Geologic Fracture Mechanics

This lively introduction to geologic fracture mechanics provides a consistent treatment of all common types of geologic structural discontinuities. It explores the formation, growth, and interpretation of fractures and deformation bands, from theoretical, field, and laboratory-based perspectives, bridging the gap between a general textbook treatment and the more advanced research literature. It allows the reader to acquire basic tools to interpret discontinuity origins, geometries, patterns, and implications using many of the leading and contemporary concepts known to specialists in the field. Exercises are provided at the end of each chapter, and worked examples are included within each chapter to illustrate topics and enable self-study. With all common geologic structures including joints, hydrofractures, faults, stylolites, and deformation bands being discussed from a fresh perspective, it will be a useful reference for advanced students, researchers, and industry practitioners interested in structural geology, neotectonics, rock mechanics, planetary geology, and reservoir geomechanics.

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To my Father,

who taught me initiative;

To my Mother,

who taught me compassion;

And to my wife and family for their loving support.

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Preface

Structural discontinuities in rock, including all types of fractures, joints, faults, and deformation bands, along with stylolites and fluid-filled cracks such as hydrofractures, veins, and dikes, have been studied extensively using the tools and terminology of geology, geomorphology, geophysics, rock engineering, geomechanics, tectonophysics, hydrology, petroleum geology, mining engineering, quarrying, soil mechanics/geotechnical engineering, crystallography, experimental rock physics, and materials science. Most of what is known about fractures and deformation bands, collectively referred to as geologic structural discontinuities in this book, comes from a synthesis of concepts flowing from these traditionally separate disciplines. Many of the basics of what structural discontinuities are, and how to identify them, can be found in various degrees by using any of a number of good textbooks on particular topics. However, these sources must necessarily cover a wide range of material appropriate for semester-long, comprehensive courses in, for example, structural geology and tectonics. On the other hand, journal articles provide in-depth explorations of these topics for the experienced and knowledgeable reader.

The purpose of this book is to help bridge the gap between general treatments of geologic structural discontinuities found in textbooks or more advanced topical monographs and the published research literature. The book explores **geologic fracture mechanics**—the formation, growth, and interpretation of geologic structural discontinuities—primarily from field-based and theoretical perspectives, with laboratory-based research incorporated as appropriate. In many cases, some large amount (like 70%) of what can be interpreted from a discontinuity set can be gained with only simple tools and observations and without extensive mathematical analysis. Many scientists and engineers working in industry utilize this to balance rigor with deadlines and the limitations of applicable data. Specialists in fracture mechanics (sometimes referred to as "crack aficionados" by other structural geologists who don't live and breathe fracture mechanics to the same extent) can use sophisticated mathematical, geodetic, and computer analysis techniques to

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pull a greater amount of understanding from the rocks, but for many professional geologists and engineers working in industry, or who may be some years away from their formal academic training, this additional insight may not be necessary. This book will help the reader acquire some basic tools that can help to interpret discontinuity origins, geometries, patterns, and implications using many of the leading or contemporary concepts known to specialists in these areas.

This book is intended to be read and used by geologists and engineers who have had some exposure to the standard principles of structural geology, whether in college-level courses, graduate study, or continuing education. It is not designed as a stand-alone textbook for a class in structural geology or rock mechanics, but it may be used to supplement such a class. Nor should it be regarded as a substitute for formal training at the graduate level for researchgrade work in geologic fracture mechanics. Instead, this book is an attempt to translate many of the major findings of the specialized literature on geologic structural discontinuities for the less specialized geoscientist or engineer.

The main emphasis of the book is *field interpretation of geologic structural discontinuities*. It is hoped that the material will provide a useful template for conceptually matching discontinuity sets on the outcrop with the implied stress states, local conditions, or three-dimensional (3-D) structural geometry, insofar as these are known or can be reasonably inferred from inspection. Equations are introduced and included as needed both to illustrate key concepts and to provide simple yet powerful tools for going deeper than just a simple visual scanning of the outcrop.

The literature bearing on geologic structural discontinuities is vast. References to the literature are inserted as called for in the text. The interested reader will quickly find that the rather extensive references provided are but the tip of the iceberg, so that by studying this book an appreciation of the overall scope, tenor, and terminology of the field may be gained that can facilitate a manageable entry into the realms of geologic fracture mechanics.

In preparing this book I have had to make difficult choices as to depth and rigor of treatment. Many of these choices, made to more succinctly or convincingly access and present the material for the nonspecialist, may challenge the purest researchers in fracture mechanics. Specialists may find other topics and applications here beyond their usual focus, while nonspecialists will perhaps appreciate the level of sophistication available about geologic structural discontinuities and the engineering approaches used to understand them.

The book begins with an overview in Chapter 1 of the main concepts, definitions, and terminology that underlie the interpretation and analysis of fractures, deformation bands, and other structures as mechanical discontinuities in an otherwise effectively continuous rock (or rock mass). The astute reader will note that some liberties from a more traditional approach have been taken which could be said to be justifiable extensions and refinements.

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Many of the key relationships between elastic *stress and strain* that are helpful in dealing with discontinuities in rock are touched on in Chapter 2. Here *rheological terminology* (such as brittle, ductile, elastic, and plastic) that is important in geologic fracture mechanics is also discussed. The important concept of *stress concentration* due to flaws, cavities, fractures, and other kinds of inhomogeneities is also covered in this chapter. Here lies the basis for fracture mechanics and the redistribution of remote stress states—by structural discontinuities—into spatially variable, inhomogeneous stress states that are so important in fractured rock masses.

Chapter 3 provides a non-traditional summary of *stress analysis, peak-strength concepts, frictional sliding* and the Coulomb criterion, tensile failure and the several Griffith criteria, and concepts of *rock-mass classification systems* and *rock-mass strength criteria*—including the important and versatile Hoek–Brown criterion—that provide an understanding of the mechanics of fracturing and associated rock-mass deformation.

Chapter 4 concentrates on *dilatant cracks*—one of the most common types of brittle geologic structure. Because mechanical and rock engineers deal extensively with these types of structural discontinuities, the understanding of the behavior and analysis of cracks is well advanced; additionally, laboratory simulations can reproduce many of the surface textures and discontinuity patterns that are encountered in geology. As a result, this chapter may bear some resemblance to other reviews and treatises on mode-I cracks that already exist. The chapter ends with an overview of anticracks, stylolites, and pure compaction bands. These structures have the opposite sense of displacement to cracks (dissolution and interpenetration of opposing walls across the surface) yet the same direction (normal to the surface). Pressure solution surfaces (in soluble rocks) and compaction bands (in porous rocks) form patterns suggestive of lateral propagation and interaction, making them a form of stress concentrator and discontinuous deformation mechanism in susceptible rock types.

Some of the common discontinuity patterns are examined in Chapter 5. Here we'll start with two *discovery patterns*—echelon discontinuities and end cracks—that can be interpreted by using the basic principles of geologic fracture mechanics including near-tip stress concentration. Other patterns that reveal key principles will be explored including growth of discontinuities into sets, spacing, fault formation, and the Riedel shear patterns that are so commonly observed in soils and soft porous granular rocks.

The extensive topic of faults and faulting is explored in Chapter 6 from the perspective of geologic fracture mechanics. Rather than relying on traditional and well-known means for determining the sense of fault offsets, such as fault-surface textures or offset stratigraphic markers, the use of stepover and fault-tip kinematics is illustrated as an alternative and additional technique for interpreting fault offsets and fault patterns. The context and growth of faults in various systems including Anderson's classification, three-dimensional (3-D)

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strain and polygonal fault sets, crustal strength envelopes, the stress polygon, and critically stressed systems is also discussed.

Chapter 7 presents an introduction to the important class of structures known as *deformation bands*. These tabular structures occur preferentially in porous granular rocks such as sandstones and are critically important as a precursor to faults in many sedimentary rocks and sedimentary basins around the world. Certain types of deformation bands can form barriers to fluid flow, defining compartments against fluid migration (water or petroleum) in the subsurface. Deformation bands display a rich variety of kinematics including opening, shearing, closing, and various combinations of these. Because much of the current theoretical or conceptual framework for deformation bands draws from critical-state soil mechanics and Cam cap-type models of pre-peak yielding, an extended but largely non-mathematical synopsis of this approach and its application to bands in porous granular rocks is included in this chapter.

In Chapter 8 an overview of *linear elastic fracture mechanics* (LEFM) is developed. It includes the ideas that are most important and useful in dealing with geologic structural discontinuities, presented in an order that, as will be seen, differs from the traditional engineering sequence. For example, the displacements and stresses generated in the vicinity of geologic structural discontinuities are emphasized early, because these are what are mapped, measured, and worked with most often in the field. Only toward the end is focus placed on the discontinuity tip, since the LEFM characterization of discontinuity tips as bounded by a negligibly small plastic zone describes actual discontinuity tips in rock only under certain sets of conditions.

The final chapter, Chapter 9, introduces some topics of relevance to the rapidly developing field of geologic fracture mechanics. These include subcritical fracture growth, more realistic (linear and "end-zone") models for discontinuity tips, models of discontinuity propagation, displacement–length scaling relations, discontinuity populations, and brittle strain. The issues chosen for inclusion are under active research in contemporary structural geology, and this chapter may provide a readable entry into these exciting topics.

A *learning map* is included at the end of each chapter. Patterned loosely after a dendrite, learning maps are graphical summaries, limited to a single page, that highlight not only the most important points and concepts covered, but also the logical flow and connections between them. They are an exceptionally useful method for synoptically visualizing and remembering an entire chapter and for helping to place the important details into their larger context.

All chapters have *exercise sets* that encourage the reader to work through the material themselves. Many worked examples within the chapters illustrate the topics being discussed, and answers or helpful hints to selected exercises are provided at the publisher's website, www.cambridge.org/schultz. Many of the chapters and the exercises have been tested by undergraduate and graduate students in courses taught by the author, with modifications made as called

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for. A *glossary* collects definitions of many of the specialized terms used in the book while providing definitions of well-known terms from the perspective of geologic fracture mechanics. Although some of these definitions may challenge traditional ones, their development in the glossary provides an additional approach to exploring the field, assumptions, methods, and utility of geologic fracture mechanics.

I have enjoyed writing this book, and I hope that you will enjoy it too. Learning about geologic fracture mechanics is an odyssey that never ends. It always gets more interesting and more fun—it is never dull or boring. I hope that something in this book spurs you to learn some new material, make new field observations, apply some new concepts, and contribute to this exciting area.

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