Quantitative Analysis of Geopressure for Geoscientists and Engineers

Geopressure, or pore pressure in subsurface rock formations impacts hydrocarbon resource estimation, drilling, and drilling safety in operations. This book provides a comprehensive overview of geopressure analysis, bringing together rock physics, seismic technology, quantitative basin modeling, and geomechanics. It provides a fundamental physical and geological basis for understanding geopressure by explaining the coupled mechanical and thermal processes. It also brings together state-of-the-art tools and technologies for analysis and detection of geopressure, along with the associated uncertainty. Prediction and detection of shallow geohazards and gas hydrates are also discussed, and field examples are used to illustrate how models can be practically applied. With supplementary Matlab codes and exercises available online, this is an ideal resource for students, researchers, and industry professionals in geoscience and petroleum engineering looking to understand and analyze subsurface formation pressure.

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Preface

How did we come to write this book? Our research suggested that the discipline of geopressure started based on fundamentals of geology (such as the pioneering works of Ruby and Hubbert and Dickinson during the middle of the twentieth century), with an excellent promise of delivery of applications to the hydrocarbon industry. As the quest for hydrocarbon exploration and exploitation required more and more integrated approaches, contributions from many diverse fields of sciences, such as geology, geophysics, petrophysics, applied physics, engineering, and applied mathematics, became the norm. However, quick-fix engineering approaches to tackle challenging problems at hand resulted in fragmented knowledge building and lack of emphasis on fundamentals. This was noted in an earlier publication (Dutta, 1987a, vii): "understanding of the geopressuring phenomenon is worth vigorous pursuit because that understanding calls for an integrated approach in unraveling its mysteries." We felt that the field of geopressure required another look – one that would culminate in a comprehensive discussion of the subject, including the industrial applications and an assessment of the road ahead. This is the goal of this book. Whether this goal is met awaits the judgment of our readers and peers.

During our professional careers, we have been fortunate enough to have witnessed some remarkable achievements in the field of geophysics, in particular, in the seismic subdiscipline. It has been propelled by high-speed computing with concomitant development of complex algorithms, such as tomography and full waveform inversion (FWI), by some brilliant geoscientists. This resulted in a step change in the subsurface seismic image quality. Therefore, some timely questions needed to be asked: Have we taken advantage of these opportunities in geopressure analysis that requires earth model building rather than velocity modeling? Are subsurface images at the right depths? Well, partly yes, but not consistently. Building *an earth model* requires a thorough understanding of the underlying basic physics to describe important subsurface phenomena, such as geopressure, among others. Just what would the effect on imaging be if we were to get this description on the right footing? This requires analysis of the geopressure phenomenon quantitatively, reliably, and making it accessible to all geoscientists and engineers so that integration with other viable model-building processes can take place. We hope the readers will appreciate the attempt undertaken in the book to address this issue.

The book has fourteen chapters that describe the geopressure phenomenon – fundamentals, models and mechanisms, and tools to predict and detect it – from borehole

centric to seismic, taking care to explain the basic physics behind these tools, including limitations of their operating envelopes. We have come to understand better the physics of rocks through careful measurements, both in the laboratory and in the field, and through theoretical analysis. This has enabled us to develop and test subsurface models with more confidence and has helped us to extract rock properties from seismic attributes using sophisticated inversion technologies. The knowledge captured from this directly impacts our understanding of geopressure. Therefore, in this book, an attempt is made to put some of the known subsurface pore pressure models on firmer ground by providing a rock physics basis for some of these models. This allowed us to extend the traditional scale of geopressure prediction envelope from exploration – say, several hundred feet – to drilling around a borehole, at a few feet. To bridge this *scale* is to lay the foundation for a best-practice approach in geopressure and to enable us to extrapolate into what is yet to come. Nonetheless, it is a snapshot at the present and obviously colored by our own biases. We hope the future generation will build on it.

A unique feature of this book deals with applications to illustrate how the geopressure models can be used not only for energy resources assessment but also for environmental issues. In this context, our experiences in dealing with prediction of subsurface geohazards, such as possible existence of shallow aquifer pressured sands in deepwater (aka shallow-water-flow sands), gas charged sands and gas hydrates, and various seabed hazardous features, will be beneficial not only to the energy resource developers and operators but also to regulatory agencies. The approach discussed in the book enables us to go beyond *color coding* a geohazard map – the current practice – to adding *qualifiers*, such as just how red is *red*, what is the extent of the *yellow*, and what is the comfort zone of the *green*? We address these geohazard issues quantitatively so that our sister community of drilling can benefit from closer interaction with geoscientists.

Several books are devoted to subsurface pressure; however, while they were classics during their times, their contents are now mostly outdated. Some other compilations consist of conference proceedings and reviews of papers dealing with special aspects of geopressure and do not include many recent and important developments. These may not be appropriate for students and researchers beginning their careers. This book aims to bridge the gap. To help the readers self-assess their understanding of various subjects addressed in the book, we have a companion website (see the Cambridge University Press site) with suggested exercises and Matlab codes.

By the time we finished the manuscript of the book, the world that we knew had changed. We are witnessing a pandemic incurred by COVID-19, resulting in many deaths and lockdowns in our homes. So the environment has changed drastically between the time we started the project some three years ago and the time when we finished it. However, the project provided some solace to us!

Now comes the most pleasant part of this preface – acknowledgments. There are so many that to mention all the names is practically impossible. Therefore, we sincerely apologize to those who contributed over the years but whose names are not mentioned. We benefited greatly from the scientific training received in the academy and the industry to the tune of more than 75 years of cumulative experience – through

knowledge sharing with students, staff, and industry partners, often with hands-on experience and project management. This has broadened our curiosity, given us strength to march on, and empowered us with tools that resulted in this book. We are very grateful to those who gave us this opportunity. Special thanks are due to Jianchun Dai, Yangjun (Kevin) Liu, and Sherman Yang – all were dear colleagues of the senior author while he was employed at Schlumberger. Thanks, guys! On a personal note, Nader Dutta presented a good portion of this book in a training course at Stanford University in 2016. Feedback from students greatly impacted the presentation of the subject matter in the book. In particular, Anshuman Pradhan – soon to be Dr. Pradhan – deserves special thanks. He was the teaching assistant when the course in geopressure was taught at Stanford. Some of Anshuman's work is included in this book in Chapters 10 and 13. Thanks, Anshuman. Thanks are also due to Dr. Huy Le, who graduated recently with a PhD from Stanford and addressed a good part of his dissertation to link seismic imaging with pore pressure constraints using FWI. The methodology is partly based on some of the material that we discuss in Chapter 6. Thanks, Huy. The encouragement of his thesis advisor at Stanford, Professor Biondo Biondi, to share knowledge is greatly appreciated. Dr. Allegra Hosford-Scheirer at Stanford provided a very constructive environment to carry on integrating basin modeling to imaging through pore pressure. Her enthusiasm and energy are legendary and inspirational to all. Thanks, Allegra! Gary Mavko provided great encouragement and practical advice – finish the book first! Thanks, Gary! Here it is! We are grateful to the members of the following affiliate groups at Stanford University for sponsoring our work over the years and for funding Nader Dutta's stay at Stanford: Stanford Rock and Borehole Geophysics (SRB), Stanford Exploration Project (SEP), Basin and Petroleum System Modeling (BPSM), and the Stanford Center for Earth Resources Forecasting (SCERF). We acknowledge additional funding from Prof. Steve Graham, Dean of the Stanford School of Earth, Energy, and Environmental Sciences. We acknowledge Schlumberger for donations of software and data used in the work of Anshuman Pradhan and Huy Le, described in this book. A special thanks to Susan Francis and Sarah Lambert of Cambridge University Press for guiding us through this project – a long and arduous journey that finished with exhilaration. Thanks! Last, but not the least, Nader Dutta is grateful to his loving spouse, Chizuko, for providing gentle and timely criticism of the manuscript and sharing his joys as well as his frustrations – there were many!

Good reading, folks! Have fun!