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David D. Pollard and Raymond C. Fletcher
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Fundamentals of Structural Geology

Fundamentals of Structural Geology provides a new framework for the investigation of geological structures by integrating field mapping and mechanical analysis. It emphasizes the observational data, modern mapping technology, principles of continuum mechanics, and the mathematical and computational skills, necessary to map, describe, model, and explain deformation in the Earth's lithosphere quantitatively.

Assuming a basic knowledge of physical geology, introductory calculus, and physics, this advanced textbook builds on more traditional courses that emphasize descriptive terminology, geometric techniques, and kinematics. In a significant departure from conventional textbooks on the subject, differential geometry is introduced and applied to quantify descriptions of geological structures. Differential geometry integrates the spatial information conventionally found on maps with orientation data from stereograms to provide reproducible descriptions of geological structures. By starting from the fundamental conservation laws of mass and momentum, the constitutive laws of material behavior, and the kinematic relationships for strain and rate of deformation, the authors demonstrate the relevance of solid and fluid mechanics to structural geology. The constitutive relations used in the book are sufficiently elementary to enable students to gain physical insight from analytical solutions, but are adequately realistic to provide compelling correlations to observational data.

This book offers a modern quantitative approach to structural geology for advanced undergraduate and graduate students and researchers in structural geology and tectonics. It will also interest those working in related disciplines, including geophysics, rock mechanics, field mapping, hydrogeology, petroleum and geotechnical engineering, and natural hazard mitigation. The book is supported by a website (www.cambridge.org/ 0521839270) hosting images from the book, additional colour images, student exercises and MATLAB® scripts. Solutions to the exercises are available to instructors.

DAVID POLLARD is the Morris Professor of Earth Sciences in the Department of Geological and Environmental Sciences at Stanford University where he co-directs the program in Structural Geology and Geomechanics. He and his students are using quantitative field data and principles of structural geology, combined with laboratory and computer modeling, to address questions about processes of faulting, fracturing, and rock deformation. The research aims to understand how faults and fractures evolve in the Earth's crust; how they affect the flow of magma, groundwater, and hydrocarbons; and what role fractures play in earthquake generation and volcanic eruption

RAYMOND FLETCHER is a Research Professor in the Department of Geosciences at the Pennsylvania State University. He and his collaborators study the continuous deformation of rock as in the emplacement of mantled gneiss domes, rock folding, and basin and range necking. He also works on processes linking chemical aspects of mineral growth or dissolution in rocks and deformation. Currently he is studying folding near the base of ice sheets, and the evolution of structures and rheological behavior of composite rock masses.

Fundamentals of Structural Geology

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Preface

Fundamentals of Structural Geology is a textbook that emphasizes modern techniques of field data acquisition and analysis, the principles of continuum mechanics, and the mathematical and computational skills necessary to describe, model, and explain quantitatively the deformation of rock in Earth's lithosphere.

With precise location data now available from the Global Positioning System (GPS) and powerful computer systems now transportable in a backpack, the quantity of reproducible field data has increased dramatically. These new data sets demand better methods for describing the geometry of structures, and we address this demand by introducing the basic concepts of differential geometry, which provide unambiguous descriptions of curved lineations and surfaces in three dimensions. Data sets from a variety of field areas are provided via the textbook website to promote the practice of opening field "notebooks" to the entire community of researchers, and as input for student exercises (see below).

Textbooks in structural geology provide elements of continuum mechanics (e.g. separate chapters on stress and strain), but rarely are these concepts tied together with constitutive laws or formulated into equations of motion or equilibrium to solve boundary or initial value problems. These textbooks largely beg the questions: what methodology should one adopt to solve the problems of structural geology; and what are the fundamental constructs that must be acknowledged and honored? These constructs are the conservation laws of mass, momentum, and energy, combined with the constitutive laws for material behavior and the kinematic relationships for strain and rate of deformation. We use these constructs to build a rational methodology for the investigation of tectonic processes and their structural products.

This textbook is designed for senior undergraduate students and graduate students who have taken an introductory physical geology course, mathematics courses that include differential and integral calculus in several variables, and a physics course covering mechanics and heat. We consider these courses to be the essential mathematical and scientific pre-requisites for a course using this textbook. Elementary concepts of vector analysis, matrix theory, linear algebra, ordinary and partial differential equations, and computer programming with MATLAB® are used throughout, but are introduced in such a way that a formal course in these subjects, while helpful, should not be considered a pre-requisite. The authors view this textbook as appropriate for a first course in structural geology, but recognize that many students will come to a course using this book after a traditional course that emphasizes the descriptive terminology, geometric techniques, and kinematic concepts of the discipline.

Although designed as a text for students, this book also should be useful as a reference for researchers in structural geology, and as an aid for updating instructors and professionals who have been exposed only to traditional courses and textbooks on the subject. Furthermore, this book should be attractive to scientists in related disciplines (geophysics, rock mechanics, tectonics, geotechnical engineering, and petroleum engineering) who are looking for a modern summary of the fundamentals of structural geology. We encourage students and professionals from these disciplines to learn about the modern methods and tools of structural geology so that they can effectively interact with geologists on multi-disciplinary projects.

One of the opportunities and challenges of publishing a textbook in the twenty-first century is the fact that the printed volume is no longer the only vehicle for communication between authors and readers. Accordingly, we have prepared a homepage for *Fundamentals of Structural Geology* that is available on the World Wide Web (www.cambridge.org/0521839270) and provides the following supplementary materials for readers, instructors, and students:

- Full color images for all outcrop photographs used in the text

- Full color images for key graphical results used in the text
- Supplementary outcrop photographs, maps, and cross sections
- A repository for supplementary images contributed by readers
- Exercises for students that reinforce the concepts introduced in the text
- Data sets from field mapping campaigns for use in the exercises
- Solutions to the exercises for instructors with password protection
- Sample MATLAB® m-files for the exercises
- Sample MATLAB® m-files for recreation of graphical figures found in the text
- A repository for exercises and MATLAB® m-files contributed by readers
- Errata

With a laptop connected to the Web and an LCD projector instructors can use the color outcrop images in the classroom to illustrate geological concepts, and run the m-files with their own choice of parameters for a dynamic demonstration of the mechanical concepts. We envision readers of the textbook having this website open on their desktop to enhance their learning experience. Today desktop PCs provide the necessary CPU power, 3D graphics cards provide the visualization environment and speed, and professional programmers have written applications such as MATLAB® that provide most of the computational tools needed by structural geologists.

For the authors of this textbook, it is not sufficient to focus on understanding the structural history of the Earth as an arcane academic exercise. We believe that structural geologists can make important contributions in natural resource recovery (including water, oil, gas, and minerals), in the assessment of natural hazards (including earthquakes, landslides, and volcanic eruptions), and in the management of the environment (for example the long-term storage of radioactive materials and the contamination of fractured aquifers by hazardous chemicals). It is the authors' hope that students and instructors alike will be as captivated as we have been by the remarkable opportunities and challenges of structural geology. Great satisfaction in the practice of this science is achieved when one successfully brings together the beauty of the natural world and the physical world of continuum mechanics to achieve a better understanding of rock deformation and the development of structures. By doing so one contributes to the knowledge of Earth's remarkable history and to the solution of important practical problems facing society today.

Acknowledgments

David Pollard would like to acknowledge four teachers who shaped his understanding of structural geology as an undergraduate and graduate student. Donald B. McIntyre of Pomona College provided the spark that ignited his curiosity about the subject and put it in an historical context. Arvid M. Johnson of Stanford University introduced him to the tools of mechanics and to a rational way to approach physical processes in the field and laboratory. John G. Ramsay of Imperial College taught him how to measure deformation in outcrop and investigate the geometry and kinematics of rock subject to ductile deformation. Neville J. Price of Imperial College introduced him to rock mechanics and the analysis of rock subject to brittle deformation. These teachers provided a diversity of viewpoints of structural geology that was fascinating as well as challenging, and the origins of many of the themes played out in this textbook can be traced directly to their classrooms. Arvid Johnson's role in the formative stages of work on the textbook was particularly important.

David Pollard was privileged to study with students who were colleagues at Pomona College, Stanford University, and Imperial College, and later to work with students in a teaching and advisory capacity at the University of Rochester, the US Geological Survey (Menlo Park), and Stanford University. Many of these students have participated in research that helped to shape the concepts and methods described in this book. They include: Atilla Aydin, Ze'ev Reches, Gary R. Holzhausen, John W. Cosgrove, Otto H. Muller, David R. Dockstader, Paul T. Delaney, Paul Segall, Jon H. Fink, J. Russell Dyer, Russell K. Davies, Laurie L. Erickson, Marie D. Jackson, Peter C. Wallmann, Stephen J. Martel, Allan M. Rubin, Larry G. Mastin, Jon E. Olson, Sarah D. Saltzer, Scott S. Zeller, Andrew L. Thomas, Carl E. Renshaw, Roland Bürgmann, Pauline M. Mollema, Marco Antonellini, Haiqing Wu, Peter P. Christiansen, Stephen K. Mathäi, Joshua J. Roering, J. Ramón Arrowsmith, George Hilley, Emanuel J. M. Willemse, Michele L. Cooke, Elissa Koenig, Juliet G. Crider, W. Lansing Taylor, Simon A. Kattenhorn, Taixu Bai, Laurent Maerten, Scott S. Young, Frantz Maerten, Stephan Bergbauer, Peter Eichhubl, Phillip G. Resor, Kurt R. Sternlof, Patricia E. Fiore, Ian W. Mynatt, W. Ashley Griffith, Nicolas Bellahsen, Gaurav Chopra, and J. Ole Kaven.

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Raymond Fletcher would like to acknowledge several people who contributed to his education as a structural geologist. William F. Brace (MIT) awarded him a C in the undergraduate structural geology course, giving useful incentive for further study of a subject that Bill's treatment showed to consist of an intriguing combination of field observation and mechanical analysis. Bill Brace also gave excellent advice on what not to do as a Ph.D. research project prior to the arrival at Brown University of his Ph.D. advisor William M. Chapple. Bill Chapple provided guidance in formulating a tractable complete mechanical model for the emplacement of a gneiss dome and M. A. Jaswon pointed him toward a method of analysis. Interaction with Bill Chapple over many years continued to enrich his experience. The foundation for his understanding of continuum mechanics was provided by the lucid presentation of this subject in a two-semester course at Brown University by E. T. Onat. Arvid M. Johnson introduced him to the disciplined mapping of small-scale structures in the field interspersed with more freewheeling discussions of mechanical modeling. Memorable discussions over coffee and pastry with Bernard Hallet continue to provide him with imaginative ideas, such as treating the Basin-and-Range Province as a string of blood sausages. He has benefited from and enjoyed collaborations with former graduate students Judi Chester, Russell Davies, Jon Fink, George Gazonas, Bill Kilsdonk, Frank Irwin, Duncan Mardon, and Tom Patton.