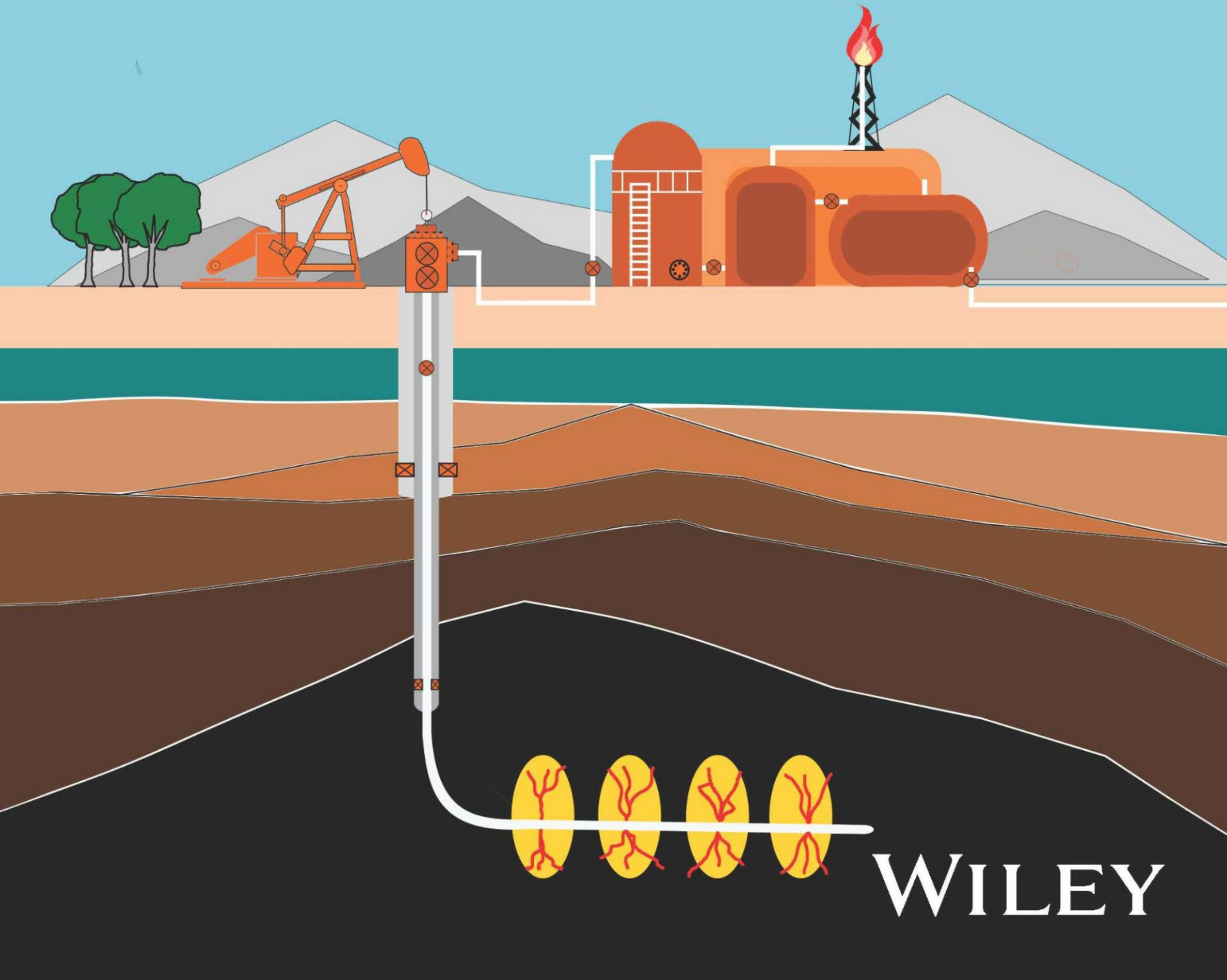
Physics of Fluid Flow and Transport in Unconventional Reservoir Rocks

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



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

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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[1], *Feng Liang*[2], *and Hui-Hai Liu*[2]

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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

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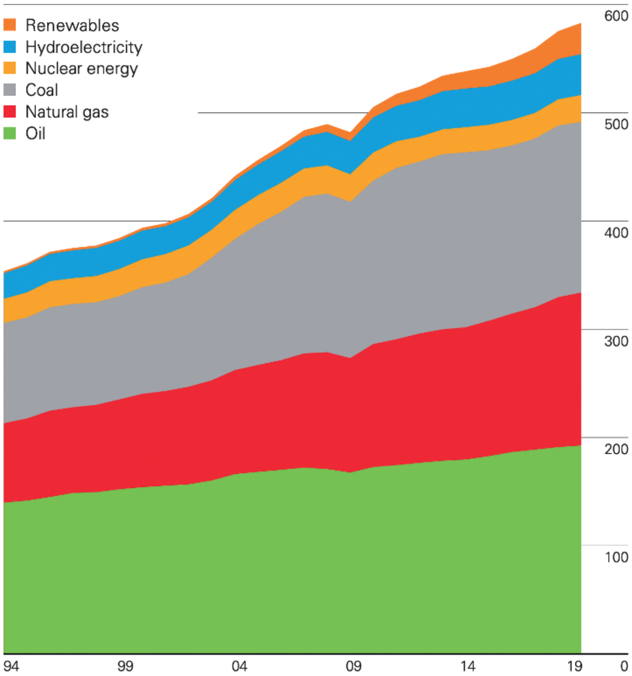

Figure 1.1 World total energy consumption between 1994 and 2019. *Source:* BP Statistical Review of World Energy (2020)/BP International Limited.

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

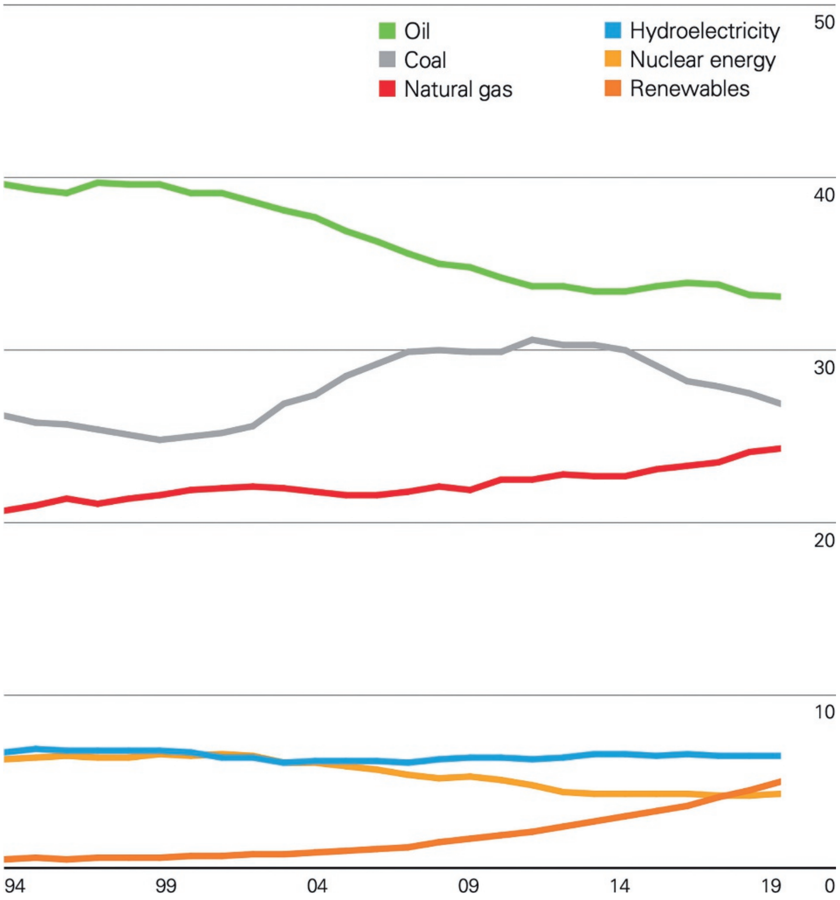

Figure 1.2 Shares of global primary energy between 1994 and 2019 (BP Statistical Review of World Energy 2020/BP International Limited).

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 CO_2-brine mixture typically showed weakly water-wet to CO_2-wet behavior, the 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

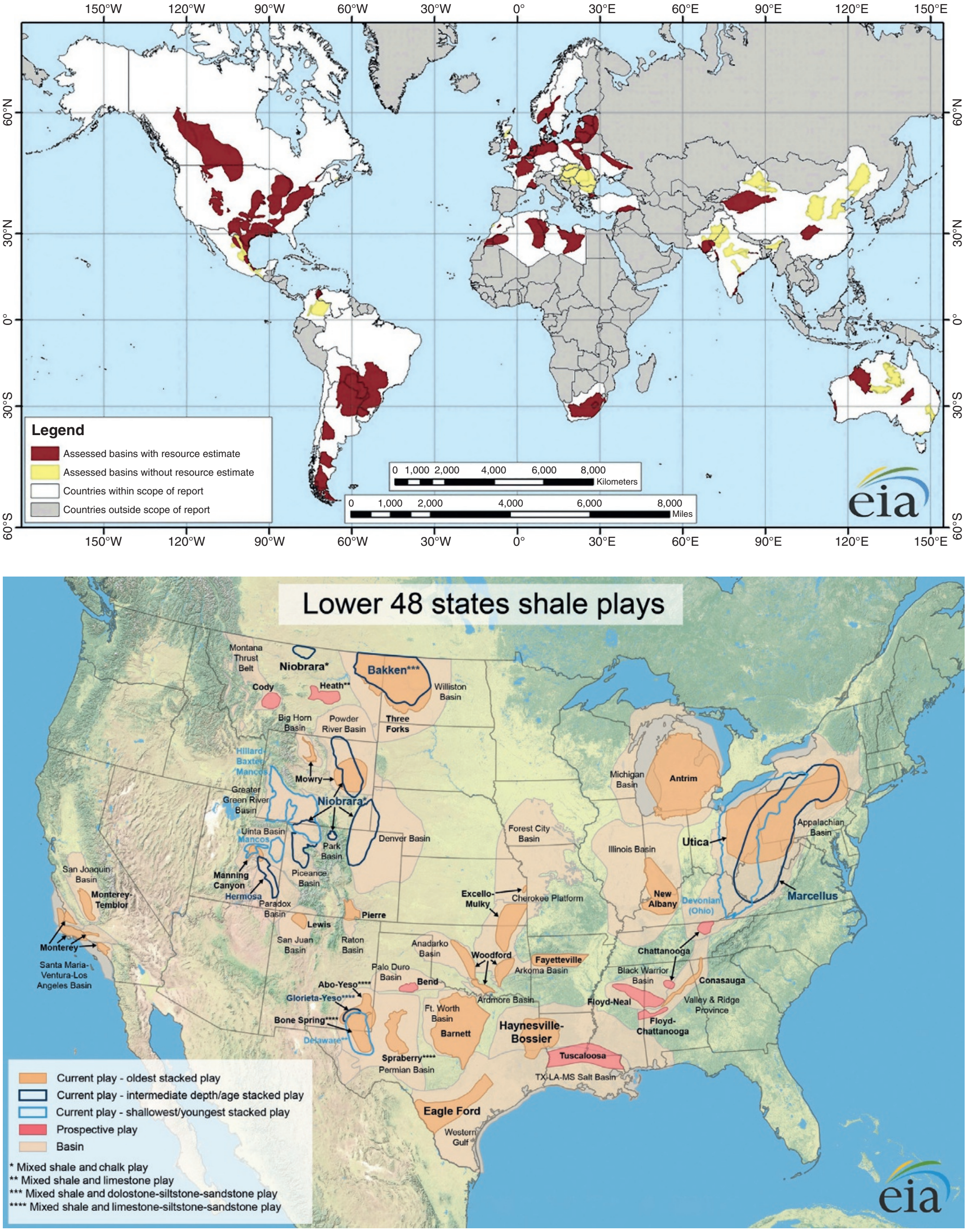

Figure 1.3 World shale gas resources (top) and shale gas and oil plays in the United States (bottom). *Source:* Both maps are from US Energy Information Administration.

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