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PREFACE

Our purpose in writing this textbook is to communicate the physical and geometric elegance of geologic structures within the Earth's crust and to describe the ways in which geologic structures reflect the nature and origin of crustal deformation through time. Geologic structures provide part of the basis for recognizing and reconstructing the profound changes that have marked the physical evolution of the Earth's outer layers, as observed from the scale of the plates down to the scale of the microscopic. Understanding the nature and extensiveness of deformational structures in the Earth's crust has both scientific value and practical benefit. But, there is a philosophical value as well. Our perceptions of who we are and where we are in time and space are shaped by facts and interpretations regarding the historical development of the crust of the planet on which we live. Knowing fully the extent to which our planet is dynamic, not static, is a reminder of the lively and special environment we inhabitat.

For example, we have come to understand that our earthly foundations are not fixed. Instead, we live on continent-size plates that are in a continual state of slow motion. The interaction of these plates has played a dominant role in both the formation and deformation of rock bodies in the Earth's crust. Knowledge of present-day plate tectonic processes aids us in interpreting past structural movements. Furthermore, evaluating and interpreting past dynamics may help us predict what the present actions hold for the future.

The focus of this book favors applications in regional tectonics, exploration geology, active tectonics, and geohydrology, but at all times it underscores the importance first of understanding fundamental concepts and principles. Perhaps, what is emphasized most is how structural geologists think about deformed rocks. Once the conceptual framework within which structural geologists operate is grasped, the Earth begins to look different. In fact, natural physical processes and natural physical phenomena, whether geologic or not, never quite look the same again. At least, that has been our experience.

We have arranged this text in three parts. *Fundamentals* (*Part I*) provides essential background for analyzing *Structures* (*Part II*). *Descriptive Analysis* (*Part III*) describes how to function in the field, and what to do with the data that are collected.

Nature of Structural Geology (*Chapter 1*), introduces the beauty, the challenging geometry, and the practical value of structural geology. It also presents the basic philosophical approach to structural geology as used throughout the book. The approach is known as **detailed structural analysis**. The steps are descriptive (the physical and geometric description of geologic structures and deformed rocks), kinematic (evaluation of changes in location, orientation, shape, and size of rocks during deformation), and dynamic (evaluation of the forces and stresses that caused deformation, and appraisal of the strength and behavior of the rock at

the time of deformation). These three steps of detailed structural analysis provide the leverage for unraveling and interpreting structures and systems of structures at any scale, from rocks to regions.

Kinematic Analysis (*Chapter 2*), presents the means for evaluating and describing how rocks have changed location, orientation, shape, and size during the course of deformation. *The very presence of structures and systems of structures in rocks in the Earth's crust reflects translation* (*change in the location*), *rotation* (*change in orientation*), *distortion* (*change in shape*), *and dilation* (*change in size*) *of the rocks in which they are found. If no such changes were required, the structures would have no reason to exist.* Kinematic analysis is applied at all scales, from movements within the lattice of an individual crystal to movements of plates.

Dynamic Analysis (*Chapter 3*) probes the origin of deformation in terms of forces, stresses, rock strength, and mechanics (the relationship of stress to strain). Down-to-earth examples give a "feel" for forces and stresses and the math that is used to describe them. Conventional laboratory testing of rock strength is employed as a useful context to think about forces and stresses, and to apply the basic math. Furthermore, laboratory evaluation of the response of rocks to force and stress permits us to see more clearly and quantitatively the influence of variables like lithology, temperature, confining pressure, fluid pressure, and strain rate on resistance to deformation.

Deformation Mechanisms And Microstructures (*Chapter 4*) explores what actually takes place at the microscopic and submicroscopic scales that enables "hard" rock to change shape and size—as if it were soft. In this chapter we see that temperature, pressure, mineralogy, strain rate, and the presence (or absence) of fluids determine which mechanisms will operate during deformation. The processes that permit rocks to deform on the grain and subgrain scales range from brittle microfracturing and grinding to plastic deformation involving the subtle "creep" of crystals. The ease (or difficulty) with which microscopic deformational mechanisms spring into action when rock is stressed controls the level of stress that rock can support.

Part II, Structures, presents the chief classes of structures. Structures are described and analyzed according to the methods and principles presented in Part I, "Fundamentals." In addition, the mechanics of formation of each class of structure is examined, using principles of applied physics. The geometry and formation of the structures is viewed from the microscopic to the regional, although the greatest descriptive attention is at the outcrop and map scale.

Within *Part II* are the following chapters: *Joints and Shear Fractures* (*Chapter 5*), *Faults* (*Chapter 6*), *Folds* (*Chapter 7*), *Cleavage, Foliation, and Lineation* (*Chapter 8*), and *Shear Zones and Progressive Deformation* (*Chapter 9*). Part II concludes with *Plate Tectonics* (*Chapter 10*), a chapter that expresses the modern concept that much, if not most, crustal deformation is directly or secondarily linked to processes of seafloor spreading and plate tectonics. In the "plates" chapter we will explore the intriguing geometry and motions of plates on a sphere. We examine the nature and magnitude of forces created by plate movements. And we view the character of active tectonism at or near modern plate boundaries.

In *Concluding Thoughts* following Chapter 10, we emphasize that structures do not exist in isolation, but are integrated within networks of interconnecting structures, at all scales, to accomplish just the right amount of deformational response to the prevailing tectonic stresses. *Concluding Thoughts* is a jumping off point for studying systems of structures at all conceivable scales.

Part III, Descriptive Analysis, is subdivided into sections A to N. It is intended to be used as preparation for field work, and as a guide to "reducing" data collected in the field. The sections in Part III are entitled: (A) Geologic Mapping, (B) Mapping Contact Relations, (C) Identifying Primary Structures, (D) Measuring Structural Orientations with a Compass, (E) Preparing Geologic Cross Sections, (F) Preparing Subsurface Contour Maps, (G) Orthographic Projection, (H) Stereographic Projection, (I) Stereographic Evaluation of Rotation, (J) Determining Slip on a Fault Through Orthographic and Stereographic Projection, (K) Stereographic Relationship of Faults To Principal Stress Directions, (L) Methods in Joint Analysis, (M) Some Additional Tips on Fold Analysis, and (N) Studying Shear Zones in the Field.

We have written this book in a way that proceeds from basic physical concepts and methods of analysis to the description and interpretation of structures and systems of structures. Yet we have also made each chapter as self-contained as possible, knowing that some users will want to read or present the material in a different order. Throughout the book, techniques, methods, experiments, and calculations are described in detail, with the aim of inviting active participation and discovery through laboratory and field work.

Those who have come to know the first edition of *Structural Geology of Rocks and Regions* will find some notable changes in this the second edition. (1) The authorship has expanded from one to two. We, Davis and Reynolds, have been close colleagues for years and now are both professors at neighboring universities. (2) The geologist pictured on the cover of the first edition, who had been sitting on the same outcrop for 11 years (!), is now up and walking around again, checking out new relationships. We asked our cover illustrator to step back a bit, to see if there was anyone

else working in the area. In fact, there is. And there may be others. (3) Two new chapters have been added, and these are ones that bear importantly on the understanding of modern structural geology: *Deformation Mechanisms and Microstructures* (*Chapter 4*) and *Shear Zones and Progressive Deformation* (*Chapter 9*). (4) Two former chapters have been eliminated (Contacts and Primary Structure), although central concepts of each have been incorporated elsewhere in the text. (5) Nitty-gritty descriptive analysis (formerly Chapter 2) is now positioned as the core of Part III. (6) The organization is more streamlined, allowing the reader to move directly from the fundamentals (kinematic analysis, dynamic analysis, deformation mechanisms) into the major structures themselves (joints, faults, folds, cleavage, foliation, lineation, and shear zones), without an interlude. Moreover, by sweeping most nitty-gritty descriptive operations into Part III, there are fewer roadblocks to smooth, uninterrupted reading. (7) *Plate Tectonics* (*Chapter 10*) comes at the end (although it could be read at the beginning), providing a natural transition into texts and courses in regional tectonics, active tectonics, and plate tectonics. Through it all, we have tried hard to make the second edition as user-friendly as the first.

Structural geology is an essential tool in unraveling the geologic history of any given area or region within the Earth, especially in mountain belts where original arrangements of rocks and geologic contacts are profoundly modified by deformational movements.

When viewed at geological scales of time and spatial dimension, *rocks must be regarded as materials almost without strength, capable of being deformed continuously even under the slightest of pressures.* The geologic mapping of mountain belts has shown this to be true time and time again. The understanding of this paradox, which we try to capture in the expression "*soft as a rock*," yields a transformed view of the strength and behavior of rocks and regions.

Practical applications of structural geology are broad ranging and powerful—traditionally in petroleum geology, exploration geology, and mining engineering, and now in environmental geology, hydrology, geothermal energy development, and civil engineering. The practical value of structural geology derives largely from the fact that movement and trapping of fluids through rock are strongly influenced by fracturing, faulting, and folding. Thus, a firm understanding of principals of structural geology is beneficial when exploring for oil and gas, when investigating for the source of contaminants in a part of the groundwater system, when evaluating the energy potential of a natural geothermal system, when appraising daring but dangerous proposals for the subterranean disposal of radioactive waste, when examining basin sediments as potential groundwater reservoirs, when assessing the fundamental stability of steep slopes underlain by rain-infiltrated fractures in the bedrock, or when planning the excavation of mines or tunnels. Because most ore deposits owe their existence to the movement of mineral-bearing hydrothermal solutions through fractured bedrock, structural geology is a basic tool in the exploration for metals, and in the "development" of an ore body. Finally, the understanding of active tectonic events like earthquakes, volcanic eruptions, and massive landsliding are intellectually demanding activities that require knowledge derived from intimacy with the principals of fracturing and faulting.

Field relations are the primary sources for structural geologists. What value "the field" has for those intent on understanding Earth dynamics! Dr. Howard Lowry, a brilliant scholar in the field of English literature, captured the significance of primary sources. His words have special meaning for geologists:

> By [primary sources] we mean the first-hand things, the authentic ground of facts and ideas, the original wells and springs out of which all the rest either is drawn or flows. . . . Regard for the primary sources makes one forever the enemy of preconceptions, of manipulated data, raw opinion, and guesswork—of all the sleek shortcuts to wisdom in ten easy lessons. . . . Exclusive reliance on second-hand things makes second-hand men and women. It deludes us into thinking we are wiser than we are. . . . Breadth of knowledge, even knowing a little about a lot, has its obvious value. But breadth that perpetually sends down no clean, strong roots in the primary sources—into the deep earth and "the hidden rivers murmuring in the dark" of the rocks—such breadth clarifies very little. It merely puts our bewilderment on a broader basis. It leads us into incredible naivete and gullibility. It makes us too quick to believe all we read. (From *College Talks* by H. F. Lowry, edited by J. R. Blackwood, pp. 86–87. Published with permission of Oxford University Press, New York, copyright © 1969.)

This text on structural geology is based on and directed to the primary sources.

One final note. Both of us like to tell stories to illustrate and to bring to life the material we present. When George tells his stories, he goes right into it: "Going to the freezer for a midnight snack, I pulled out a pizza whose form is portrayed in the geologic map shown in . . . ." When Steve tells his stories, he inserts an (SJR): "When I (SJR) prepared the Geologic Map of Arizona, I gave careful attention to which rocks would be . . . ." In this way you will know who is telling which personal story within a book that "we" have so enjoyed writing together.

GEORGE H. DAVIS AND STEPHEN J. REYNOLDS