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Haakon Fossen
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Structural Geology

Second Edition

This market-leading textbook has been fully updated in response to extensive user feedback. It includes a new chapter on joints and veins, additional examples from around the world, stunning new field photos, and extended online resources with new animations and exercises. The book's practical emphasis, hugely popular in the first edition, features applications in the upper crust, including petroleum and groundwater geology, highlighting the importance of structural geology in exploration and exploitation of petroleum and water resources. Carefully designed full-color illustrations work closely with the text to support student learning, and are supplemented with high-quality photos from around the world. Examples and parallels drawn from practical everyday situations engage students, and end-of-chapter review questions help them to check their understanding. Updated e-learning modules are available online for most chapters and further reinforce key topics using summaries, innovative animations to bring concepts to life, and additional examples and figures.

Haakon Fossen is Professor of Structural Geology at the University of Bergen, Norway, where he is affiliated with the Department of Earth Science and the Natural History Collections. His professional career has involved work as an exploration and production geologist/geophysicist for Statoil and as a Professor at the University of Bergen (1996 to present), in addition to 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 other books and several book chapters. He has taught undergraduate structural geology courses for twenty years and has a keen interest in developing electronic teaching resources to aid student visualization and understanding of geological structures.

Structural Geology

SECOND EDITION

Haakon Fossen
UNIVERSITY OF BERGEN, NORWAY

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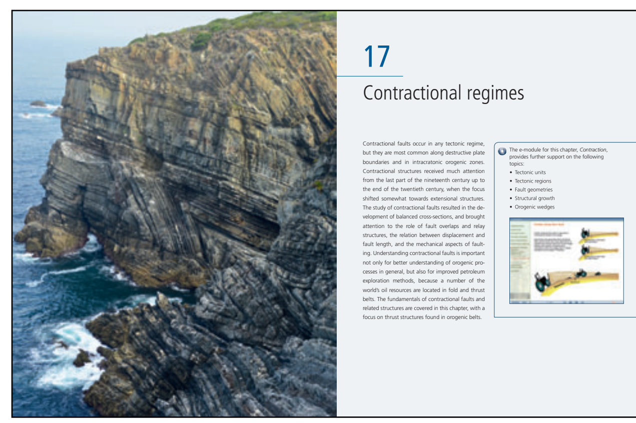
How to use this book

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. The box alongside identifies which online e-module accompanies the chapter and the topics that it covers.



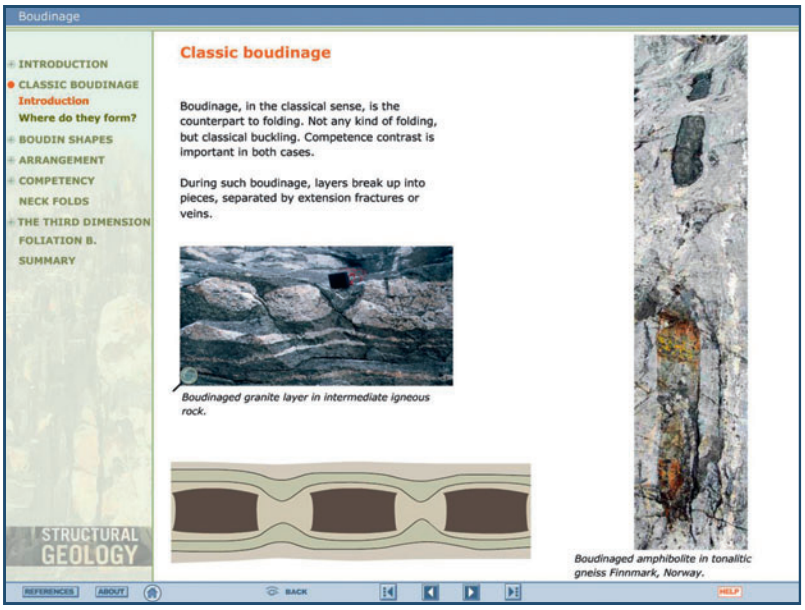
The main text contains **highlighted terms** and **key expressions** that you will need to understand and become familiar with. Many of these terms are listed in the **Glossary** at the back of the book. The Glossary allows you to easily look up terms whenever needed and can also be used to review important 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.

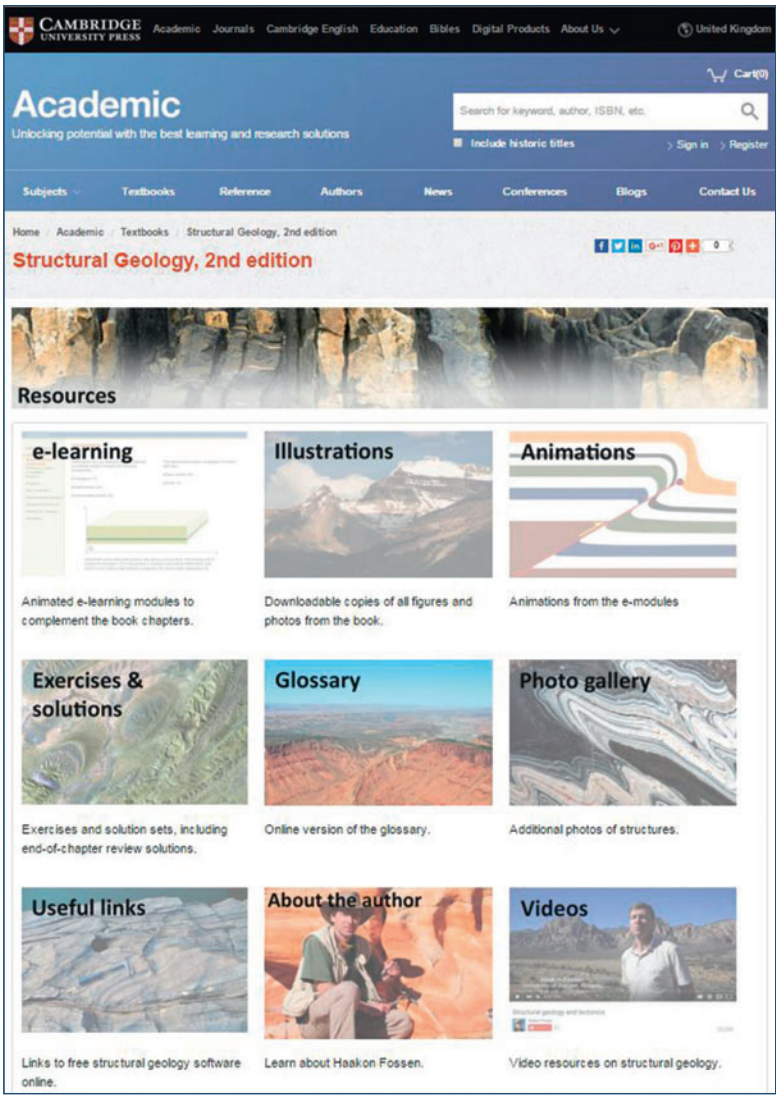
> in Figure 4.7, now known as the Mohr diagram, where the horizontal and vertical axes represent the normal (σ_n) and shear (σ_s) stresses that act on a plane through a point. The value of the maximum and minimum principal stresses (σ_1 and σ_3, also denoted σ_1 and σ_2 for two dimensional cases) are plotted on the horizontal axis, and the distance between σ_1 and σ_3 defines the diameter of a circle centered at $((\sigma_1 + \sigma_3)/2, 0)$. This circle is called the **Mohr circle**.
>
> The Mohr circle describes the normal and shear stress acting on planes of all possible orientations through a point in the rock.

Boxes present 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 webpage. **Further reading** sections provide references to selected papers and books for those interested in more detail or advanced information.

> ## Review questions
>
> 1. What is structural geology all about?
> 2. Name the four principal ways a structural geologist can learn ation. How would you rank them?
> 3. How can we collect structural data sets? Name important data analysis.
> 4. What are the advantages and disadvantages of seismic reflecti
> 5. What is a scale model?
> 6. What is kinematic analysis?

E-learning modules further reinforce key topics using summaries, additional examples and figures, and innovative animations to bring concepts to life. Use of these e-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.





Online resources

www.cambridge.org/fossen2e

Specially prepared resources, unique to this book, are available from the book's webpage. These include:

- E-learning modules that combine animations, text, illustrations and photographs. These present key aspects of structural geology in a highly visual and interactive environment.
- Answers to the end-of-chapter review questions for instructors.
- Additional student exercises (with solutions for instructors).
- All of the figures for each chapter as jpeg and PowerPoint files.
- An electronic glossary of terms.
- A gallery of supplementary figures illustrating additional geologic structures and field examples.
- Tutorial videos from the field.
- Links to other web-based structural geology resources including software.
- Links to the author's blog and community Face-book page.

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Preface

This is the second edition of *Structural Geology;* a textbook that was first published in 2010. The first edition was very well received among students, lecturers and industry professionals alike. I received a lot of encouraging comments and helpful feedback from readers, and this has been a motivating factor for preparing a new and improved version with updated text, illustrations and photographs that preserves the overall structure of the previous edition.

The purpose of the book is to introduce undergraduate students, and others with a general geologic background, to the 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. This philosophy is extended with the second edition, particularly by the addition of a new chapter on joints and veins.

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 7–10). Of these, Chapter 2 contains some 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 11), ductile deformation structures such as folding, boudinage, foliations and shear zones are discussed (Chapters 12–16). Three consecutive chapters then follow that are founded on the three principal tectonic regimes (Chapters 17–19) before salt tectonics and restoration principles are presented (Chapters 20 and 21). 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, which I know from my years with the Norwegian oil company Statoil and later academic research. Another is the Colorado Plateau, 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, balanced by the much hotter Araçuai-Ribeira Belt in Brazil. Many of the examples used to illustrate structures typical of the plastic regime come from these orogenic belts.

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Acknowledgments

During the writing of this textbook I have built on experience and knowledge achieved as a student, during various industrial and academic positions, and through the writing of this book. 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 special thanks for generously sharing their knowledge during my time as a student, and also once fellow student Basil Tikoff for valuable discussions and exchange of ideas in Pillsbury Hall. Among my many co-workers, colleagues and former students I wish to extend special thanks to Roy Gabrielsen, Jan Inge Faleide, Jonny Hesthammer, Rich Schultz, Roger Soliva, Gregory Ballas, Rob Gawthorpe, Ritske Huismans and Carolina Cavalcante.

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, Bruce Trudgill, Carolina Cavalcante, Luiz Morales and Fred Vollmer for critically reading various parts of the text. Valuable assistance and company in the field that have influenced this book were provided by Julio Almeida, Renato Almeida, Nicolas Badertscher, Wallace Bothner, Jean M. Crespi, Rui Dias, Marcos Egydia, Jim Evans, Jonny Hesthammer, Fernando O. Marques, Roger Soliva, John Walsh and Adolph Yonkee. Thanks also to readers who sent comments on various parts of the first editions. Finally, other textbooks have been of invaluable worth both during my time as a student of structural geology in general and during the preparation of this book. In particular I have enjoyed and learned a lot from the books by Hobbs, Means and Williams (1976), Twiss and Moores (2007), van der Pluijm and Marshak (2004), and various editions of George H. Davis and co-authors' *Structural Geology* text, as well as the excellent *Microtectonics* text by Passchier and Trouw (2005).

Symbols

a	long axis of ellipse representing a microcrack
A	area; empirically determined constant in flow laws
B	layer thickness
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 (de / dt)
$\dot{e}_x$, $\dot{e}_y$	elongation rates in the x and y directions (s^{-1})
$\mathbf{e}_1$, $\mathbf{e}_2$, $\mathbf{e}_3$	eigenvectors of deformation matrix, identical to the three axes of the strain ellipsoid
$\bar{e}$	logarithmic (natural) elongation
$\bar{e}_s$	natural octahedral unit shear
E	Young's modulus; activation energy for migration of vacancies through a crystal ($J\ mol^{-1}\ K^{-1}$)
E^*	activation energy
$\mathbf{F}$	force vector ($kg\ m\ s^{-2}$, N)
F_n	normal component of the force vector
F_s	shear component of the force vector
g	acceleration due to gravity (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	parameter describing the shape of the strain ellipsoid (lines in the Flinn diagram)
K	bulk modulus
K_i	stress intensity factor
K_c	fracture toughness
k_x, 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 (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
$\dot{S}$	stretching tensor, symmetric part of **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 (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 **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 (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
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
$\lambda_1, \lambda_2, \lambda_3$	eigenvalues of deformation matrix
$\sqrt{\lambda_1}, \sqrt{\lambda_2}, \sqrt{\lambda_3}$	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_w^n	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)
$\boldsymbol{\Phi}$	porosity
ψ	angular shear
$\boldsymbol{\omega}$	angular velocity vector