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.

Nader C. Dutta is a recognized industry expert on geopressure and was the senior science advisor of Schlumberger prior to retiring in 2015. He is currently a visiting scholar at the Geological Sciences Department, Stanford University. He is the editor of SEG’s book Geopressure (1987) and has been a member of United Nations Environmental Program (UNEP) and USA-DOE Gas Hydrate Assessment Committee.

Ran Bachrach is a scientific advisor for Schlumberger, supporting both research and operations and specializing in various geoscience topics, including high-resolution geophysics, rock physics and geomechanics, 3D/4D imaging of subsurface processes, seismic inversion, and seismic reservoir analysis.

Tapan Mukerji is a professor in the Department of Energy Resources Engineering and by courtesy in the Departments of Geophysics and Geological Sciences at Stanford University. He received the Society of Exploration Geophysicists’ Karcher Award in 2000 and shared the 2014 ENI award for pioneering innovations in theoretical and practical rock physics for seismic reservoir characterization. He is also a coauthor of The Rock Physics Handbook (2020), Value of Information in Earth Sciences (2015), and Quantitative Seismic Interpretation (2005), Cambridge University Press.
Quantitative Analysis of Geopressure for Geoscientists and Engineers

NADER C. DUTTA
Stanford University

RAN BACHRACH
Schlumberger

TAPAN MUKERJI
Stanford University
## Contents

**Preface**

1 Basic Pressure Concepts and Definitions
   1.1 Introduction 1
   1.2 Basic Concepts 2
   1.3 Pore Pressure Gradient 5
   1.4 Overburden Stress 7
   1.5 Effective Vertical Stress and Terzaghi’s Law 9
   1.6 Formation Pressure 12
   1.7 Casing Design 18
   1.8 Importance of Geopressure 19

2 Basic Continuum Mechanics and Its Relevance to Geopressure
   2.1 Introduction 32
   2.2 Stresses and Forces in a Continuum 32
   2.3 Deformation and Strain 39
   2.4 Fundamental Laws of Continuum Mechanics 41
   2.5 Hooke’s Law and Constitutive Equations 44
   2.6 Elasticity, Stress Path, and Rock Mechanics 54
   2.7 Poroelasticity 56
   2.8 Linear Stress–Strain Formulation for Poroelastic Media (Static Poroelasticity) 59
   2.9 Mechanical Compaction from Plastic–Poroelastic Deformation Principles 65
   2.10 Fracture Mechanics and Hydraulic Fracturing 71
   2.11 Rock Physics Basis for Detection and Estimation of Geopressure 75

3 Mechanisms of Geopressure
   3.1 Introduction 84
   3.2 Stress Related: Vertical (Compaction Disequilibrium) 85
   3.3 Stress Related: Lateral (Associated with Compaction Disequilibrium) 96
   3.4 Chemical Diagenesis as a Geopressure Mechanism 97
   3.5 Kerogen Conversion and Hydrocarbon Generation as Mechanisms of Geopressure 112


3.6 Chemical Diagenesis due to Gypsum-to-Anhydrite Transformation 119
3.7 Charging through Subsurface Structures (Lateral Transfer of Fluids) 119
3.8 Hydrocarbon Buoyancy as a Cause of Overpressure 122
3.9 Hydraulic Head as a Cause of Overpressure (Erosion/Uplift, Elevation Related to Datum) 126
3.10 Aquathermal Pressuring as a Mechanism of Geopressure 127
3.11 Osmotic Pressure as a Source of Geopressure 128
3.12 Summary 128

4 Quantitative Geopressure Analysis Methods
4.1 Introduction 130
4.2 Normal Compaction Trends and Characteristics of Undercompacted Zones 133
4.3 Methods to Predict Geopressure 135
4.4 Pore Pressure Prediction in Carbonates (and Other Competent Rocks) Where Common Shale-Based Techniques Do Not Work 175
4.5 Measurement of Pore Pressure 180
4.6 Leak-Off Test, Extended Leak-Off Test, and Fracture Gradient 185
4.7 Subsalt Pore Pressure and Fracture Pressure 197
4.8 Overburden Stress Evaluation 200
4.9 Effect of Water Depth on Overburden and Fracture Pressure Gradients 209
4.10 Temperature Evaluation (Direct and Indirect Methods) 210
4.11 Summary 215

5 Seismic Methods to Predict and Detect Geopressure
5.1 Introduction 218
5.2 Measurements of Velocity 220
5.3 Seismic Velocity from Traveltime Analysis and Anisotropy 228
5.4 Seismic Velocity from Inversion 245
5.5 Summary: Seismic Velocity Analysis and Guidelines for Applications to Pore Pressure 277

6 Integrating Seismic Imaging, Rock Physics, and Geopressure
6.1 Introduction 281
6.2 Rock Physics Guided Velocity Modeling (RPGVM) with Reflection (CIP) Tomography for Pore Pressure Analysis 282
6.3 Example Applications of Rock Physics Guided Velocity Modeling for Geopressure and Imaging with CIP Tomography 291
6.4 Subsalt Pore Pressure Applications 297
6.5 Rock Physics Guided Velocity Modeling for Pore Pressure and Imaging with FWI 306
6.6 Summary 308
## Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Methods for Pore Pressure Detection: Well Logging and Drilling Parameters</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>7.1 Introduction</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>7.2 Logging Tools</td>
<td>311</td>
</tr>
<tr>
<td></td>
<td>7.3 Pore Pressure from Well Logging Methods</td>
<td>313</td>
</tr>
<tr>
<td></td>
<td>7.4 Recommendations on Use of Wireline Logs for Pore Pressure Analysis</td>
<td>327</td>
</tr>
<tr>
<td></td>
<td>7.5 Drilling Parameters for Pore Pressure Analysis</td>
<td>329</td>
</tr>
<tr>
<td>8</td>
<td>Gravity and EM Field Methods Aiding Pore Pressure Prediction</td>
<td>338</td>
</tr>
<tr>
<td></td>
<td>8.1 Introduction</td>
<td>338</td>
</tr>
<tr>
<td></td>
<td>8.2 Gravity Method</td>
<td>339</td>
</tr>
<tr>
<td></td>
<td>8.3 Electromagnetic Method</td>
<td>341</td>
</tr>
<tr>
<td></td>
<td>8.4 Joint Inversion</td>
<td>343</td>
</tr>
<tr>
<td></td>
<td>8.5 Concluding Remarks</td>
<td>347</td>
</tr>
<tr>
<td>9</td>
<td>Geopressure Detection and Prediction in Real Time</td>
<td>348</td>
</tr>
<tr>
<td></td>
<td>9.1 Introduction</td>
<td>348</td>
</tr>
<tr>
<td></td>
<td>9.2 Strategy for Real-Time Update and Prediction Ahead of the Bit</td>
<td>348</td>
</tr>
<tr>
<td></td>
<td>9.3 Pore Pressure Prediction Methods in Real-Time</td>
<td>352</td>
</tr>
<tr>
<td></td>
<td>9.4 Seismic-While-Drilling Technology for Real-Time Pore Pressure Prediction</td>
<td>356</td>
</tr>
<tr>
<td></td>
<td>9.5 Geopressure Prediction in Real-Time Using Basin Modeling</td>
<td>365</td>
</tr>
<tr>
<td></td>
<td>9.6 Summary</td>
<td>367</td>
</tr>
<tr>
<td>10</td>
<td>Geopressure Prediction Using Basin History Modeling</td>
<td>368</td>
</tr>
<tr>
<td></td>
<td>10.1 Introduction: Basin and Petroleum System Modeling</td>
<td>368</td>
</tr>
<tr>
<td></td>
<td>10.2 Governing Equations for Mathematical Basin Modeling</td>
<td>369</td>
</tr>
<tr>
<td></td>
<td>10.3 Basin Modeling: Compaction, Diagenesis, and Overpressure</td>
<td>371</td>
</tr>
<tr>
<td></td>
<td>10.4 Basin Modeling in 3D</td>
<td>389</td>
</tr>
<tr>
<td>11</td>
<td>Geohazard Prediction and Detection</td>
<td>392</td>
</tr>
<tr>
<td></td>
<td>11.2 Shallow-Waterflow-Sands (SWF)</td>
<td>393</td>
</tr>
<tr>
<td></td>
<td>11.3 Shallow Gas as Geohazard</td>
<td>411</td>
</tr>
<tr>
<td></td>
<td>11.4 Gas Hydrate as Geohazard</td>
<td>414</td>
</tr>
<tr>
<td></td>
<td>11.5 Geohazard Mitigation (Dynamic Kill Drill or DKD Procedure)</td>
<td>418</td>
</tr>
<tr>
<td></td>
<td>11.6 Recommendations for Detection of Geohazards</td>
<td>419</td>
</tr>
<tr>
<td></td>
<td>11.7 Concluding Remarks</td>
<td>420</td>
</tr>
<tr>
<td>12</td>
<td>Petroleum Geomechanics and the Role of Geopressure</td>
<td>421</td>
</tr>
<tr>
<td></td>
<td>12.1 Introduction</td>
<td>421</td>
</tr>
<tr>
<td></td>
<td>12.2 Borehole Stability and Pore Pressure</td>
<td>423</td>
</tr>
</tbody>
</table>
Contents

12.3 Petroleum Geomechanics Modeling 428
12.4 4D Geomechanics and 4D Earth Model Building 446
12.5 Summary 451

13 Guidelines for Best Practices: Geopressure Prediction and Analysis 452
13.1 Introduction 452
13.2 Subsurface Geological Habitat for Geopressure (Geology) 453
13.3 Physics of Pore Pressure Generation (Models) 458
13.4 Technology for Subsurface Prediction (Tools) 461
13.5 Uncertainty Analysis 468

14 Recent Advances in Geopressure Prediction and Detection Technology and the Road Ahead 479
14.1 Introduction 479
14.2 Seismic Technology 479
14.3 Models That Relate Velocity to Pore Pressure 481
14.4 Seismic Velocity Analysis for Pore Pressure Prediction: What We Have Learned and the Road Ahead 482
14.5 Pore Pressure Prediction in Real-Time 486
14.6 Integration of Disciplines 487
14.7 Data Analytics and Machine Learning 487
14.8 Summary 490

Appendices 491
A Empirical Relations for Fluid (Brine, Oil, Gas) Properties 491
B Basic Definitions 496
C Dimensionless Coordinate Transformation of 1D Basin Modeling Equation 498

References 501
Index 532

Color plates can be found between pages 268 and 269.
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 geopressing 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!