Reservoir Geomechanics

This interdisciplinary book encompasses the fields of rock mechanics, structural geology, and petroleum engineering to address a wide range of geomechanical problems that arise during the exploitation of oil and gas reservoirs.

Covering the exploration, assessment, and production phases of petroleum reservoir development, the book considers key practical issues such as prediction of pore pressure; estimation of hydrocarbon column heights and fault seal potential; determination of optimally stable well trajectories; casing set points and mud weights; changes in reservoir performance during depletion; and production-induced faulting and subsidence. The first part of the book establishes the basic principles of geomechanics in a way that allows readers from different disciplinary backgrounds to understand the key concepts. It then goes on to introduce practical measurement and experimental techniques before illustrating their successful application, through case studies taken from oil and gas fields around the world, to improve recovery and reduce exploitation costs.

Reservoir Geomechanics is a practical reference for geoscientists and engineers in the petroleum and geothermal industries, and for research scientists interested in stress measurements and their application to problems of faulting and fluid flow in the crust.

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CAMBRIDGE UNIVERSITY PRESS

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UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521146197

First published 2007
Paperback edition 2010
13th printing 2015

Printed in the United States of America by Sheridan Books Inc.

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

ISBN 978-0-521-77069-9 Hardback
ISBN 978-0-521-14619-7 Paperback

Cambridge University Press
978-0-521-14619-7 - Reservoir Geomechanics
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This book is dedicated to the Ph.D. students and post-docs at Stanford University whom I've had the privilege to teach, and learn from, over the past 22 years. This book would not have been possible without many contributions from these talented scientists. I thank them for their efforts, enthusiasm and friendship.

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Preface

This book has its origin in an interdisciplinary graduate class that I've taught at Stanford University for a number of years and a corresponding short course given in the petroleum industry. As befitting the subject matter, the students in the courses represent a variety of disciplines – reservoir engineers and geologists, drilling engineers and geophysicists. In this book, as in the courses, I strive to communicate key concepts from diverse disciplines that, when used in a coordinated way, make it possible to develop a comprehensive geomechanical model of a reservoir and the formations above it. I then go on to illustrate how to put such a model to practical use. To accomplish this, the book is divided into three major sections: The first part of the book (Chapters 1–5) addresses basic principles related to the state of stress and pore pressure at depth, the various constitutive laws commonly used to describe rock deformation and rock failure in compression, tension and shear. The second part of the book (Chapters 6–9) addresses the principles of wellbore failure and techniques for measuring stress orientation and magnitude in deep wells of any orientation. The techniques presented in these chapters have proven to be reliable in a diversity of geological environments. The third part of the book considers applications of the principles presented in the first part and techniques presented in the second. Hence, Chapters 10–12 address problems of wellbore stability, fluid flow associated with fractures and faults and the effects of depletion on both a reservoir and the surrounding formations.

Throughout the book, I present concepts, techniques and investigations developed over the past 30 years with a number of talented colleagues. Mary Lou Zoback (formerly with the U.S. Geological Survey) and I developed the methodologies for synthesis of various types of data that indicate current stress orientations and relative magnitudes in the earth's crust. As summarized in Chapter 1, Mary Lou and I demonstrated that it was possible to develop comprehensive maps of stress orientation and relative magnitude and interpret the current state of crustal stress in terms of geologic processes that are active today. The quality ranking system we developed for application to the state of stress in the conterminous U.S. (and later North America) is presented in Chapter 6. It has been used as the basis for almost all stress mapping endeavors carried out over the past 20 years and provided the basis for the compilation of stress at a global scale (the World Stress Map project), led by Mary Lou.

The examples of regional stress fields from various regions around the world presented in Chapters 1 and 6 are taken from collaborative research done with former Ph.D. students David Castillo, Lourdes Colmenares, Balz Grollimund and Martin Brudy. This work, and much of the other work done with students and post-docs at Stanford, was supported by the companies participating in the Stanford Rock and Borehole Geophysics Consortium (SRB). Chapter 2, on pore pressure, refers to work done with former Ph.D. students Thomas Finkbeiner, David Wiprut, Balz Grollimund and Alvin Chan. The concepts in this chapter benefited from discussions with Peter Flemings (Penn State) and Chris Ward. Chapter 3, on elasticity and constitutive laws, includes a section on viscoelastic and viscoplastic constitutive laws for uncemented reservoir sands that is based on research done in collaboration with former Ph.D. students Carl Chang, Dan Moos and Paul Hagin. Chapter 4, on rock failure, was done in part in collaboration with Lourdes Colmenares, former Ph.D. student John Townend, former post-docs Chandong Chang and Lev Vernik and Dan Moos. James Byerlee (USGS retired) was an inspirational Ph.D. advisor and teacher in rock mechanics. His work on rock friction, discussed in Chapter 4, is of critical importance on establishing bounds on stress magnitudes at depth in the crust. Chapter 5 is on fractures and faults at depth, and is based largely on wellbore imaging studies initiated with former Ph.D. student Colleen Barton and includes applications done with Thomas Finkbeiner and Sneha Chanchani.

At the beginning of the second part of the book on *Measuring Stress Orientation and Magnitude*, Chapter 6 discusses stress concentrations around vertical wells and compressional and tensional wellbore failures. This work was done in part in collaboration with Dan Moos, Martin Brudy, David Wiprut and David Castillo, as well as former post-docs Pavel Peska and Marek Jarosinski. John Healy and Steve Hickman of the USGS were early collaborators on the use of hydraulic fracturing for stress measurements. The stress measurement methods based on wellbore failures in vertical (Chapters 7) and deviated wellbores (Chapter 8) were developed in collaboration with Pavel Peska, Martin Brudy and Dan Moos. Former Ph.D. student Naomi Boness and I developed the methodologies presented in Chapter 8 for utilizing cross-dipole shear velocity logs for mapping stress orientation in deviated wells. The techniques described in these chapters are not intended to be a comprehensive review of the numerous techniques proposed over the years for stress measurement (or stress estimation) at depth. Rather, I emphasize stress measurement techniques that have proven to work reliably in deep wells under conditions commonly found in oil and gas reservoirs. Chapter 9 reviews stress magnitude measurements made in various sedimentary basins around the world in the context of global patterns of *in situ* stress and some of the mechanisms responsible for intraplate stress. Chapter 9 also includes a case study related to deriving stress magnitude information from geophysical logs carried out with former Ph.D. student Amie Lucier.

The final part of the book, *Applications*, starts with a discussion of wellbore stability in Chapter 10. Many of the examples considered in the section are taken from studies done with Pavel Peska and Dan Moos and several of the topics considered (such as the degree of *acceptable* wellbore failure with well deviation, the influence of weak bedding planes on wellbore stability and the circumstances under which it might be possible to drill with mud weights greater than the least principal stress) were undertaken at the suggestions of Steve Willson and Eric van Oort. The theory presented on drilling with mud weights in excess of the least principal stress was developed with Takatoshi Ito of Tohoku University. The wellbore stability study of the SAFOD research borehole was done in collaboration with former Ph.D. student Pijush Paul. At the time of this writing, the principles discussed in the sections dealing with wellbore stability have been successfully applied in over 500 studies carried out over the past several years by colleagues at GeoMechanics International (GMI) and other companies. This success validates the practical utility of both the techniques outlined in Chapters 7 and 8 for estimating *in situ* stress magnitude and orientation and the effectiveness of using a relatively straightforward *strength of materials* approach in assessing wellbore stability in many situations. I thank GMI for use of its software in many of the applications presented in this book.

The brief discussion of formation stability during production (referred to as sand, or solids, production) is based on the work of Martin Brudy and Wouter van der Zee, principally using finite element techniques. The work on flow through fractured reservoirs in Chapter 11 and the importance of critically stressed faults on controlling fluid flow is based on research initially carried out with Colleen Barton and Dan Moos and extended with John Townend. Work on localized fluctuations of stress orientation due to slip on faults was done originally with Gadi Shamir and subsequently extended with Colleen Barton. Extension of this work to the fault seal problem was initially done with David Wiprut. Studies related to dynamic constraints on hydrocarbon migration were done with Thomas Finkbeiner. Roger Anderson (Columbia University) and Peter Flemings played instrumental roles in this research. The work done on the state of stress and hydrocarbon leakage in the northern North Sea was motivated by Bjorn Larsen. Chapter 12 considers a number of topics related to reservoir depletion, including subsidence and production-induced faulting. The majority of this work was done in collaboration with Alvin Chan, with contributions from former post-doc Jens Zinke and former Ph.D. student Ellen Mallman. The work on depletion-induced stress orientation changes was done principally with former Ph.D. student Amy Day-Lewis based on work done originally with Sangmin Kim.

Finally, I'd like to thank Steve Willson, Chris Ward, Dan Moos, John Townend and Mary Lou Zoback for their comments on the first draft of this book.

Mark Zoback
Stanford University
2006

Comments for the paperback edition

Since the first printing of this book in 2007, there have been several areas where application of some of the principles of geomechanics that are discussed have seen such rapid increases of utilization that they deserve mention. One is the widespread utilization of three- (and four)-dimensional numerical geomechanical models. As explained at the end of Chapter 1, utilization of three-dimensional numerical models is essential in the vicinity of salt domes, where both stress magnitudes and orientations are perturbed by the presence of the salt. Examples of cases where four-dimensional reservoir models are important are in cases where the coupling between stress and deformation in (and around) reservoirs is affected by depletion. One obvious example is the coupling between depletion and compaction drive as discussed briefly in Chapter 12 for an idealized hypothetical example.

A second area of recent activities that involves application of the principles discussed in this book is the triggering of slip on critically stressed faults during so-called *slick-water frac'ing* operations. These are being employed in thousands of wells that are drilled to enhance production from shale gas and tight gas (very low permeability) reservoirs, somewhat analogously to what has been done in geothermal reservoirs for several decades. As discussed in Chapters 5 and 11, the induced slip on these faults creates a network of faults with sufficiently enhanced permeability that gas can be exploited economically from otherwise impermeable reservoirs. At the time of this writing, a great deal of research is being done to better understand how to optimize the creation of such networks and to accurately model fluid flow through them.

Finally, many projects involving injection of CO_2 into saline aquifers and depleted oil and gas reservoirs are getting under way as part of efforts to limit greenhouse gas emissions. One critically important issue concerning such activities is whether the increase in formation pressure caused by injection is likely to induce slip on pre-existing faults. Geomechanically constrained reservoir simulations of CO_2 injection in different kinds of reservoirs have been carried out with former Ph.D. students Amie Lucier, Laura Chiaramonte, and Hannah Ross. The techniques described in Chapter 11 are being increasingly used to assess limits on safe injection pressures and maximum rates of CO_2 injection.

Mark Zoback, 2010