1) chemical composition, (2) grain size, (3) degree of sorting, (4) degree and type of packing, (5) cohesion, (6) cementation, and (7) permeability or porosity.

The conditions under which sediment is deposited impart distinctive characteristics to the layering. This is reflected in the nature of the layers, in the arrangement of the material within the strata, in features on the bedding planes, and sometimes in the shape of the sedimentary unit. Some stratification arises directly from sedimentation, as in varves, layering in deep-sea carbonate and siliceous oozes, evaporites in playa lakes and behind fringing reefs, and chemical precipitates in general. Layering is formed indirectly when the water is agitated so that sediment is reworked and previously deposited sediment is broken up and redeposited, as in graded bedding and flat pebble conglomerates. This is most likely to occur in shallow water. Still other layers form under combined conditions of direct and indirect stratification.