Rock Fractures in Geological Processes

Rock fractures largely control many of the Earth's dynamic processes. Examples include plate-boundary formation and development, tectonic earthquakes, volcanic eruptions, and fluid transport in the crust. How rock fractures form and develop is of fundamental importance in many theoretical and applied fields of earth sciences and engineering, such as volcanology, seismology, hydrogeology, petroleum geology, natural hazards, and engineering geology. An understanding of rock fractures is essential for effective exploitation of many of the Earth's natural resources including ground water, geothermal water, and petroleum.

This book combines results from fracture mechanics, materials science, rock mechanics, structural geology, hydrogeology, and fluid mechanics to explore and explain fracture processes and fluid transport in the crust. Basic concepts are developed from first principles and are illustrated with numerous worked examples that link models of geological processes to real field observations and measurements. Calculations in the worked examples are presented in detail with simple steps that are easy to follow – providing the readers with the skills to formulate and quantitatively test their own models, and to practise their new skills using real data in a range of applications. Review questions and numerical exercises are given at the end of each chapter, and further homework problems are available at www.cambridge.org/gudmundsson. Solutions to all numerical exercises are available to instructors online.

Rock Fractures in Geological Processes is designed for courses at the advanced-undergraduate and beginning-graduate level, but also forms a vital resource for researchers and industry professionals concerned with fractures and fluid transport in the Earth's crust.

Agust Gudmundsson holds a University of London Chair of structural geology at Royal Holloway. He has a Ph.D. in Tectonophysics from the University of London and has previously held positions as research scientist at the University of Iceland, professor and Chair at the University of Bergen, Norway, and professor and Chair at the University of Göttingen, Germany. Professor Gudmundsson's research interests include volcanotectonics, seismotectonics, and fluid transport in rock fractures and reservoirs. He has published more than 130 research papers on these and related topics, is on the editorial boards of *Terra Nova*, *Tectonophysics*, *Journal of Geological Research*, and *Journal of Volcanology & Geothermal Research*, and is a fellow of the Iceland Academy of Sciences and Academia Europaea. The book draws on Professor Gudmundsson's extensive experience in field, analytical, and numerical studies of crustal fractures and of teaching undergraduate and graduate courses in structural geology, geodynamics, hydrogeology, rock mechanics, reservoir geoscience, seismotectonics, and volcanotectonics.

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Preface

Many of the Earth's most fascinating natural processes are related to rock fractures. Volcanic eruptions, tectonic earthquakes, geysers, large landslides and the formation and development of mid-ocean ridges all depend on fracture formation and propagation. Rock fractures are also of fundamental importance in more applied fields such as those related to fluid-filled reservoirs, deep crustal drilling, tunnelling, road construction, dams, geological and geophysical mapping and field geology and geophysics.

There has been great progress in understanding fracture initiation and propagation over the past decades. The results of this progress are summarised in many papers, textbooks and monographs within the fields of fracture mechanics and materials science. Much of this improved knowledge of fracture development is of great relevance for understanding and modelling geological processes that relate to rock fractures.

The purpose of this book is to offer a modern treatment of rock fractures for earth scientists and engineers. The book is primarily aimed at, first, undergraduate or beginning graduate students in geology, geophysics and geochemistry and, second, scientists, engineers and other professionals who deal with rock fractures in their work. The book has been designed so that it can be used (1) for an independent study, (2) as a textbook for a course in rock fractures in geological processes and (3) as a supplementary text for courses in structural geology, seismology, volcanology, hydrogeology, geothermics, hazard studies, engineering geology, rock mechanics and petroleum geology.

Each chapter begins with an overview of aims and ends with a summary of the main topics discussed and a list of all the main symbols used in that chapter. There are many worked examples (solved problems) and exercises (supplementary problems) in each chapter. The worked examples serve to illustrate the theoretical principles and show how they may be applied to fracture-related processes in the crust. The examples and exercises are meant to provide a deeper understanding of the basic principles of rock fractures, so that the reader can use them with great confidence in solving rock-fracture problems.

I have taught much of the material in the book over the past 12 years to earth science students in Norway, Germany and England. The basic material has been used in undergraduate and graduate courses on such diverse topics as volcanotectonics, seismotectonics, structural geology, geodynamics, rock mechanics, rock-fracture mechanics, hydrogeology, petroleum geology and applied geology. While most of these students were educated in geology, many were educated in geophysics, geochemistry, physical geography and engineering. Based on this experience, almost all the material in the book should be suitable for students with a very modest knowledge of mathematics and physics. The only exceptions are parts of Sections 13.4, 13.5 and 14.6, where more advanced mathematics is used. All the necessary physics is explained in the book.

The book is also meant for professional scientists whose work involves rock fractures, in particular fluid transport in fractured rocks. These include geologists, geophysicist, geochemists, hydrogeologists, civil engineers, petroleum engineers and experts in related fields. Many of these may neither have the time nor inclination to read the entire book. I have therefore written the chapters, particularly those in the second half of the book, so as to make each of them comparatively independent of the other chapters. Thus it should generally be possible to read and understand the content of one chapter without having to read all the other chapters. For this reason, and also for pedagogical reasons, there is considerable repetition of various basic principles and results, particularly in the chapters that constitute the second half of the book. The repetition should help in effective learning of the main topics.

As regards referencing of the technical literature, I follow the common tradition of citing comparatively few references in the part of the text dealing with general solid mechanics in the first half of the book. The basic topics treated in this part are well established and are treated in numerous standard textbooks and monographs, many of which are included in the reference lists at the ends of the chapters. Many of the topics discussed in the second half of the book, however, are still the subject of very active research in the field of rock-fracture development and related fluid transport. In this part of the book there are thus many more references in the text, as well as extensive reference lists at the ends of the chapters. Although the reference lists cannot be exhaustive, they indicate the papers and books that were used when writing the chapters and may also serve as guides to the general literature on rock fractures.

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Acknowledgements

Many colleagues and students have made contributions to this book, some through technical discussions over the years, which have helped in my formulating some of the ideas presented in the book. An exhaustive list of all these people is not possible, but below I mention some colleagues, students and friends who have been most directly involved with the book itself.

First, I would like to mention two colleagues and friends who are no longer with us. Both shared my interest in, and enthusiasm for, rock fractures. One, Neville J. Price, wrote the first monograph on rock fractures, Fault and Joint Development in Brittle and Semi-Brittle Rock, which had very great effects on the field of rock fractures. The other, Jacques Angelier, was the world's leading expert on palaeostresses and their relation to rock fractures – topics that are still at the forefront of fracture-related research.

Then, I would like to mention several colleagues who read and commented on the manuscript. Very helpful reviews of the manuscript were provided by Adelina Geyer, Shigekazu Kusumoto and Sonja L. Philipp. They read the entire manuscript and made many corrections and suggestions for improvement for which I am very gratefully. In addition, many of the numerical models in the book are from my collaboration with Adelina Geyer and Sonja L. Philipp, whereas some of the analytical parts in Chapter 13 are from my collaboration with Shigekazu Kusomoto. Additional numerical models were made in collaboration with Ruth E.B. Andrew, Otilie Gjesdal, Belinda Larsen, Ingrid F. Lotveit and Trine H. Simmenes. I also thank Ken Macdonald, Philip Meredith and Stephen Sparks for providing the very positive, and much appreciated, general comments on the back cover of the book.

Most of the illustrations in the book are either original or have been remade from various sources. All the sources are cited in the reference lists. For some of the illustrations, particularly those that are not much modified, if at all, and are from recent papers, there are also direct citations in the figure captions. Most of the previously published illustrations are from my own papers in various journals (see the note 'Illustrations' below). I thank the publishers for permission to use the illustrations in the book.

Many people have helped with the illustrations, most of which have been modified many times. Some were originally made by the technical staff at the University of Bergen, Norway, and by students and assistants at the University of Göttingen, Germany. Others were originally made by students and colleagues in France, Germany, Iceland, Italy, Norway and Spain. Any list of names would necessarily be incomplete, so I prefer to offer here a warm thank you to all those who have contributed to the illustrations in the book.

Several people provided photographs, as mentioned in the appropriate captions. These include Valerio Acocella, Jacques Angelier, Ines Galindo, Aevar Johannesson and

Sonja L. Philipp. I am particularly grateful to Valerio Acocella for the photograph on the front cover of the book.

While working on this book, I have received much, and greatly appreciated, help from Nahid Mohajeri. She has redrawn and modified most of the earlier illustrations and made many of the original illustrations in the book.

Although this book project has not received direct funding as such, many of the ideas and results presented have been obtained through many funded projects. In particular, some of the results presented here derive from various projects on seismic and volcanic risk funded by the European Union.

At Cambridge University Press, Laura Clark, Susan Francis, David Hemsley and Emma Walker have been very helpful and positive during the work on the book. In particular, Susan Francis has been very encouraging and patient during the time it took to complete the book. I take this opportunity to thank Cambridge University Press for a splendid collaboration.

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Illustrations

Apart from the papers cited in the appropriate figure captions, the following papers are the main sources for the illustrations modified from scientific journals. I am an author on all the papers; the titles and other details are in the reference lists. *Earth-Science Reviews*, **79**, 1–31, 2006 (Figs. 2.10, 6.13, 6.14, 6.15, 6.16, 6.17, 6.19, 6.26, 6.27); *Tectonophysics*, **220**, 205–221, 1993 (Figs. 2.12, 14.13); *Journal of Structural Geology*, **9**, 61–69, 1987 (Fig. 3.13); *Journal of Structural Geology*, **32**, 1643–1655, 2010 (Figs. 6.3, 14.21, 14.22, 14.24, 14.25, 14.26); *Tectonophysics*, **336**, 183–197, 2001 (Figs. 12.2, 16.2); *Tectonophysics*, **139**, 295–308, 1987 (Fig. 13.4); *Bulletin of Volcanology*, **67**, 768–782, 2005 (Fig. 13.6); *Journal of Geophysical Research*, **103**, 7401–7412, 1998 (Fig. 13.7); *Hydrogeology Journal*, **11**, 84–99, 2003 (Figs. 13.25, 14.15); *Bulletin of Volcanology*, **65**, 606–619, 2003 (Figs. 13.29, 13.30); *Journal of Structural Geology*, **22**, 1221–1231, 2000 (Fig. 14.18); *Geophysical Research Letters*, **18**, 2993–2996, 2000 (Figs. 16.4, 16.7, 16.8); *Terra Nova*, **15**, 187–193, 2003 (Fig. 16.9); *Journal of Structural Geology*, **23**, 343–353, 2001 (Figs. 17.1, 17.2).