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978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
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Frontmatter
More Information

Structural Geology:
A Quantitative Introduction

Tackling structural geology problems today requires a quantitative understanding of the underlying physical principles, and the ability to apply mathematical models to deformation processes within the Earth.

Accessible, yet rigorous, this unique textbook demonstrates how to approach structural geology quantitatively using calculus and mechanics, and prepares students to interface with professional geophysicists and engineers who appreciate and utilize the same tools and computational methods to solve multidisciplinary problems. Clearly explained methods are used throughout the book to quantify field data, set up mathematical models for the formation of structures, and compare model results to field observations.

An extensive online package of coordinated laboratory exercises enables students to consolidate their learning and put it into practice by analyzing structural data and building insightful models. Designed for single-semester undergraduate courses, this pioneering text prepares students for graduates studies and careers as professional geoscientists.

David D. Pollard is a Professor Emeritus in Geology at Stanford University. He holds a Ph.D. in Geology from Stanford University and a Diploma of Imperial College (University of London). He has been on the faculty at Stanford since 1983, where he taught an undergraduate course in structural geology from which this textbook emerged. He co-authored *Fundamentals of Structural Geology*, published by Cambridge University Press in 2005, which won the Best Publication of the Year Award from the Structural Geology and Tectonics Division of the Geological Society of America in 2007. He is a Fellow of the Geological Society of America and the American Geophysical Union.

Stephen J. Martel is a Professor in Earth Sciences at the University of Hawai'i. He holds a Ph.D. in Applied Earth Sciences from Stanford University. Since joining the faculty in Hawai'i in 1992, he has taught both structural geology and engineering geology. He previously worked at the Bureau of Economic Geology at The University of Texas at Austin, and at Lawrence Berkeley National Laboratory. Particular research interests include landslides, nuclear waste disposal, neotectonics, fault mechanics, rock fracture, detailed geologic mapping, and the influence of topography on stresses in rock masses. He is a Fellow of the Geological Society of America.

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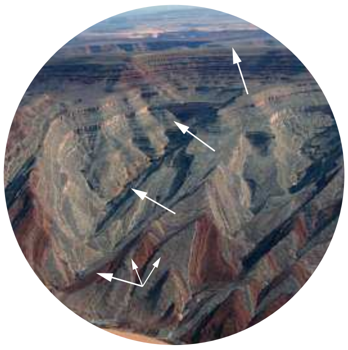
Frontmatter
More Information



Structural Geology

A Quantitative Introduction

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University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

79 Anson Road, #06–04/06, Singapore 079906

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www.cambridge.org
Information on this title: www.cambridge.org/9781107035065
DOI: 10.1017/9781139547222

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First published 2020

Printed in Singapore by Markono Print Media Pte Ltd

A catalogue record for this publication is available from the British Library.

ISBN 978-1-107-03506-5 Hardback

Additional resources for this publication at www.cambridge.org/SGAQI.

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CAMBRIDGE

Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

CONTENTS

CAMBRIDGE

Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

Contents

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Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

PART IV

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978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

Contents

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CAMBRIDGE

Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

BOXES

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SYMBOLS

$\mathbf{a}$	acceleration vector
α	azimuth angle (Greek alpha)
$\mathbf{b}$	Burgers vector for a dislocation
B	bending modulus for a thin elastic layer
$\mathbf{c}(t)$	parametric representation of a curved line; a vector-valued function of the arbitrary parameter t
c	specific heat capacity
C_t	conventional triaxial compressive strength
C_u	uniaxial compressive strength
CPO	Crystallographic Preferred Orientation
D_c	differential strength in compression
$d\mathbf{c}$	differential tangent vector to a curved line
df	total differential of a scalar function $f(x, y, z)$
$\frac{Df}{Dt}$	material time derivative of a scalar function $f(x, y, z, t)$
$\vec{\nabla} f$	gradient of a scalar function $f(x, y, z)$; a vector
$\nabla \mathbf{v}$	gradient of a vector function $\mathbf{v}(x, y, z)$; a tensor
Δp, ΔP	driving pressure (Greek capital delta)
$\Delta\sigma$	differential stress
$\Delta\sigma_I$, $\Delta\sigma_{II}$,	driving stress for mode I, mode II fracture
$\Delta\mathbf{u}$	displacement discontinuity vector
Δx, Δy, Δz	lengths of the edges of a volume element
$\bar{D}$	sample mean
$\mathbf{D}$	rate of deformation tensor; rate of stretch tensor
$\mathbf{D}'$	deviatoric rate of deformation tensor
DEM	Digital Elevation Model
EBSD	Electron Backscatter Diffraction
E	Young's modulus of elasticity
E, N, U	geographic coordinates: East, North, Up
E, F, G	coefficients of the first fundamental form for a curved surface
$\mathbf{E}$	Lagrangian finite strain tensor
$\begin{matrix} E_{xx} & E_{xy} & E_{xz} \\ E_{yx} & E_{yy} & E_{yz} \\ E_{zx} & E_{zy} & E_{zz} \end{matrix}$	components of the Lagrangian finite strain tensor
$\underset{3\times3}{[\mathrm{E}]}$	matrix form of the Lagrangian finite strain tensor
[=]	"has units"
{=}	"has dimensions"
$\boldsymbol{\varepsilon}$	small strain tensor (Greek epsilon)
$\begin{matrix} \varepsilon_{xx}, \varepsilon_{xy}, \varepsilon_{xz} \\ \varepsilon_{yx}, \varepsilon_{yy}, \varepsilon_{yz} \\ \varepsilon_{zx}, \varepsilon_{zy}, \varepsilon_{zz} \end{matrix}$	components of the small strain tensor
$\underset{3\times3}{[\varepsilon]}$	matrix form of the small strain tensor
$\dot{\varepsilon}$	rate of axial strain
f_{H_2O}	fugacity of water
$\mathbf{f}$, $\mathbf{F}$	force vector

Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

$\mathbf{F}_{\text{grav}}$	gravitational body force vector
$\mathbf{F}_{\text{buoy}}$	buoyant body force vector
$\mathbf{F}$	spatial gradient of deformation tensor
$\frac{\partial x}{\partial X}\ \frac{\partial x}{\partial Y}\ \frac{\partial x}{\partial Z}$ $\frac{\partial y}{\partial X}\ \frac{\partial y}{\partial Y}\ \frac{\partial y}{\partial Z}$ $\frac{\partial z}{\partial X}\ \frac{\partial z}{\partial Y}\ \frac{\partial z}{\partial Z}$	components of the gradient of deformation tensor
$\underset{3\times3}{[\mathrm{F}]}$	matrix form of the gradient of deformation tensor
$\mathbf{g}$	acceleration of gravity vector
$\mathbf{g}^*$	representative acceleration of gravity vector for the lithosphere
g_x^*, g_y^*, g_z^*	components of the representative gravity acceleration vector
G	shear modulus of elasticity
$\mathbf{G}$	displacement gradient tensor
$\frac{\partial u_x}{\partial X}\ \frac{\partial u_x}{\partial Y}\ \frac{\partial u_x}{\partial Z}$ $\frac{\partial u_y}{\partial X}\ \frac{\partial u_y}{\partial Y}\ \frac{\partial u_y}{\partial Z}$ $\frac{\partial u_z}{\partial X}\ \frac{\partial u_z}{\partial Y}\ \frac{\partial u_z}{\partial Z}$	Cartesian components of the displacement gradient tensor
$\underset{3\times3}{[\mathrm{G}]}$	matrix form of the displacement gradient tensor
GPS	Global Positioning System
η	Newtonian viscosity (Greek eta)
I	first fundamental form for a curved surface
II	second fundamental form for a curved surface
[I]	identity matrix
$\hat{\mathbf{i}}, \hat{\mathbf{j}}, \hat{\mathbf{k}}$	base vectors for the Cartesian coordinate system
k	thermal conductivity
$\mathbf{k}$	curvature vector for a curved line
kg	kilogram; base unit for mass in SI
K	kelvin; base unit for temperature in SI
$K_{\text{I}}, K_{\text{II}}, K_{\text{III}}$	mode I, mode II, and mode III stress intensity
K_{IC}	mode I fracture toughness
κ	scalar curvature for a curved line (Greek kappa)
κ	thermal diffusivity
κ_{n}	normal curvature of a curved surface
κ_1, κ_2	principal values (eigenvalues) of normal curvature for a curved surface
κ_{g}	Gaussian curvature
κ_{m}	mean normal curvature
L	length dimension
$\mathbf{L}$	spatial gradient of velocity tensor
$\frac{\partial v_x}{\partial x}\ \frac{\partial v_x}{\partial y}\ \frac{\partial v_x}{\partial z}$ $\frac{\partial v_y}{\partial x}\ \frac{\partial v_y}{\partial y}\ \frac{\partial v_y}{\partial z}$ $\frac{\partial v_z}{\partial x}\ \frac{\partial v_z}{\partial y}\ \frac{\partial v_z}{\partial z}$	components of the spatial gradient of velocity tensor
$\underset{3\times3}{[\mathrm{L}]}$	matrix form of the spatial gradient of velocity tensor
L, M, N	coefficients of the second fundamental form for a curved surface
LNB	Level of Neutral Buoyancy

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CAMBRIDGE

Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

λ, λ_o	current and initial wavelength of a buckled layer (Greek lambda)
λ	Lame's constant of elasticity (Greek lambda)
Λ	bulk viscosity (Greek capital lambda)
m	meter; base unit for length in SI
m	mass
M	mass dimension
M	bending moment on the cross section of a thin layer
$\mathrm{M_0}$	seismic moment
$\mathrm{M_w}$	seismic moment magnitude
μ_i	coefficient of internal friction (Greek mu)
μ_c	coefficient of friction
$\hat{\mathbf{n}}$	unit normal vector
$\hat{\mathbf{N}}$	unit normal vector to a surface
ν	Poisson's ratio of elasticity (Greek nu)
[O]	shape operator for a curved surface
p	pressure, thermodynamic pressure
$\bar{p}_o$	pressure in a static liquid
$\bar{p}$	mean normal pressure in a flowing liquid
P_c	confining pressure in a conventional triaxial test
P_p	pore fluid pressure
p, x, X	position vectors
$\vec{PQ}$	vector from point P to point Q
ϕ	inclination angle (Greek phi)
ϕ	angle of shearing
Φ	Airy stress function (Greek capital phi)
Ψ	Stokes stream function (Greek capital psi)
q	fold limb slope amplification factor
q	heat flux vector
Q	activation energy
Q	volume flow rate
r, θ, ϕ	spherical coordinates (Greek theta, phi)
R	universal gas constant
R	flexural rigidity of a bending elastic layer
Re	Reynolds number
R	pure rotation tensor
U	pure stretch tensor
ρ	mass density (Greek rho)
ρ	radius of curvature of a curved line
ρ_d	dislocation density
s	second; base unit for time in SI
s	estimated standard deviation
s^2	estimated variance
s	spherical variance
SI	International System of Units
S	stretch tensor
S_1, S_2, S_3	principal values of the stretch tensor
S	shear force on the cross section of a thin layer

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CAMBRIDGE
Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

S_o	inherent shear strength
S_f	frictional strength
$\mathbf{s}(u, v)$	parametric representation of a curved surface; vector-valued function of the arbitrary parameters u and v
SfM	Structure from Motion
$\boldsymbol{\sigma}$	stress tensor (Greek sigma)
$\sigma_{xx}, \sigma_{xy}, \sigma_{xz}$ $\sigma_{yx}, \sigma_{yy}, \sigma_{yz}$ $\sigma_{zx}, \sigma_{zy}, \sigma_{zz}$	Cartesian components of the stress tensor
$\underset{3\times3}{[\sigma]}$	matrix form of the stress tensor
σ_1, σ_2, σ_3	principal values (eigenvalues) of the stress tensor
$\hat{\mathbf{l}}, \hat{\mathbf{m}}, \hat{\mathbf{n}}$	principal vectors (eigenvectors) of the stress tensor
$\underset{3\times3}{[\sigma']}$	matrix form of the deviatoric stress tensor
$\underset{3\times3}{[\sigma^e]}$	matrix form of the effective stress tensor
σ_{ys}, k	yield strength
σ_s	maximum shear stress
t	time
t	arbitrary parameter for a curved line
$\mathbf{t}$	traction vector acting on a surface
$\mathbf{t}$	tangent vector for a dislocation line
$\hat{\mathbf{t}}$	unit tangent vector
T	temperature
T	time dimension
T_u	uniaxial tensile strength
$\mathbf{T}$	tangent vector to curve
$\theta_{\mathbf{v}\hat{\mathbf{i}}}, \theta_{\mathbf{v}\hat{\mathbf{j}}}, \theta_{\mathbf{v}\hat{\mathbf{k}}}$	direction angles between vector **v** and base vectors (Greek theta)
$\cos\theta_{\mathbf{v}\hat{\mathbf{i}}}$, $\cos\theta_{\mathbf{v}\hat{\mathbf{j}}}$, $\cos\theta_{\mathbf{v}\hat{\mathbf{k}}}$	direction cosines of direction angles
θ_c	Coulomb angle; orientation of potential shear fractures
Θ	temperature dimension (Greek capital theta)
u, v	arbitrary parameters for curved surface
$\mathbf{u}$	displacement vector
u_x, u_y, u_z	components of the displacement vector
$\underset{1\times3}{[\mathrm{u}]}$	matrix form of the displacement vector
UTM	Universal Transverse Mercator projection
UDF	undefined angle
$\mathbf{v}$	velocity vector
v_x, v_y, v_z	components of the velocity vector
$\underset{1\times3}{[\mathrm{v}]}$	matrix form of the velocity vector
$\mathbf{W}$	rate of spin tensor; vorticity tensor
x, y, z	Cartesian coordinates
ω_x, ω_y, ω_z	small rotation angles (Greek omega)
$\boldsymbol{\Omega}$	small rotation tensor (Greek capital omega)

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CAMBRIDGE

Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

PREFACE

Structural geology is a core course in the curriculum for undergraduate students majoring in Geology at the college and university level. Usually, structural geology is a junior or senior level course, taken after students complete introductory and core courses in geology and the supporting courses in mathematics and physics that are appropriate for a major in the *science* part of a more broadly conceived Science, Technology, Engineering, and Mathematics (STEM) curriculum. This textbook is an *introduction* to structural geology for the undergraduate major that builds upon those formative geology courses, and makes extensive use of the relevant concepts and tools from the supporting courses in mathematics and physics.

This textbook also is appropriate for geology students whose first course in structural geology was primarily descriptive and qualitative. In addition, the quantitative approach used here has proven to be accessible and useful for students from other disciplines, such as geophysics, petroleum engineering, and civil engineering, who are likely to be working with structural geologists in their professional careers. Both authors have welcomed students from other disciplines in their structural geology courses, and both have found that these students enrich the experience for the geology students.

Although this textbook is a first course in structural geology, it takes a decidedly different approach to the subject matter than other "first course" textbooks, which focus on descriptions of structures and *qualitative* explanations for their formation. Our goal is to provide a balance between description and analysis of structures, so we offer *quantitative* explanations for their formation, based on the physics of deformation. Despite this difference in approach, the topics we cover are similar to those in other "first course" textbooks. For example, chapters are devoted to the basic categories of geologic structures including fractures, faults, folds, fabrics, and intrusions. However, the shift to a quantitative treatment of the formation of structures necessarily relies on more equations to build the student's knowledge base. We find that carefully labeled diagrams complement the equations substantially, so we include many diagrams in the textbook.

The mathematical pre-requisite for this book is a course in calculus that includes differential calculus and integral calculus of functions of one variable. Some calculus courses include analytic geometry and vector calculus, while others introduce aspects of linear algebra. Some of the elementary concepts from analytic geometry, vector calculus, and linear algebra are used in this textbook, but they are at a level that does not require a pre-requisite course. Instead, we introduce the necessary concepts and motivate readers to learn them by offering direct applications to structural geology.

The differential calculus of more than one variable is used throughout the book, but a course in multivariate calculus is not considered a pre-requisite. We introduce the few necessary extensions from differential calculus of one variable to multiple variables, including the partial derivative, the gradient vector, and the material time derivative. Finally, although differential equations appear throughout the book, a course in ordinary and partial differential equations is not a pre-requisite. Differential equations appear solely for displaying the underlying physical concepts and relationships. Solutions are provided where they illustrate applications to structural geology, but solution methods are left to more advanced textbooks and courses.

We recognize that some college and university students struggle with spatial thinking tasks encountered in their first structural geology class. They are challenged to learn to "think in 3D." The authors of this textbook have found that a modern graphical user interface and a computational engine like MATLAB provide many helpful tools and needed support for this learning process. Scripts with dynamic three-dimensional graphical output are run, modified, and rerun using MATLAB to obtain spatial feedback, to alter incorrect mental models, and to build intuition. These tools, along with an elementary understanding of vector calculus and differential geometry, open the door for thinking in 3D.

The goal of this textbook is to build confidence in students that they know not only what the common geologic structures are, and how to name, describe, and map them, but they also know how to apply a set of fundamental physical principles of deformation to explain the origins of these structures. To promote this goal, most of the analyses in this book follow a *step-by-step* procedure, starting with the most basic principles and leading to a result that can be compared to observations or data. This approach results in many equations, but each of them adds incrementally to the mathematical derivations, and to understanding

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Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

the physics of the tectonic processes. Memorization of equations is not the authors' objective for this book. Instead, we advocate *reading* the equations as an integral part of the text to build confidence and understanding.

Commitment to the step-by-step procedure described in the previous paragraph presented the authors with a significant challenge. If we analyzed all of the structures described in other "first course" textbooks, this book would be too big for a typical first course. Instead, we selected a subset of those structures that admit an analysis at the introductory level. As a consequence, this textbook is *tutorial rather than encyclopedic*. For each of the five categories of structures we identify a "canonical problem" that illuminates the underlying physics and provides a template for the student to use in the analysis of other similar structures. The canonical problems also are the building blocks for developing a sound physical intuition that should help students analyze other structures in the future.

Each chapter of this textbook ends with a section on Further Reading. This is aimed at students who desire to expand their horizons and delve into related textbooks, monographs, and review papers. The Further Reading section also provides faculty with resources for enriching their lectures and conversations with students. The books and review papers listed in these sections would form a good working library for a practicing structural geologist in academia, industry, or a government laboratory.

This textbook contains abundant color photographs of outcrops, hand samples, and thin sections. These, and all the diagrams, graphs, and maps are freely available for instructors and students to download for teaching and learning purposes from the textbook website: www.cambridge.org/SGAQI. This material comes largely from the senior author's photographic collection, and from the Ph.D. theses and published papers of his students. The choice to use "in house" graphical material, data, maps, and analysis results was made because of accessibility and familiarity. We encourage instructors to provide their students with materials from their own collections, and to enrich their courses with results from their own research. Also available from this website are the .kmz files referred to in the captions of selected figures, so readers can take virtual field trips to these outcrops and map areas using Google Earth.

The book is supported by online student exercises, which are also available at the website given above. Students are encouraged to work through the online exercises after reading and addressing the chapter review questions. For many of the online exercises, students write MATLAB® scripts to solve quantitative problems and present graphical results. Other online exercises ask students to derive key mathematical relationships using paper and pencil. Solutions for selected online exercises and sample MATLAB® scripts are available to instructors for download.

This textbook was originally conceived as one of a pair of books by the authors; the other being a Lab Manual of practical and field-based instruction together with student exercises and activities. Writing of the Lab Manual is underway and we anticipate that it will be published within the next year or two. In the meantime, we intend to post some of the draft exercises and activities at www.cambridge.org/SGAQI so that instructors can start testing them out in their classes. These include introductory exercises for mapping, orthographic projections, stereonets and three-point problems, rotations and cross sections. Please continue to check back to the website regularly for new materials. We welcome any feedback on any of the online resources posted there.

This textbook has four parts. Part I (Chapter 1) summarizes the scope of structural geology. Part II (Chapters 2 and 3) reviews and summarizes the mathematical tools and physical principles used in this textbook. Part III (Chapters 4–6) covers the three major styles of deformation: brittle, ductile, and viscous. Part IV (Chapters 7–11) covers the five broad categories of geologic structures: fractures, faults, folds, fabrics, and intrusions. For each category we introduce the canonical model for that structure and derive the resulting stress, strain, displacement, or velocity fields.

This textbook contains more material than could reasonably be presented in a one-quarter or one-semester course. At Stanford University, the senior author developed the following schedule for a one-quarter (10 week, 20 lecture) course:

- Chapter 1 – lecture 1
- Chapter 2 – lectures 2 and 3
- Chapter 3 – lectures 4 and 5
- Chapter 4 – lectures 6, 7, and 8
- Chapter 6 – lectures 9, 10, and 11
- Chapter 7 – lectures 12, 13, and 14
- Chapter 8 – lectures 15, 16, and 17
- Chapter 11 – lectures 18, 19, and 20

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CAMBRIDGE

Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

This selection emphasizes brittle and viscous deformation and uses fractures, faults, and intrusions as the representative structures. An alternative selection substitutes Chapters 5 and 10 for Chapters 6 and 11, and thereby includes ductile deformation and rock fabrics instead of viscous deformation and intrusions. Another alternative is to be more selective within chapters and cover more deformation styles and structures, while omitting some of the analyses.

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CAMBRIDGE

Cambridge University Press
978-1-107-03506-5 — Structural Geology: A Quantitative Introduction
David D. Pollard , Stephen J. Martel
Frontmatter
More Information

ACKNOWLEDGEMENTS

David Pollard thanks the students who enrolled in his course at Stanford University and provided valuable motivation and feedback for developing his lecture notes into a textbook. He also thanks the Ph.D. students and colleagues who carried out research with him and provided materials that appear here as graphical data, diagrams, photographs, and maps. These students and colleagues shared the pleasures of discovering new structures in the field, mapping structures with many different high-tech instruments, and solving boundary and initial value problems of continuum mechanics using both analytical and numerical models to reveal new insights about structures. He especially thanks his co-author, Steve Martel, for many enjoyable Skype conversations about the manuscript, and for countless exchanges of edited drafts that eventually grew into the published book.

Steve Martel is fortunate to have had the privilege to learn from, and work with, David Pollard and many of his graduate students at Stanford University. He also is grateful for the wonderful opportunity to work with many undergraduate and graduate students at the University of Hawai'i, as well as colleagues there and around the world. The ongoing collaborative experience of trying to understand the world better through a combination of new discoveries and the use of tools developed by our forerunners has been fascinating, humbling, and rewarding.

The authors thank Richard Stultz for helping to set up the tabletop experiments used to illustrate the mechanical behavior of materials in Chapters 4, 5, 6, and 9, and for his expertise in taking and editing the photographs of these experiments. The authors also thank Ryan McCarty for his expertise in digitizing, colorizing, and editing all the maps and many of the diagrams. His graphics skill and artistry have added a significant dimension to the textbook. David Pollard thanks Professors Bernard Hallet and Darrel Cowan of the Department of Earth and Space Sciences, University of Washington, for hosting his sabbatical in 2010, during which the outlines of this textbook emerged.

Finally, we thank those scientists and engineers who, in past generations, laid down the cornerstones of continuum mechanics, and those philosophers who established the self-correcting methodology of science advocated in this textbook that compensates for human fallibility, technological innovation, and random discovery. Using that methodology we may, in the words of Charles S. Peirce, confidently "pile the ground before the foot of the outworks of truth with the carcasses of this generation, and perhaps of others to come after it, until some future generation, by treading on them, can storm the citadel" (Peirce, 2011).

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