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Structural Geology

Lavishly illustrated in color, this textbook takes an applied approach to introduce undergraduate students to the basic principles of structural geology. The book provides unique links to industry applications in the upper crust, including petroleum and groundwater geology, which highlight the importance of structural geology in exploration and exploitation of petroleum and water resources. Topics range from faults and fractures forming near the surface to shear zones and folds of the deep crust. Students are engaged through examples and parallels drawn from practical everyday situations, enabling them to connect theory with practice. Containing numerous end-of-chapter problems, e-learning modules, and with stunning field photos and illustrations, this book provides the ultimate learning experience for all students of structural geology.

Haakon Fossen is Professor of Structural Geology at the University of Bergen, Norway. His professional career has also involved work as an exploration and production geologist/geophysicist for Statoil and periods of geologic mapping and mineral exploration in Norway. His research ranges from hard to soft rocks and includes studies of folds, shear zones, formation and collapse of the Caledonian Orogen, numerical modeling of deformation (transpression), the evolution of the North Sea rift, and studies of deformed sandstones in the western United States. He has conducted extensive field work in various parts of the world, notably Norway, Utah/Colorado and Sinai, and his research is based on field mapping, microscopy, physical and numerical modeling, geochronology and seismic interpretation. Professor Fossen has been involved in editing several international geology journals, has authored over 100 scientific publications, and has written two books and several book chapters. He has taught undergraduate structural geology courses for over fifteen years and has a keen interest in developing electronic teaching resources to aid student visualization and understanding of geologic structures.

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Contents

HOW TO USE THIS BOOK

Each chapter starts with a general **introduction**, which presents a context for the topic within structural geology as a whole. These introductions provide a roadmap for the chapter and will help you to navigate through the book.

BOX 4.2 | VECTORS, MATRICES AND TEN

A scalar is a real number, reflecting temperature, mass
no direction. A vector has both magnitude (length) ar
or velocity. A matrix is a two-dimensional array of nu
meaning that they have 9 or 4 components). Matrices
The term tensor is, in rock mechanics, applied to v
scalars as tensors of order zero, vectors as first-orde
Hence, for our purposes, the terms matrix and seco
cases where numbers are arranged in matrices that

The main text contains **highlighted terms** and **key expressions** that you will need to understand and become familiar with. Many of these terms are listed in the **Glossary** at the back of the book. The Glossary allows you to easily look up terms whenever needed and can also be used to review important topics and key facts. Each chapter also contains a series of **highlighted statements** to encourage you to pause and review your understanding of what you have read.

Most chapters have one or more **boxes** containing in-depth information about a particular subject, helpful examples or relevant background information. Other important points are brought together in the **chapter summaries. Review questions** should be used to test your understanding of the chapter before moving on to the next topic. **Answers** to these questions are given on the book's web-page.

Review questions

1. When is it appropriate to use the term pressure in geology?
2. How can we graphically visualize the state of stress in two and thr
3. Where could we expect to find tensile stress in the crust?
4. How will the shape and orientation of the stress ellipsoid change system?
5. Will the stress tensor (matrix) look different if we choose a differe
6. A diagonal tensor has numbers on the diagonal running from the with all other entries being zero. What does a diagonal stress tens

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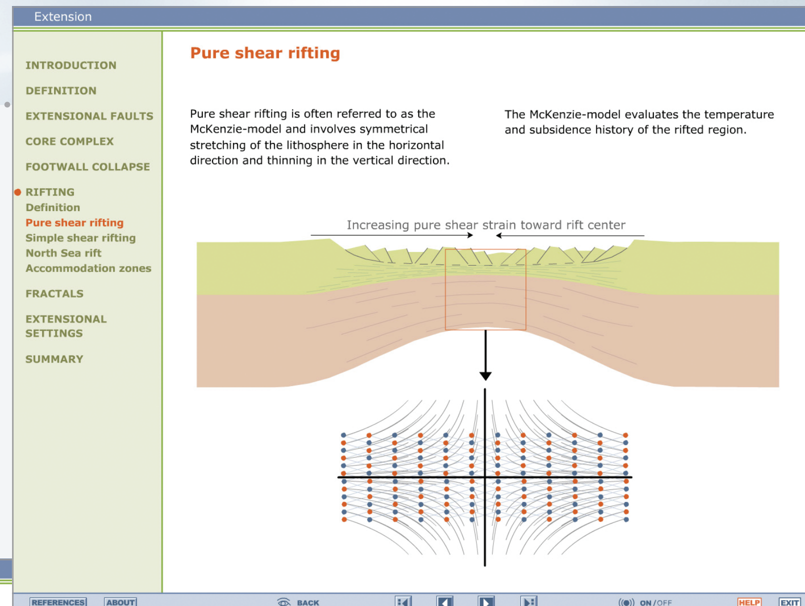

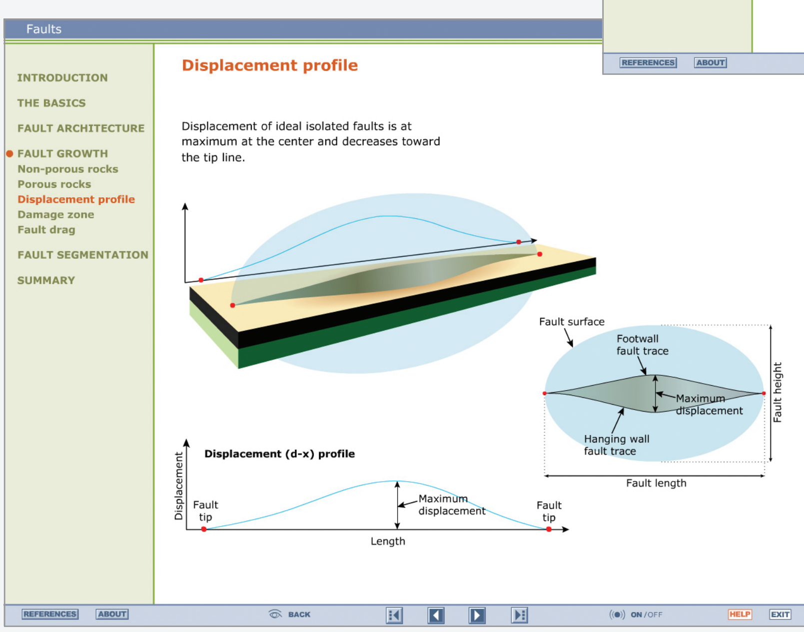

Further reading sections provide references to selected papers and books for those interested in more detailed or advanced information. In addition, there are links to web-based **e-learning modules** at the end of the chapters. Using these modules is highly recommended after reading the chapter as part of review and exam preparation. The modules provide supplementary information that complements the main text.

Web-based resources

Specially prepared resources, unique to this book, are available from the book's web-page: www.cambridge.org/fossen. These are:

- Flash based e-learning modules that combine animations, text, illustrations and photographs. These present key aspects of structural geology in a highly visual and interactive environment.
- All of the figures for each chapter as jpeg files for use by instructors and readers.
- Supplementary figures illustrating additional geologic structures and field examples.
- Answers to the review questions presented at the end of each chapter.
- Additional exercises and solutions.
- A repository for further images, animations, videos, exercises and other resources provided by readers and instructors as a community resource.

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Preface

This textbook is written to introduce undergraduate students, and others with a general geologic background, to basic principles, aspects and methods of structural geology. It is mainly concerned with the structural geology of the crust, although the processes and structures described are relevant also for deformation that occurs at deeper levels within our planet. Further, remote data from Mars and other planets indicate that many aspects of terrestrial structural geology are relevant also beyond our own planet.

The field of structural geology is very broad, and the content of this book presents a selection of important subjects within this field. Making the selection has not been easy, knowing that lecturers tend to prefer their own favorite aspects of, and approaches to, structural geology, or make selections according to their local departmental course curriculum. Existing textbooks in structural geology tend to emphasize the ductile or plastic deformation that occurs in the middle and lower crust. In this book I have tried to treat the frictional regime in the upper crust more extensively so that it better balances that of the deeper parts of the crust, which makes some chapters particularly relevant to courses where petroleum geology and brittle deformation in general are emphasized.

Obtaining this balance was one of several motivating factors for writing this book, and is perhaps related to my mixed petroleum geology and hard-rock structural geology experience. Other motivating factors include the desire to make a book where I could draw or redraw all of the illustrations and be able to present the first full-color book in structural geology. I also thought that a fundamental structural geology text of the twenty-first century should come with specially prepared e-learning resources, so the package of e-learning material that is presented with this book should be regarded as part of the present book concept.

Book structure

The structure of the book is in many ways traditional, going from strain (Chapters 2 and 3) to stress (Chapters 4 and 5) and via rheology (Chapter 6) to brittle deformation (Chapters 7 and 8). Of these, Chapter 2 contains material that would be too detailed and advanced for some students and classes, but selective reading is possible. Then, after a short introduction to the microscale structures and processes that distinguish crystal-plastic from brittle deformation (Chapter 10), ductile deformation structures such as folding, boudinage, foliations and shear zones are discussed (Chapters 11–15). Three consecutive chapters then follow that are founded on the three principal tectonic regimes (Chapters 16–18) before salt tectonics and restoration principles are presented (Chapters 19 and 20). A final chapter, where links to metamorphic petrology as well as stratigraphy are drawn, rounds off the book, and suggests that structural geology and tectonics largely rely on other disciplines. The chapters do not have to be read in numerical order, and most chapters can be used individually.

Emphasis and examples

The book seeks to cover a wide ground within the field of structural geology, and examples presented in the text are from different parts of the world. However, pictures and illustrations from a few geographic areas reappear. One of those is the North Sea rift system, notably the Gullfaks oil field, which I know quite well from my years with the Norwegian oil company Statoil. Another is the Colorado Plateau (mostly Utah), which over the last two decades has become one of my favorite places to do field work. A third, and much wetter and greener one, is the Scandinavian Caledonides. From this ancient orogen I have chosen a number of examples to illustrate structures typical of the plastic regime.

Acknowledgments

During the writing of this textbook I have built on experience and knowledge achieved through my entire career, from early days as a student, via various industrial and academic positions, to the time I have spent writing the manuscript. In this respect I want to thank fellow students, geologists and professors with whom I have interacted during my time at the Universities of Bergen, Oslo, Minnesota and Utah, at Utah State University, in Statoil and at the Geological Survey of Norway. In particular, my advisers and friends Tim Holst, Peter Hudleston and Christian Teyssier deserve thanks for sharing their knowledge during my three years in Minnesota, and among the many fellow PhD students there special thanks are due to Jim Dunlap, Eric Heatherington, David Kirschner, Labao Lan and, particularly, Basil Tikoff for valuable discussions and exchange of ideas as we were exploring various aspects of structural geology. Among coworkers and colleagues I wish to extend special thanks to Roy Gabrielsen, who contributed to the Norwegian book on which this book builds, Jonny Hesthammer for good company in Statoil and intense field discussions, Egil Rundhovde for co-leading multiple field trips to the Colorado Plateau, and to Rich Schultz who is always keen on intricate discussions on fracture mechanics and deformation bands in Utah and elsewhere.

Special thanks also go to Wallace Bothner, Rob Butler, Nestor Cardozo, Declan DePaor, Jim Evans, James Kirkpatrick, Stephen Lippard, Christophe Pascal, Atle Rotevatn, Zoe Shipton, Holger Stunitz and Bruce Trudgill for reading and commenting on earlier versions of the text. I am also thankful to colleagues and companies who assisted in finding appropriate figures and seismic examples of structures, each of which is acknowledged in connection with the appearance of the illustration in the book, and to readers who will send their comments to me so that improvements can be made for the next edition.

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Symbols

a	long axis of ellipse representing a microcrack
A	area; empirically determined constant in flow laws
c	short axis of ellipse representing a microcrack
C	cohesion or cohesional strength of a rock
C_f	cohesive strength of a fault
d	offset
d_cl	thickness of clay layer
D	displacement; fractal dimension
D_max	maximum displacement along a fault trace or on a fault surface
$\mathbf{D}$	deformation (gradient) matrix
$e = \varepsilon$	elongation
$\dot{e} = \dot{\varepsilon}$	elongation rate ($\mathrm{d}e/\mathrm{d}t$)
$\dot{e}_x$ and $\dot{e}_y$	elongation rates in the x and y directions (s^{-1})
$\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$	eigenvectors of deformation matrix, identical to the three axes of strain ellipsoid
$\bar{e}$	logarithmic (natural) elongation
$\bar{e}_\mathrm{s}$	natural octahedral unit shear
E	Young's modulus; activation energy for migration of vacancies through a crystal ($\mathrm{J\,mol^{-1}\,K^{-1}}$)
E^*	activation energy
$\mathbf{F}$	force vector ($\mathrm{kg\,m\,s^{-2}}$, N)
F_n	normal component of the force vector
F_s	shear component of the force vector
g	acceleration due to gravity ($\mathrm{m/s^2}$)
h	layer thickness
h_0	initial layer thickness
h_T	layer thickness at onset of folding (buckling)
ISA_{1-3}	instantaneous stretching axes
K	bulk modulus
K_i	stress intensity factor
K_c	fracture toughness
k	parameter describing the shape of the strain ellipsoid (lines in the Flinn diagram)
k_x and k_y	pure shear components, diagonal elements in the pure shear and simple shear matrices
l	line length (m)

l_0	line length prior to deformation (m)
$\mathbf{L}$	velocity tensor (matrix)
L	fault length;
	wavelength
L_d	dominant wavelength
L_T	actual length of a folded layer over the distance of one wavelength
n	exponent of displacement-length scaling law
p_f	fluid pressure
P	pressure (Pa)
Q	activation energy
R	ellipticity or aspect ratio of ellipse (long over short axis);
	gas constant ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
R_f	final ellipticity of an object that was non-circular prior to deformation
R_i	initial ellipticity of an object (prior to deformation)
R_s	same as R, used in connection with the R_f/ϕ-method to distinguish
	it from R_f
R_{xy}	X/Y
R_{yz}	Y/Z
s	stretching
$\dot{\mathbf{S}}$	stretching tensor, symmetric part of $\mathbf{L}$
t	time (s)
T	temperature (K or °C);
	uniaxial tensile strength (bar);
	local displacement or throw of a fault when calculating SGR and SSF
$\mathbf{v}$	velocity vector (m/s)
V	volume ($\mathrm{m^3}$)
V_0	volume prior to deformation
V_p	velocity of P-waves
V_s	velocity of S-waves
$\mathbf{w}$	vorticity vector
w	vorticity
$\mathbf{W}$	vorticity (or spin) tensor, which is the skew-symmetric component of $\mathbf{L}$
W_k	kinematic vorticity number
$\mathbf{x}$	vector or point in a coordinate system prior to deformation
$\mathbf{x}'$	vector or point in a coordinate system after deformation
x, y, z	coordinate axes, z being vertical
X, Y, Z	principal strain axes; $X \geq Y \geq Z$
Z	crustal depth (m)
α	thermal expansion factor ($\mathrm{K^{-1}}$);
	Biot poroelastic parameter;
	angle between passive marker and shear direction at onset of
	non-coaxial deformation (Chapter 15);
	angle between flow apophyses (Chapter 2)
α'	angle between passive marker and shear direction after a non-coaxial
	deformation
β	stretching factor, equal to s
Δ	volume change factor
$\Delta\sigma$	change in stress

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γ	shear strain
$\bar{\gamma}_{oct}$	octahedral shear strain
$\dot{\gamma}$	shear strain rate
Γ	non-diagonal entry in deformation matrix for subsimple shear
η	viscosity constant ($N\,s\,m^{-2}$)
λ	quadratic elongation
λ_1, λ_2 and λ_3	eigenvalues of deformation matrix
$\sqrt{\lambda_1}$, $\sqrt{\lambda_2}$ and $\sqrt{\lambda_3}$	length of strain ellipse axes
μ	shear modulus; viscosity
μ_f	coefficient of sliding friction
μ_L	viscosity of buckling competent layer
μ_M	viscosity of matrix to buckling competent layer
ν	Poisson's ratio; Lode's parameter
θ	angle between the normal to a fracture and $\sigma_{1;}$ angle between ISA_1 and the shear plane
θ'	angle between X and the shear plane
ρ	density (g/cm^3)
σ	stress ($\Delta F/\Delta A$) (bar: 1 bar $= 1.0197\ kg/cm^2 = 10^5$ Pa$= 10^6$ dyne/cm^2)
$\boldsymbol{\sigma}$	stress vector (traction vector)
$\sigma_1 > \sigma_2 > \sigma_3$	principal stresses
$\bar{\sigma}$	effective stress
σ_a	axial stress
σ_{dev}	deviatoric stress
σ_{diff}	differential stress ($\sigma_1 - \sigma_3$)
σ_H	max horizontal stress
σ_h	min horizontal stress
σ_h*	average horizontal stress in thinned part of the lithosphere (constant-horizontal-stress model)
σ_m	mean stress $(\sigma_1 + \sigma_2 + \sigma_3)/3$
σ_n	normal stress
σ_r	remote stress
σ_s	shear stress
σ_t	tectonic stress
σ_{tip}	stress at tip of fracture or point of max curvature along pore margin
σ_{tot}	total stress ($\sigma_m + \sigma_{dev}$)
σ_v	vertical stress
σ_n^g	normal stress at grain–grain or grain–wall contact areas in porous medium
σ_n^w	average normal stress exerted on wall by grains in porous medium
ϕ	internal friction (rock mechanics); angle between X and a reference line at onset of deformation (R_f/ϕ-method)
ϕ'	angle between X and a reference line after a deformation (R_f/ϕ-method)
Φ	porosity
ψ	angular shear
$\boldsymbol{\omega}$	angular velocity vector

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