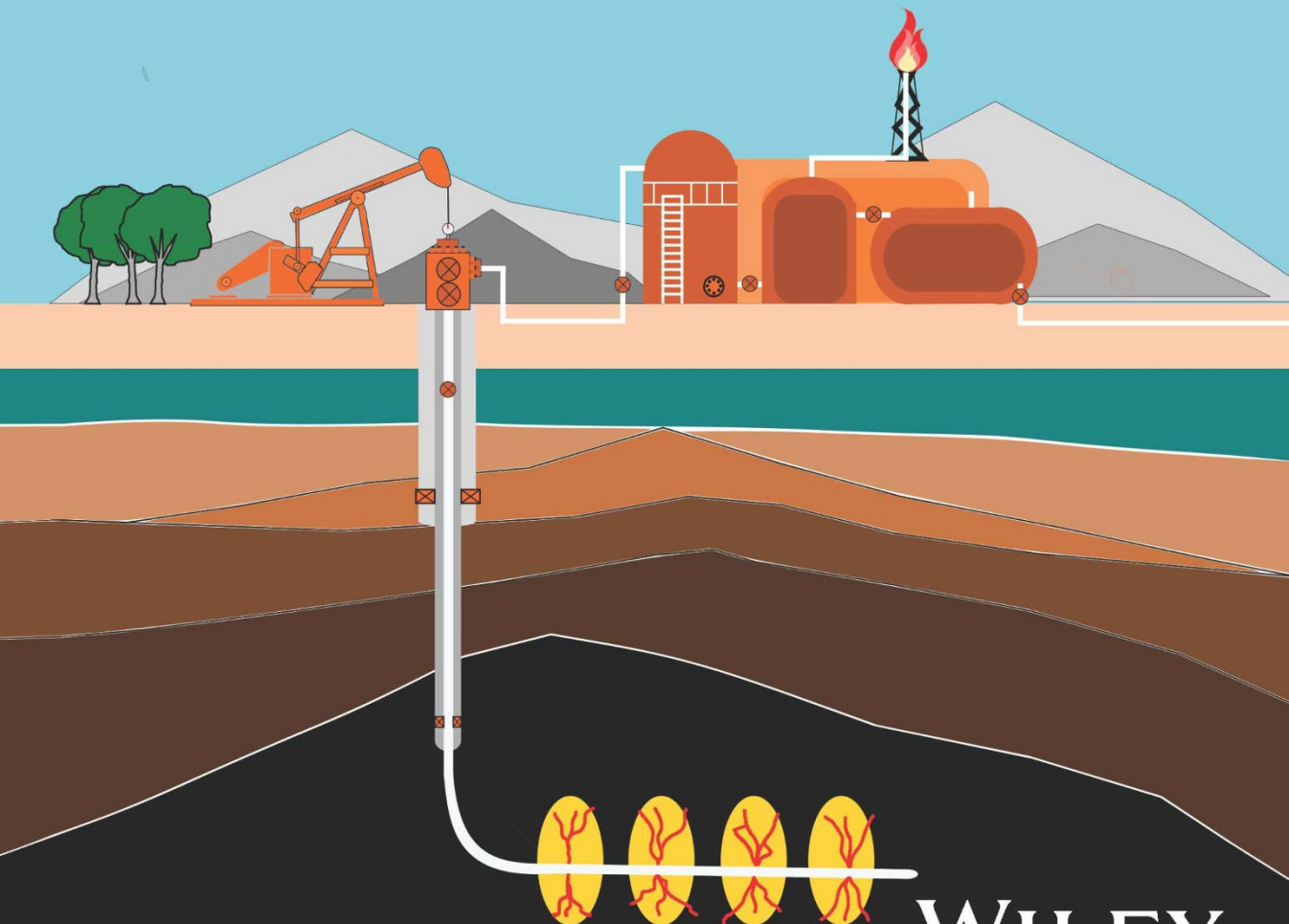


# Physics of Fluid Flow and Transport in Unconventional Reservoir Rocks

Edited by **Behzad Ghanbarian**  
**Feng Liang** • **Hui-Hai Liu**



**WILEY**



**Physics of Fluid Flow and Transport in  
Unconventional Reservoir Rocks**



# Physics of Fluid Flow and Transport in Unconventional Reservoir Rocks

*Edited by*

*Behzad Ghanbarian*

*Feng Liang*

*Hui-Hai Liu*

**WILEY**

Copyright © 2023 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.  
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at [www.copyright.com](http://www.copyright.com). Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Trademarks: Wiley and the Wiley logo are trademarks or registered trademarks of John Wiley & Sons, Inc. and/or its affiliates in the United States and other countries and may not be used without written permission. All other trademarks are the property of their respective owners. John Wiley & Sons, Inc. is not associated with any product or vendor mentioned in this book.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at [www.wiley.com](http://www.wiley.com).

#### *Library of Congress Cataloging-in-Publication Data*

Names: Ghanbarian, Behzad, editor. | Liang, Feng, editor. | Liu, Hui-Hai, editor.

Title: Physics of fluid flow and transport in unconventional reservoir rocks / edited by Behzad Ghanbarian, Feng Liang, Hui-Hai Liu.

Description: First edition. | Hoboken, NJ, USA : John Wiley & Sons, Inc., 2023. | Includes bibliographical references and index.

Identifiers: LCCN 2022052921 (print) | LCCN 2022052922 (ebook) | ISBN 9781119729877 (hardback) | ISBN 9781119727842 (adobe pdf) | ISBN 9781119729907 (epub)

Subjects: LCSH: Hydrocarbon reservoirs—Analysis. | Rocks—Permeability. | Petroleum—Migration. | Gas reservoir engineering. | Fluid dynamics. | Transport theory. | Petrology.

Classification: LCC TN870.56 .P54 2023 (print) | LCC TN870.56 (ebook) | DDC 622/.338—dc23/eng/20221230

LC record available at <https://lcn.loc.gov/2022052921>

LC ebook record available at <https://lcn.loc.gov/2022052922>

Cover Design: Wiley

Cover Image: © BalLi8Tic/Shutterstock

Set in 9.5/12.5pt STIXTwoText by Straive, Pondicherry, India

*Our families for their countless support, endless inspiration, and more importantly unconditional love.*





## Contents

**List of Contributors** *xvii*

**Preface** *xxi*

**Introduction** *1*

### **1 Unconventional Reservoirs: Advances and Challenges** *3*

*Behzad Ghanbarian, Feng Liang, and Hui-Hai Liu*

- 1.1 Background *3*
- 1.2 Advances *4*
  - 1.2.1 Wettability *4*
  - 1.2.2 Permeability *5*
- 1.3 Challenges *7*
  - 1.3.1 Multiscale Systems *7*
  - 1.3.2 Hydrocarbon Production *9*
  - 1.3.3 Recovery Factor *9*
  - 1.3.4 Unproductive Wells *9*
- 1.4 Concluding Remarks *11*
- References *11*

### **Part I Pore-Scale Characterizations** *15*

### **2 Pore-Scale Simulations and Digital Rock Physics** *17*

*Junjian Wang, Feifei Qin, Jianlin Zhao, Li Chen, Hari Viswanathan, and Qinjun Kang*

- 2.1 Introduction *17*
- 2.2 Physics of Pore-Scale Fluid Flow in Unconventional Rocks *18*
  - 2.2.1 Physics of Gas Flow *18*
    - 2.2.1.1 Gas Slippage and Knudsen Layer Effect *18*
    - 2.2.1.2 Gas Adsorption/Desorption and Surface Diffusion *20*
  - 2.2.2 Physics of Water Flow *22*
  - 2.2.3 Physics of Condensation *23*
- 2.3 Theory of Pore-Scale Simulation Methods *23*
  - 2.3.1 The Isothermal Single-Phase Lattice Boltzmann Method *23*

2.3.1.1	Bhatnagar–Gross–Krook (BGK) Collision Operator	24
2.3.1.2	The Multi-Relaxation Time (MRT)-LB Scheme	24
2.3.1.3	The Regularization Procedure	26
2.3.2	Multi-phase Lattice Boltzmann Simulation Method	27
2.3.2.1	Color-Gradient Model	27
2.3.2.2	Shan-Chen Model	28
2.3.3	Capture Fluid Slippage at the Solid Boundary	29
2.3.4	Capture the Knudsen Layer/Effective Viscosity	30
2.3.5	Capture the Adsorption/Desorption and Surface Diffusion Effects	30
2.3.5.1	Modeling of Adsorption in LBM	30
2.3.5.2	Modeling of Surface Diffusion Via LBM	31
2.4	Applications	32
2.4.1	Simulation of Gas Flow in Unconventional Reservoir Rocks	32
2.4.1.1	Gas Slippage	32
2.4.1.2	Gas Adsorption	33
2.4.1.3	Surface Diffusion of Adsorbed Gas	35
2.4.2	Simulation of Water Flow in Unconventional Reservoir Rocks	35
2.4.3	Simulation of Immiscible Two-Phase Flow	39
2.4.4	Simulation of Vapor Condensation	43
2.4.4.1	Model Validations	44
2.4.4.2	Vapor Condensation in Two Adjacent Nano-Pores	44
2.5	Conclusion	48
	References	49

### **3 Digital Rock Modeling: A Review 53**

*Yuqi Wu and Pejman Tahmasebi*

3.1	Introduction	53
3.2	Single-Scale Modeling of Digital Rocks	54
3.2.1	Experimental Techniques	54
3.2.1.1	Imaging Technique of Serial Sectioning	54
3.2.1.2	Laser Scanning Confocal Microscopy	54
3.2.1.3	X-Ray Computed Tomography Scanning	55
3.2.2	Computational Methods	55
3.2.2.1	Simulated Annealing	56
3.2.2.2	Markov Chain Monte Carlo	56
3.2.2.3	Sequential Indicator Simulation	56
3.2.2.4	Multiple-Point Statistics	57
3.2.2.5	Machine Learning	58
3.2.2.6	Process-Based Modeling	58
3.3	Multiscale Modeling of Digital Rocks	59
3.3.1	Multiscale Imaging Techniques	60
3.3.2	Computational Methods	60
3.3.2.1	Image Superposition	60
3.3.2.2	Pore-Network Integration	61

- 3.3.2.3 Image Resolution Enhancement 63
- 3.3.2.4 Object-Based Reconstruction 63
- 3.4 Conclusions and Future Perspectives 65
- Acknowledgments 66
- References 66

## **4 Scale Dependence of Permeability and Formation Factor: A Simple Scaling Law 77**

*Behzad Ghanbarian and Misagh Esmailpour*

- 4.1 Introduction 77
- 4.2 Theory 78
  - 4.2.1 Funnel Defect Approach 78
  - 4.2.2 Application to Porous Media 79
- 4.3 Pore-network Simulations 80
- 4.4 Results and Discussion 81
- 4.5 Limitations 86
- 4.6 Conclusion 86
- Acknowledgment 86
- References 87

## **Part II Core-Scale Heterogeneity 89**

## **5 Modeling Gas Permeability in Unconventional Reservoir Rocks 91**

*Behzad Ghanbarian, Feng Liang, and Hui-Hai Liu*

- 5.1 Introduction 91
  - 5.1.1 Theoretical Models 91
  - 5.1.2 Pore-Network Models 92
  - 5.1.3 Gas Transport Mechanisms 93
  - 5.1.4 Objectives 93
- 5.2 Effective-Medium Theory 93
- 5.3 Single-Phase Gas Permeability 95
  - 5.3.1 Gas Permeability in a Cylindrical Tube 95
  - 5.3.2 Pore Pressure-Dependent Gas Permeability in Tight Rocks 96
  - 5.3.3 Comparison with Experiments 96
  - 5.3.4 Comparison with Pore-Network Simulations 98
  - 5.3.5 Comparison with Lattice-Boltzmann Simulations 99
- 5.4 Gas Relative Permeability 100
  - 5.4.1 Hydraulic Flow in a Cylindrical Pore 100
  - 5.4.2 Molecular Flow in a Cylindrical Pore 101
  - 5.4.3 Total Gas Flow in a Cylindrical Pore 101
  - 5.4.4 Gas Relative Permeability in Tight Rocks 101
  - 5.4.5 Comparison with Experiments 102
  - 5.4.6 Comparison with Pore-Network Simulations 107
- 5.5 Conclusions 108
- Acknowledgment 109
- References 109

<b>6</b>	<b>NMR and Its Applications in Tight Unconventional Reservoir Rocks</b>	<b>113</b>
	<i>Jin-Hong Chen, Mohammed Boudjatit, and Stacey M. Althaus</i>	
6.1	Introduction	113
6.2	Basic NMR Physics	113
6.2.1	Nuclear Spin	114
6.2.2	Nuclear Zeeman Splitting and NMR	114
6.2.3	Nuclear Magnetization	115
6.2.4	Bloch Equations and NMR Relaxation	116
6.2.5	Simple NMR Experiments: Free Induction Decay and CPMG Echoes	117
6.2.6	NMR Relaxation of a Pure Fluid in a Rock Pore	118
6.2.7	Measured NMR CPMG Echoes in a Formation Rock	119
6.2.8	Inversion	119
6.2.8.1	Regularized Linear Least Squares	120
6.2.8.2	Constraints of the Resulted NMR Spectrum in Inversion	120
6.2.9	Data from NMR Measurement	121
6.3	NMR Logging for Unconventional Source Rock Reservoirs	121
6.3.1	Brief Introduction of Unconventional Source Rocks	121
6.3.2	NMR Measurement of Source Rocks	122
6.3.2.1	NMR Log of a Source Rock Reservoir	122
6.3.3	Pore Size Distribution in a Shale Gas Reservoir	124
6.4	NMR Measurement of Long Whole Core	125
6.4.1	Issues of NMR Instrument for Long Sample	125
6.4.2	HSR-NMR of Long Core	126
6.4.3	Application Example	128
6.5	NMR Measurement on Drill Cuttings	130
6.5.1	Measurement Method	131
6.5.1.1	Preparation of Drill Cuttings	131
6.5.1.2	Measurements	131
6.5.2	Results	132
6.6	Conclusions	133
	References	135
<b>7</b>	<b>Tight Rock Permeability Measurement in Laboratory: Some Recent Progress</b>	<b>139</b>
	<i>Hui-Hai Liu, Jilin Zhang, and Mohammed Boudjatit</i>	
7.1	Introduction	139
7.2	Commonly Used Laboratory Methods	140
7.2.1	Steady-State Flow Method	140
7.2.2	Pressure Pulse-Decay Method	141
7.2.3	Gas Research Institute Method	143
7.3	Simultaneous Measurement of Fracture and Matrix Permeabilities from Fractured Core Samples	144
7.3.1	Estimation of Fracture and Matrix Permeability from PPD Data for Two Flow Regimes	144

7.3.2	Mathematical Model	146
7.3.3	Method Validation and Discussion	148
7.4	Direct Measurement of Permeability-Pore Pressure Function	150
7.4.1	Knudsen Diffusion, Slippage Flow, and Effective Gas Permeability	150
7.4.2	Methodology for Directly Measuring Permeability-Pore Pressure Function	152
7.4.3	Experiments	155
7.5	Summary and Conclusions	159
	References	159
<b>8</b>	<b>Stress-Dependent Matrix Permeability in Unconventional Reservoir Rocks</b>	<b>163</b>
	<i>Athma R. Bhandari, Peter B. Flemings, and Sebastian Ramiro-Ramirez</i>	
8.1	Introduction	163
8.2	Sample Descriptions	164
8.3	Permeability Test Program	165
8.4	Permeability Behavior with Confining Stress Cycling	166
8.5	Matrix Permeability Behavior	170
8.6	Concluding Remarks	172
	Acknowledgments	174
	References	174
<b>9</b>	<b>Assessment of Shale Wettability from Spontaneous Imbibition Experiments</b>	<b>177</b>
	<i>Zhiye Gao and Qinhong Hu</i>	
9.1	Introduction	177
9.2	Spontaneous Imbibition Theory	178
9.3	Samples and Analytical Methods	179
9.3.1	SI Experiments	179
9.3.2	Barnett Shale from United States	180
9.3.3	Silurian Longmaxi Formation and Triassic Yanchang Formation Shales from China	180
9.3.4	Jurassic Ziliujing Formation Shale from China	182
9.4	Results and Discussion	183
9.4.1	Complicated Wettability of Barnett Shale Inferred Qualitatively from SI Experiments	183
9.4.1.1	Wettability of Barnett Shale	184
9.4.1.2	Properties of Barnett Samples and Their Correlation to Wettability	186
9.4.1.3	Low Pore Connectivity to Water of Barnett Samples	187
9.4.2	More Oil-Wet Longmaxi Formation Shale and More Water-Wet Yanchang Formation Shale	188
9.4.2.1	TOC and Mineralogy	188
9.4.2.2	Pore Structure Difference Between Longmaxi and Yanchang Samples	188
9.4.2.3	Water and Oil Imbibition Experiments	191
9.4.2.4	Wettability of Longmaxi and Yanchang Shale Samples Deduced from SI Experiments	197

- 9.4.3 Complicated Wettability of Ziliujing Formation Shale 197
  - 9.4.3.1 TOC and Mineralogy 197
  - 9.4.3.2 Pore Structure 197
  - 9.4.3.3 Water and Oil Imbibition Experiments 200
  - 9.4.3.4 Wettability of Ziliujing Formation Shale Indicated from SI Experiments and its Correlation to Shale Pore Structure and Composition 201
- 9.4.4 Shale Wettability Evolution Model 201
- 9.5 Conclusions 204
  - Acknowledgments 204
  - References 204

## **10 Permeability Enhancement in Shale Induced by Desorption 209**

*Brandon Schwartz and Derek Elsworth*

- 10.1 Introduction 209
  - 10.1.1 Shale Mineralogical Characteristics 209
  - 10.1.2 Flow Network 210
    - 10.1.2.1 Bedding-Parallel Flow Network 211
    - 10.1.2.2 Bedding-Perpendicular Flow Paths 212
- 10.2 Adsorption in Shales 214
  - 10.2.1 Langmuir Theory 214
  - 10.2.2 Competing Strains in Permeability Evolution 215
    - 10.2.2.1 Poro-Sorptive Strain 215
    - 10.2.2.2 Thermal-Sorptive Strain 218
- 10.3 Permeability Models for Sorptive Media 218
  - 10.3.1 Strain Based Models 219
- 10.4 Competing Processes during Permeability Evolution 220
  - 10.4.1 Resolving Competing Strains 220
  - 10.4.2 Solving for Sorption-Induced Permeability Evolution 221
- 10.5 Desorption Processes Yielding Permeability Enhancement 223
  - 10.5.1 Pressure Depletion 223
  - 10.5.2 Lowering Partial Pressure 224
  - 10.5.3 Sorptive Gas Injection 225
  - 10.5.4 Desorption with Increased Temperature 225
- 10.6 Permeability Enhancement Due to Nitrogen Flooding 225
- 10.7 Discussion 226
- 10.8 Conclusion 228
  - References 229

## **11 Multiscale Experimental Study on Interactions Between Imbibed Stimulation Fluids and Tight Carbonate Source Rocks 235**

*Feng Liang, Hui-Hai Liu, and Jilin Zhang*

- 11.1 Introduction 235
- 11.2 Fluid Uptake Pathways 236

11.2.1	Experimental Methods	236
11.2.1.1	Materials	236
11.2.1.2	Experimental Procedure	237
11.2.2	Results and Discussion	237
11.2.2.1	Surface Characterization	237
11.2.2.2	Spontaneous Imbibition Tests	239
11.3	Mechanical Property Change After Fluid Exposure	240
11.3.1	Experimental Methods	242
11.3.1.1	Materials	242
11.3.1.2	Experimental Procedure	242
11.3.2	Results and Discussion	243
11.3.2.1	UCS and Brazilian Test on Cylindrical Core Plugs	243
11.3.2.2	Microindentation Test	243
11.4	Morphology and Minerology Changes After Fluid Exposure	245
11.4.1	Experimental Methods	247
11.4.1.1	Materials	247
11.4.1.2	Experimental Procedure	248
11.4.2	Results and Discussion	248
11.4.2.1	SEM and EDS Mapping of Thin-Section Surface before Fluid Treatment	248
11.4.2.2	SEM and EDS Mapping of Thin-Section Surface after Fluid Treatment	251
11.4.2.3	Quantification of Dissolved Ions in the Treatment Fluids	256
11.5	Flow Property Change After Fluid Exposure	257
11.5.1	Experimental Methods	258
11.5.1.1	Materials	258
11.5.1.2	Experimental Procedure	258
11.5.2	Results and Discussion	258
11.5.2.1	Changes in Flow Characteristics	258
11.6	Conclusions	259
	References	261

### Part III Large-Scale Petrophysics 265

## 12 Effective Permeability in Fractured Reservoirs: Percolation-Based Effective-Medium Theory 267

*Behzad Ghanbarian*

12.1	Introduction	267
12.1.1	Percolation Theory	267
12.1.2	Effective-Medium Theory	268
12.2	Objectives	269
12.3	Percolation-Based Effective-Medium Theory	269
12.4	Comparison with Simulations	270
12.4.1	Chen et al. (2019)	270
12.4.1.1	Two-Dimensional Simulations	271

12.4.1.2	Three-Dimensional Simulations	273
12.4.2	New Three-Dimensional Simulations	274
12.5	Conclusion	275
	Acknowledgment	277
	References	277
<b>13</b>	<b>Modeling of Fluid Flow in Complex Fracture Networks for Shale Reservoirs</b>	<b>281</b>
	<i>Hongbing Xie, Xiaona Cui, Wei Yu, Chuxi Liu, Jijun Miao, and Kamy Sepehrnoori</i>	
13.1	Shale Reservoirs with Complex Fracture Networks	281
13.2	Complex Fracture Reservoir Simulation	281
13.3	Embedded Discrete Fracture Model	283
13.4	EDFM Verification	286
13.5	Well Performance Study – Base Case	290
13.6	Effect of Natural Fracture Connectivity on Well Performance	294
13.6.1	Effect of Natural Fracture Azimuth	294
13.6.2	Effect of Number of Natural Fractures	295
13.6.3	Effect of Natural Fracture Length	298
13.6.4	Effect of Number of Sets of Natural Fractures	301
13.6.5	Effect of Natural Fracture Dip Angle	305
13.7	Effect of Natural Fracture Conductivity on Well Performance	306
13.8	Conclusions	311
	References	312
<b>14</b>	<b>A Closed-Form Relationship for Production Rate in Stress-Sensitive Unconventional Reservoirs</b>	<b>315</b>
	<i>Hui-Hai Liu, Huangye Chen, and Yanhui Han</i>	
14.1	Introduction	315
14.2	Production Rate as a Function of Time in the Linear Flow Regime Under the Constant Pressure Drawdown Condition	317
14.3	An Approximate Relationship Between Parameter $A$ and Stress-Dependent Permeability	318
14.4	Evaluation of the Relationship Between Parameter $A$ and Stress-Dependent Permeability	321
14.5	Equivalent State Approximation for the Variable Pressure Drawdown Conditions	327
14.6	Discussions	328
14.7	Concluding Remarks	329
	Nomenclature	329
	Subscript	330
	Appendix 14.A Derivation of Eq. (14.22) with Integration by Parts	330
	References	331



<b>15</b>	<b>Sweet Spot Identification in Unconventional Shale Reservoirs</b>	<b>333</b>
	<i>Rabah Mesdour, Mustafa Basri, Cenk Temizel, and Nayif Jama</i>	
15.1	Introduction	333
15.2	Reservoir Characterization	334
15.3	Sweet Spot Identification	334
15.3.1	The Method Based on Organic, Rock and Mechanical Qualities	335
15.3.2	Methods Based on Geological and Engineering Sweet Spots	337
15.3.3	Methods Based on Other Quality Indicators	340
15.3.4	Methods Based on Data Mining and Machine Learning	343
15.4	Discussion	345
15.5	Conclusion	346
	References	347
	<b>Index</b>	<b>351</b>



## List of Contributors

**Stacey M. Althaus**

Aramco Americas: Aramco Research  
Center—Houston  
Houston, TX, USA

**Mustafa Basri**

Saudi Aramco, Dhahran  
Saudi Arabia

**Athma R. Bhandari**

Institute for Geophysics, Jackson  
School of Geosciences  
The University of Texas at Austin  
Austin, TX, USA

**Mohammed Boudjatit**

Saudi Aramco, Dhahran  
Saudi Arabia

**Huangye Chen**

Aramco Americas: Aramco Research  
Center—Houston  
Houston, TX, USA

**Jin-Hong Chen**

Aramco Americas: Aramco Research  
Center—Houston  
Houston, TX, USA

**Li Chen**

Key Laboratory of Thermo-Fluid Science and  
Engineering of MOE  
School of Energy and Power Engineering  
Xi'an Jiaotong University  
Xi'an, Shaanxi, China

**Xiaona Cui**

SimTech LLC  
Katy, TX, USA

**Derek Elsworth**

Department of Energy and Mineral Engineering  
EMS Energy Institute and G3 Center  
Penn State University  
University Park, PA  
USA

**Misagh Esmailpour**

Porous Media Research Lab  
Department of Geology  
Kansas State University  
Manhattan, KS, USA

**Peter B. Flemings**

Institute for Geophysics  
Jackson School of Geosciences  
The University of Texas at Austin  
Austin, TX, USA  
and  
Department of Geological Sciences  
Jackson School of Geosciences  
The University of Texas at Austin  
Austin, TX, USA

**Zhiye Gao**

State Key Laboratory of Petroleum Resources  
and Prospecting  
China University of Petroleum, Beijing, China  
and  
Unconventional Petroleum Research Institute,  
China University of Petroleum, Beijing, China

***Behzad Ghanbarian***

Porous Media Research Lab  
Department of Geology  
Kansas State University  
Manhattan, KS, USA

***Yanhui Han***

Aramco Americas: Aramco Research  
Center—Houston  
Houston, TX, USA

***Qinhong Hu***

Department of Earth and Environmental  
Sciences  
University of Texas at Arlington  
Arlington, TX, USA

***Nayif Jama***

Saudi Aramco, Dhahran, Saudi Arabia

***Qinjun Kang***

Earth and Environmental Sciences Division  
Los Alamos National Laboratory  
Los Alamos, NM, USA

***Feng Liang***

Aramco Americas: Aramco Research  
Center—Houston  
Houston, TX, USA

***Chuxi Liu***

The University of Texas at Austin  
Hildebrand Department of Petroleum  
and Geosystems Engineering  
Austin, TX, USA

***Hui-Hai Liu***

Aramco Americas: Aramco Research  
Center—Houston  
Houston, TX, USA

***Rabah Mesdour***

Saudi Aramco, Dhahran, Saudi Arabia

***Jijun Miao***

SimTech LLC  
Katy, TX, USA

***Feifei Qin***

Chair of Building Physics  
Department of Mechanical and Process  
Engineering  
ETH Zürich, Zurich, Switzerland

***Sebastian Ramiro-Ramirez***

Institute for Geophysics, Jackson School of  
Geosciences  
The University of Texas at Austin  
Austin, TX, USA  
and  
Department of Geological Sciences  
Jackson School of Geosciences  
The University of Texas at Austin  
Austin, TX, USA

***Brandon Schwartz***

Department of Energy and Mineral  
Engineering, EMS Energy Institute  
and G3 Center  
Penn State University  
University Park, PA, USA

***Kamy Sepehrnoori***

The University of Texas at Austin  
Hildebrand Department of Petroleum  
and Geosystems Engineering  
Austin, TX, USA

***Pejman Tahmasebi***

Colorado School of Mines  
Golden 80401, USA

***Cenk Temizel***

Saudi Aramco  
Dhahran, Saudi Arabia

***Hari Viswanathan***

Earth and Environmental Sciences Division  
Los Alamos National Laboratory  
Los Alamos, NM, USA

***Junjian Wang***

Klohn Crippen Berger Ltd  
Brisbane, Queensland  
Australia

***Yuqi Wu***

Shandong Provincial Key Laboratory of Deep  
Oil and Gas  
China University of Petroleum (East China)  
Qingdao, China  
and

School of Geosciences, China University of  
Petroleum (East China), Qingdao, China

***Hongbing Xie***

SimTech LLC  
Katy, TX, USA

***Wei Yu***

SimTech LLC  
Katy, TX, USA  
and

The University of Texas at Austin  
Hildebrand Department of Petroleum  
and Geosystems Engineering  
Austin, TX, USA

***Jilin Zhang***

Aramco Americas: Aramco Research  
Center—Houston  
Houston, TX, USA

***Jianlin Zhao***

Chair of Building Physics  
Department of Mechanical and Process  
Engineering  
ETH Zürich  
Zurich, Switzerland



## Preface

This book provides basic concepts and recent advances of fluid flow and transport in unconventional reservoirs across different scales (from pore to core and to reservoir) for a broad range of audiences from various scientific disciplines, such as geology, geoscience, geochemistry, geophysics, rock mechanics, and petroleum engineering. In the Introduction chapter, we address recent progress and ongoing challenges related to hydrocarbon exploration and production in tight and ultra-tight formations. The first part of the book on pore-scale characterizations consists of three chapters. In the second chapter, Wang and his coworkers present an overview of recent progress on pore-scale simulations and digital rock physics to unconventional reservoir rocks. They emphasize that further small-scale experiments are still required to validate numerical models. In Chapter 3, Wu and Tahmasebi review digital rock models. They discuss that incorporating multiresolution and multiscale structures and generating large-scale digital models are still very challenging. In Chapter 4, Ghanbarian and Esmaeilpour address the effect of scale on permeability and formation factor. They present a simple scaling law and show reasonable agreement between theoretical estimations and pore-network simulations. Part II of the book on core-scale heterogeneity includes seven chapters. In Chapter 5, Ghanbarian et al. study theoretical modeling of single-phase and gas relative permeabilities in shales and tight porous rocks. They apply concepts of the effective-medium approximation and demonstrate that by including the physics of gas flow, one can estimate permeability reasonably well at the core scale. Chapter 6 by Chen and his coworkers addresses applications of nuclear magnetic resonance and its recent advances to determine total porosity and partial porosity in organic matter of unconventional reservoir rocks. In Chapter 7, recent progress on tight rock permeability measurement is addressed by Liu, Zhang, and Boudjatit. They present two newly developed laboratory methods and evaluate them using laboratory measurements. Chapter 8 by Bhandari et al. presents permeability evolution under cycling confining stress conditions. They demonstrate that micro-fractures might be closed due to confining stress leading to permeability reduction under cyclic loading. In Chapter 9, Gao and Hu provide insights into shale wettability using spontaneous imbibition experiments. Their results demonstrate the co-existence of water and oil in the pore network of shales proving their mixed-wet characteristics. In Chapter 10, Schwartz and Elsworth study permeability enhancement in shales induced by desorption. Those authors argue that the magnitude of permeability enhancement depends on the distribution of sorptive mineral components, geometry of flow path, and initial permeability. Chapter 11 by Liang, Liu, and Zhang provides insights that help improve oil and gas production in unconventional reservoirs. More specifically, their experimental evidence shows that aqueous-based fracturing fluid may have positive impacts on gas production from organic-rich carbonate source rocks. The last part of the book focuses on large-scale petrophysics of unconventional reservoirs, which has broad applications to field.

In Chapter 12, Ghanbarian proposes percolation-based effective-medium theory to model effective permeability in matrix-fracture systems. By comparing with numerical simulations, he shows that effective permeability can be accurately estimated at different fracture densities. In Chapter 13, Xie et al. apply embedded discrete fracture model to simulate fluid flow in complex fracture networks. They address the effect of natural fracture properties, such as fracture azimuth, length, and dip angle. Chapter 14 by Liu and his coauthors presents a closed-form relationship for production rate. By comparing with numerical simulations, Liu et al. validate their proposed model for different initial reservoir pressures, pressure drawdowns, and pressure sensitivity factors for permeability. In the last chapter, Mesdour et al. discuss sweet spots and their identification in shale reservoirs. They provide a state-of-art review of existing methods developed for sweet spot identification and address relevant challenges and knowledge gaps.

Many colleagues and students contributed to our understanding of fluid flow and transport in unconventional reservoirs. We are grateful to those who helped us with this book. We also acknowledge those who contributed to this book by writing different chapters on several topics. We hope this book helps geologists and petroleum engineers in industry as well as faculty and students in academia.

Behzad Ghanbarian  
Feng Liang  
Hui-Hai Liu  
January 2023



## Introduction



# 1

## Unconventional Reservoirs

### Advances and Challenges

*Behzad Ghanbarian<sup>1</sup>, Feng Liang<sup>2</sup>, and Hui-Hai Liu<sup>2</sup>*

<sup>1</sup> Porous Media Research Lab, Department of Geology, Kansas State University, Manhattan, KS, USA

<sup>2</sup> Aramco Americas: Aramco Research Center—Houston, Houston, TX, USA

### 1.1 Background

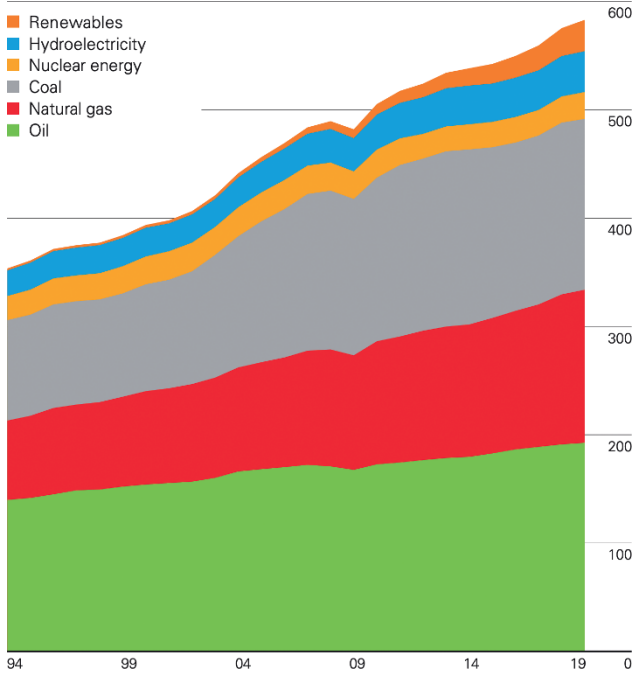
Energy is one of the most important components in the world. Primary sources of energy take various forms, such as fossil energy, nuclear energy, and renewable energy sources. Fossil energy resources (e.g. coal, oil, and natural gas) were formed when plants and animals died and were buried underground. The quality of hydrocarbon accordingly depends on organic content as well as temperature and pressure conditions. Although there are limited reserves of fossil energy resources and despite recent advances in renewable energy, global economy still depends on fossil fuels to a great extent (Figure 1.1). Statistics reported by the British Petroleum (BP) company based on data from 1994 to 2019 show that the world primary energy consumption growth in 2019 slowed to 1.3%. This is less than half the growth rate i.e. 2.8% in 2018. Three-quarters of the energy consumption increase was driven by natural gas and renewable resources in 2019.

Based on analyses reported by the BP company, oil has contributed to the share of global primary energy more than others since 1994 (Figure 1.2) with 33.1% contribution in 2019. After oil, coal and natural gas are the second and third largest contributors. Although coal lost its share to account for nearly 27%, the contribution of natural gas increased to 24% in 2019. The share of renewable resources rose to record highs of 5% in 2019, and they overtook nuclear energy with about 4% contribution. Figure 1.2 shows the share of hydroelectricity has been nearly constant and about 6%.

Unconventional reservoirs, including oil and gas shales and tight sandstones, are distributed around the world (Figure 1.3) with an estimated endowment of several thousand trillion cubic feet (Kim et al. 2000). Since shale reservoirs have been successfully explored and produced in the United States (Figure 1.3), they recently became one of the major contributors to energy supplies.

There exist three general types of unconventional reservoirs, i.e. (i) organic-rich source rocks, (ii) tight oil reservoirs, and (iii) hybrid plays in which production occurs from source rocks and conventional reservoirs (Zoback and Kohli 2019). These types of unconventional reservoirs are different in geologic formations and, therefore, should be optimally exploited using different and appropriate approaches.

Despite numerous practical applications in oil/gas exploration and production as well as recent progress, we are still far from fully understanding all mechanisms of flow and transport in shales



**Figure 1.1** World total energy consumption between 1994 and 2019. *Source:* BP Statistical Review of World Energy (2020)/BP International Limited.

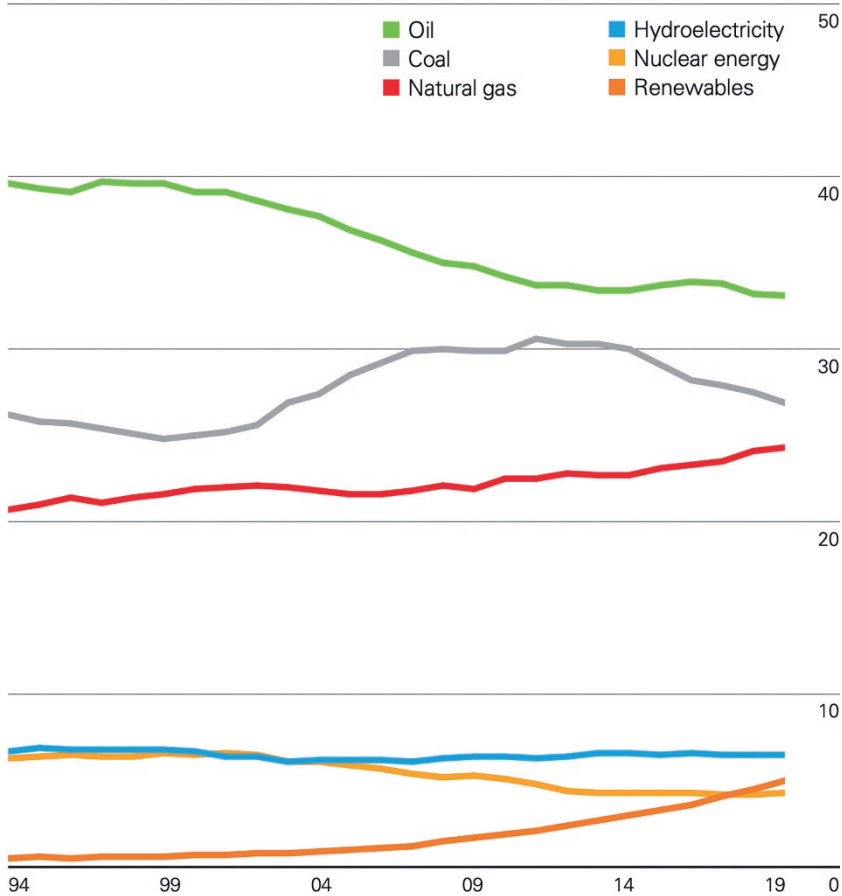
and tight sandstones across scales, *particularly from pore to reservoir*. In the following, we briefly address recent advances in unconventional reservoirs and discuss current challenges in oil and gas exploration and production.

## 1.2 Advances

Since 2005, the beginning of shale gas revolution in the United States, unconventional oil and gas resources as well as their developments and productions have received a remarkable amount of attention around the world (Zoback and Kohli 2019). Despite various challenges that still exist, the petroleum engineering community made tremendous progress, particularly in the past decade. In what follows, we briefly address several notable achievements. For further details and comprehensive recent advances, see e.g. Barati and Alhubail (2020), Rezaee (2021), and Moghanloo (2022).

### 1.2.1 Wettability

Characterizing the contact angle of fluids (e.g. water, oil, and gas) and its spatial variability within unconventional reservoirs and under in situ conditions are essential not only to understand the trapping phenomenon and enhance oil and gas recovery but also to improve greenhouse gas (e.g. carbon dioxide and hydrogen) sequestration underground. In the literature, various methods, such as contact angle measurements (Iglauer et al. 2015; Roshan et al. 2016), spontaneous imbibition (Liu et al. 2019; Siddiqui et al. 2019), and nuclear magnetic resonance (Odusina et al. 2011; Su et al. 2018) were proposed to determine wettability in unconventional reservoir rocks. Recently, Arif et al. (2021) collected



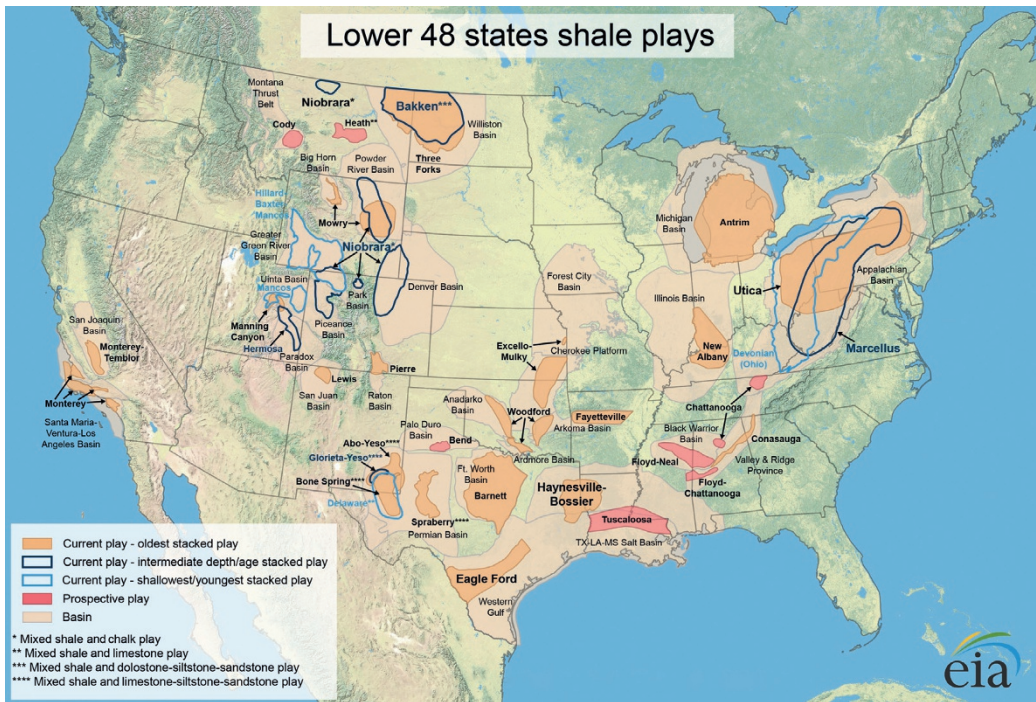
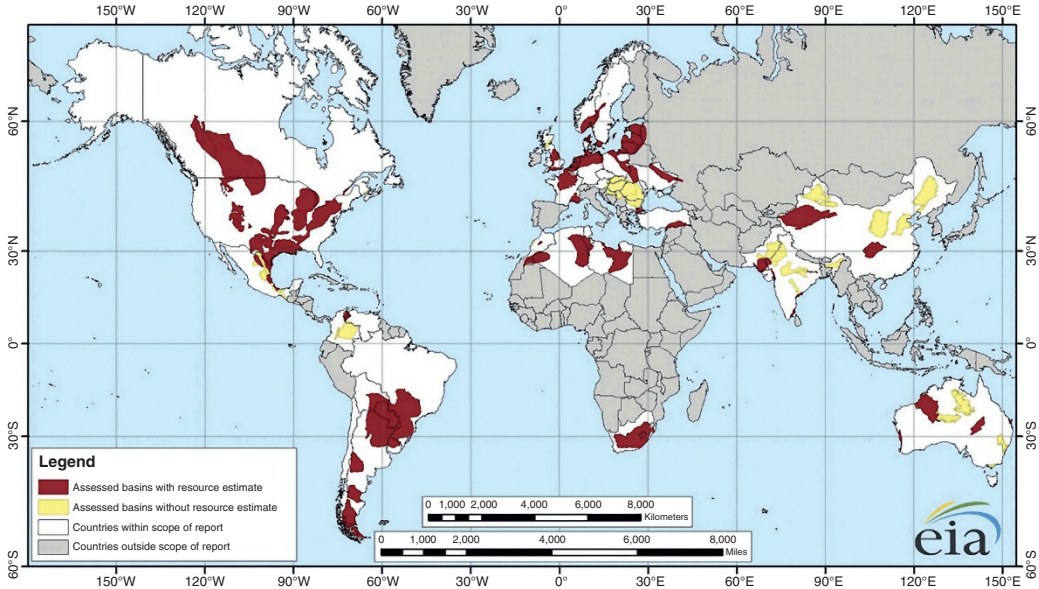
**Figure 1.2** Shares of global primary energy between 1994 and 2019 (BP Statistical Review of World Energy 2020/BP International Limited).

published data on shale contact angle measurements and developed a repository. They concluded that the oil-brine mixture in shales behaved in terms of wettability over a wide range from water-wet to strongly oil-wet. Although the  $\text{CO}_2$ -brine mixture typically showed weakly water-wet to  $\text{CO}_2$ -wet behavior, the  $\text{CH}_4$ -brine mixture in shales was weakly water-wet. Arif et al. (2021) also investigated what causes high variabilities in shale wettability and found that the main factors were pressure, temperature, thermal maturity, total organic content, and mineralogy of shales.

Although our knowledge of shale wettability has improved, further investigations are still needed to study the solid–fluid and fluid–fluid contact angles under realistic reservoir conditions more comprehensively. This would help enhance oil and gas recovery and exploit unconventional reservoirs even more successfully.

### 1.2.2 Permeability

Liquid and gas transports in shales and tight porous rocks were widely studied, particularly at the pore and core levels. The literature on gas permeability and its modeling is indeed vast and extensive (Javadpour et al. 2021; Liu 2017; Tahmasebi et al. 2020; Zhang et al. 2019). Numerous models



**Figure 1.3** World shale gas resources (top) and shale gas and oil plays in the United States (bottom). Source: Both maps are from US Energy Information Administration.

were developed to address gas flow in nanostructures of shales by taking the effect of different transport mechanisms, such as slip flow, Knudsen diffusion, surface diffusion, and sorption into account. For example, Beskok and Karniadakis (1999) incorporated the effect of slip flow and modified the Poiseuille equation to describe gas flow in a cylindrical tube. Civan (2010) later applied the