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Part I

Physical Properties of Unconventional Reservoirs

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1 Introduction

The goal of this book is to address a range of topics that affect the recovery of hydrocarbons from extremely low-permeability unconventional oil and gas reservoirs. While there are various definitions of *unconventional reservoirs*, in this book we consider oil- and gas-bearing formations with permeabilities so low that economically meaningful production can only be realized through horizontal drilling and multi-stage hydraulic fracturing. These reservoirs have permeabilities measured in nanodarcies, not millidarcies – in other words, a million times lower than conventional reservoirs. Despite their ultra-low permeability, there is no question about the scale and impact of production from unconventional oil and reservoirs in the US and Canada over the past decade.

The topics addressed in this book are presented from the perspectives of first principles. To establish these fundamentals, we draw on extensive laboratory investigations of core samples (from nanometer to cm scale) as well as studies in the fields of geology, geophysics, earthquake seismology, rock mechanics and reservoir engineering. We will discuss first principles in the context of multi-disciplinary case studies, mostly from unconventional reservoirs of various types in North America. In the chapters that follow, we integrate and synthesize information about the response of unconventional reservoir to stimulation (as indicated by hydraulic fracturing, microseismic and production data) with available geologic and geophysical data and geomechanics (knowledge of the state stress, natural fractures and faults and pore pressure) in both the producing formations and those surrounding it.

Part I of this book (Chapters 1–7) addresses the physical properties of unconventional reservoirs. In seven chapters, we discuss a number of the formations exploited to date in North America in terms of their composition, microstructure, mechanical and flow properties, state of stress and pore pressure and pre-existing fractures and faults. To some degree, Chapters 2–7 consider topics that progressively increase in scale, starting with laboratory studies on core samples that focus on the physical properties from the cm- to nanometer scale (the rocks matter) and concluding by discussing basin-scale stress fields and fracture and fault systems (which control hydraulic fracture propagation and the efficiency of reservoir stimulation). In fact, an interesting aspect of unconventional reservoir development is that the factors and processes that affect development span an extraordinary wide range of scales – from hydrocarbon flow through nanometer-scale pores to variations of stress orientation and magnitude that can occur at scales ranging from tens of meters to hundreds of kilometers.

Chapters 2–5 focus on the composition, fabric, physical properties and pore networks of different types of unconventional reservoir rocks, which despite their common feature of ultra-low permeability, are currently being economically produced. Chapter 6 addresses the physics of flow in the ultra-low permeability matrix and its sensitivity to pressure depletion. Although there is always a great deal of discussion related to optimizing stimulation in an unconventional play from operational perspectives (well spacing and hydraulic fracturing operations), the fundamental challenge is that hydrocarbon flow must be stimulated from very small scale (micrometer- to nanometer-scale) pores in an economically viable manner.

Chapter 7 concludes Part I with a discussion of stress fields, pore pressure and natural fracture and fault systems. As mentioned above, the physical properties of the reservoir rocks matter but so does their geomechanical setting. The physical state of the formations *in situ* affects both hydraulic stimulation and the production of hydrocarbons. This includes the state of stress in the formations (both the producing formations and those surrounding it), temperature and thermal history, pore pressure and the characteristics of pre-existing fractures and faults. These topics were discussed at some length in the context of conventional reservoirs by Zoback (2007).

Perhaps the most challenging aspect of optimizing production from unconventional reservoirs is related to the linkages among what appear to be intrinsic properties of the rocks (their composition, fabric, the degree of diagenesis, kerogen content and maturity, etc.) and apparently extrinsic attributes (the state of stress, temperature, pore pressure and the presence of fractures and faults, etc.). We attempt to clarify many of these linkages throughout the book. For example, in Chapter 6 we discuss the ultra-low matrix permeability of unconventional reservoir rocks which, in Chapter 12, we use to develop a conceptual framework for understanding the relationship between depletion and production. This, in turn, helps the reader understand the applicability of microseismic data for defining the stimulated rock volume, or SRV (discussed in Chapters 9, 10 and 12). Another example of linkages is encapsulated in the mechanical property known as *brittleness*, which is frequently used in the industry as a metric identifying desirable intervals for drilling and stimulation in unconventional reservoirs. As discussed in Chapter 3, brittleness is conventionally defined in terms of elastic stiffness and the nature of rock failure in compression. In Chapters 10 and 11 we discuss the relationships between factors affecting variations of brittleness and stress magnitude, which has a first-order effect on vertical hydraulic fracture growth and proppant placement. Still another example is how detailed knowledge of stress state and pore pressure (discussed in Chapter 7) is of first-order importance when considering stimulation (Chapter 10) and the effects of depletion (Chapter 12).

Part II of the book addresses the process of stimulating production from unconventional reservoirs using horizontal drilling and multi-stage hydraulic fracturing. While the importance of horizontal drilling and multi-stage hydraulic fracturing are well understood, the third key technological development that led to successful exploitation of unconventional reservoirs was the utilization of low viscosity hydraulic fracturing fluids (often referred to as *slickwater*). Chapter 8 reviews several important engineering aspects of horizontal drilling and multi-stage hydraulic fracturing as well as a few engineering and geologic issues that affect both vertical and lateral hydraulic fracture propagation. Chapter 9 covers the basics of microseismic monitoring, which is currently the best tool available for monitoring the spatial and temporal characteristics of the stimulation process. The technologies associated with microseismic monitoring are largely based on principles developed over many decades to study natural earthquakes. In Chapter 10 we discuss the importance of interactions among the state of stress, pre-existing fractures and faults, and hydraulic fractures, which are critical to understanding hydraulic stimulation. In Chapter 11 we discuss hydraulic fracture propagation and proppant placement in the context of operational parameters, geomechanical implications for exploiting stacked pay and what it means to stay *in zone* for some formations. Chapter 12 presents a unified overview of flow from nano-scale pores to hydraulic fractures via the stimulated fracture network. We attempt to show how the matrix composition, fabric, permeability and mechanical properties of the producing formation (as well as the surrounding formations) dictate how hydraulic stimulation should be performed.

Part III of the book addresses the environmental impacts of unconventional development, in particular the occurrence of induced seismicity. Chapter 13 provides an approach for understanding how to identify (and minimize) the environmental impacts of development, while balancing the benefits of producing enormous supplies of natural gas and oil from domestic sources. One of the important benefits of the recent abundance of natural gas in the US is related to the greenhouse gas emission reductions resulting from switching from coal to natural gas for producing electricity. Figure 1.1 illustrates the dramatic increase in the availability of natural gas in the United States as production began to increase from the Barnett formation in the Fort Worth Basin of northeast Texas from 2005 to 2006. Note the marked reduction in CO_2 emissions resulting from fuel-switching from coal to natural gas from electrical power generation (red and blue curves) that began at about that time. In about a decade, coal went from providing 48.2% of electricity in the US to 33.4%, as the use of gas for electrical power generation increased from 21.4% to 32.5%. Consequently, CO_2 emissions dropped about 15% to levels not seen for over 25 years, as did emissions of particulate matter and of a number of other air pollutants associated with coal use. Another point worth recognizing is that at the time the shale gas revolution began, natural gas was in short supply, gas prices were quite high and a number of liquified natural gas (LNG) import terminals were under construction in the US. Because of the increases in the production from unconventional gas reservoirs, gas production after 2008 continued to increase, despite historically low prices. Fortunately, none of the LNG import terminals were completed, and by 2015 they began to be converted to LNG export terminals.

That said, there are a number of environmental and social impacts associated with unconventional reservoir development, which are exacerbated by the very large number of wells being drilled. Although it is beyond the scope of the book to discuss this topic comprehensively, at the beginning of Chapter 13 we address the potential for contamination of aquifers and methane leakage related to improper well construction, as well as whether hydraulic fracturing operations might compromise well integrity. A somewhat

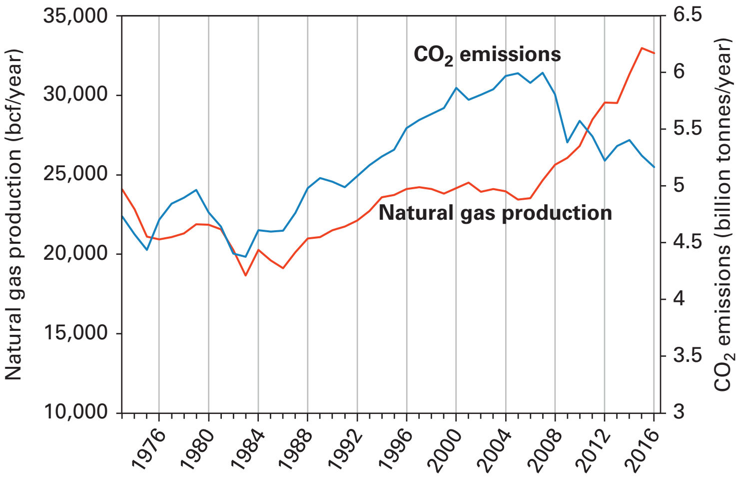

Figure 1.1 Annual production of natural gas in the United States over the past 43 years (red curve) and CO_2 emissions from the electrical power sector (blue curve). Data from the Energy Information Agency (2017).

unexpected environmental issue that has arisen in the US and Canada has been the increase in seismicity in a number of areas where unconventional reservoir development has been occurring. Chapter 13 discusses seismicity induced by hydraulic fracturing, the disposal of flowback water after hydraulic fracturing and the disposal of produced water. Chapter 14 presents strategies for managing the risks associated with induced seismicity. Some of these are also applicable to the exploitation of geothermal reservoirs as well as CO_2 injection and storage.

In the remainder of this introductory chapter, we will establish a framework for understanding a number of the topics discussed later in the book. This includes a brief discussion of the different types of unconventional formations being produced and the fundamental challenge of low recovery factors which is discussed at length in Chapter 12. We also provide a brief overview of how horizontal drilling and multi-stage hydraulic fracturing are carried out in unconventional reservoirs. The chapters that follow will address many of the issues introduced here in much more detail.

Unconventional Resources

It is incontrovertible that an enormous quantity of both natural gas and oil have been produced from unconventional reservoirs in just over a decade. Figure 1.2 is a summary of cumulative production of natural gas (Fig. 1.2a) and oil (Fig. 1.2b) from ~100,000 horizontal wells drilled in the major unconventional plays in the US. The plots show a three-fold increase in unconventional gas production and five-fold increase in unconventional oil production. So much natural gas is being produced in the US that the LNG

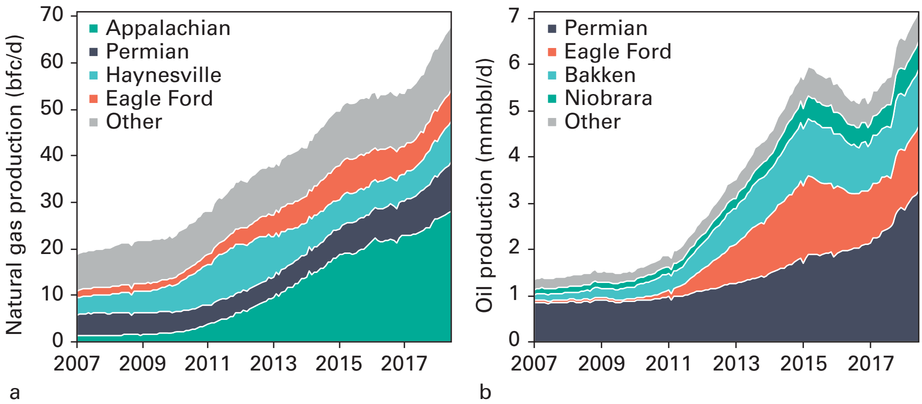

Figure 1.2 Cumulative production of (a) natural gas and (b) oil from unconventional reservoirs in the United States. Data from US Energy Information Agency (2017).

import terminals that were under construction in the early 2000s were being converted to LNG export terminals a little more than a decade later. While the initial production of natural gas from the Barnett shale occurred at a time of unusually high gas prices, the steady increase in production of shale gas in the US since 2008 occurred despite a steady *decrease* in gas prices. As discussed below, this was achieved through remarkable improvements in operational efficiency. The situation in Canada is similar. Thus, both private citizens and companies using large amounts of energy throughout North America (Mexico has started to import significant quantities of natural gas from the US and Canada) have benefited from the increasingly abundant supplies of inexpensive natural gas while experiencing decreasing rates of air pollution and greenhouse gas emissions.

Similarly, production from ultra-low-permeability oil reservoirs in the US has increased markedly, dramatically reducing the volume of imported oil (Fig. 1.2b). By 2017, the US was importing less than half as much oil as it did a decade earlier, resulting in a dramatic reduction of the US trade deficit and its reliance on imported oil as well as growth of the US economy. As oil is used primarily for transportation in the US, improved efficiency of cars and trucks has also contributed to the decrease in imported oil, but so has production of millions of barrels of oil per day from unconventional reservoirs.

The great majority of unconventional production had been from five gas producing regions and four oil producing regions. Some regions which experienced extensive development over the past decade will decline in the face of oil prices decreasing from about \$100/BBL prior to 2015 to about \$60/BBL in 2018. One such area is the Williston Basin, which hosts the Bakken shale. However, other areas like the Permian Basin are currently seeing a marked increase in the amount of drilling and production because it has been recognized that *stacked pay* (multiple producing formations at the same location) can be economically produced due to continued improvements in operational efficiency.

Past and Future Unconventional Development in the US – As impressive as the production figures shown in Fig. 1.2 are, according to Bureau of Economic Geology at the University of Texas as many as 1.6 million new wells could be drilled in these plays in the coming decades (Fig. 1.3). It should be noted that this estimate is based on estimates of technically recoverable reserves, a realistic density of wells in any given area and the presumption that drilling will occur in areas where drilling was allowed in 2017. Also shown on this map are important plays like the Niobrara and Mancos shales of Colorado and New Mexico, respectively, the SCPOOP, STACK and Merge plays in the Anadarko Basin of Oklahoma, which will likely involve tens of thousands of new wells. Not shown are the Utica formation (principally natural gas in Ohio) and important plays in Canada such as the Montney and Duvernay as well as other potentially significant plays that have not yet been identified (or announced).

The need for significant continued improvements in recovery factors from unconventional reservoirs is introduced later in this chapter and revisited throughout the book. Suffice it to say at this point that the importance of improving recovery factors goes well beyond its impact for any one company, any one play or any one country.

Global Unconventional Resources – Figure 1.4 summarizes the potential for unconventional oil and gas production in many parts of the world. While most unconventional production to date has been in North America, unconventional oil and gas development in other parts of the world could have a tremendous impact assuming that it is done in a manner that builds upon both the operational experience and knowledge gained over

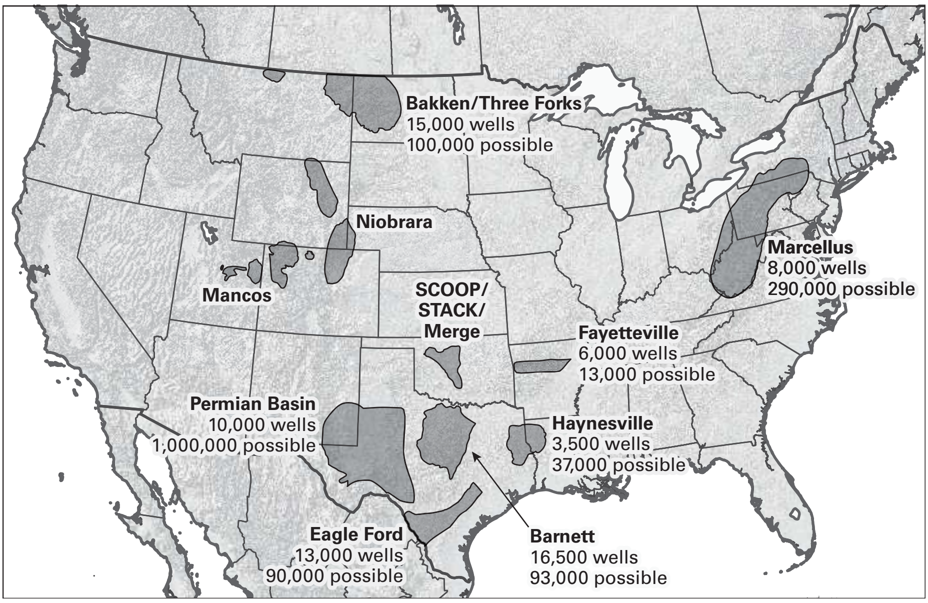

Figure 1.3 Horizontal wells drilled in major unconventional plays in the US as of 2017 and the numbers of wells that could be drilled in the future based on technically recoverable reserves. From Svetlana Ikonnikova, Bureau of Economic Geology, 2017.

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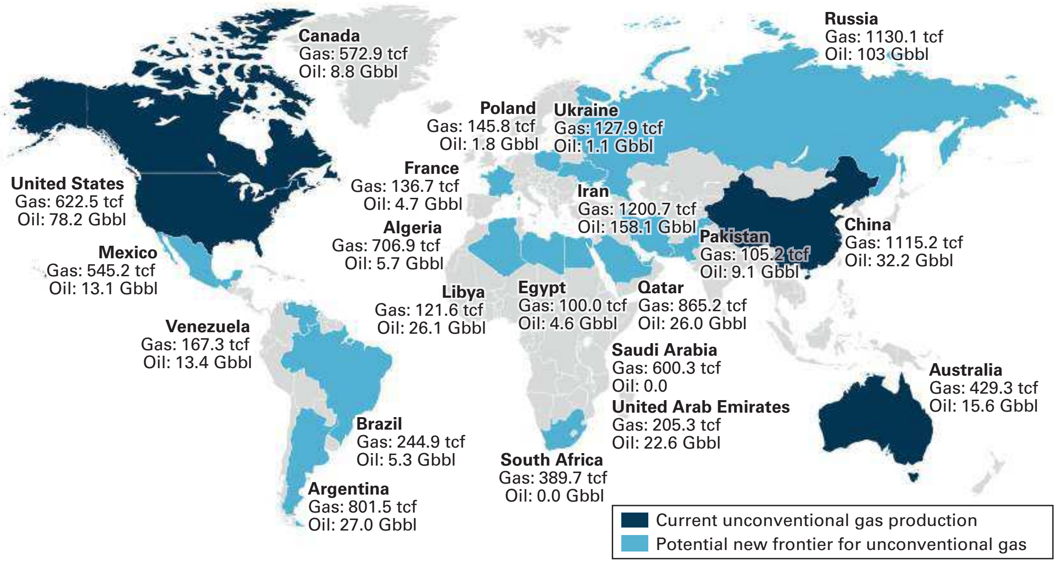

Figure 1.4 Locations of unconventional oil and gas plays throughout the world and estimates of technically recoverable reserves. World Energy Council, 2016; US Energy Information Agency.

the past decade of development in North America. Note that globally, unconventional production could increase available *wet* natural gas (natural gas and natural gas liquids) by almost 50%. Due to the vast quantities of proven conventional reserves in the Middle East, the cumulative impact on oil is lower (11% globally) but the distributed nature of these resources is extremely important.

It is abundantly clear that as the global energy system progressively decarbonizes over the next half century, it is important to recognize that there are more than adequate supplies of unconventional oil and gas from widely distributed sources to meet global needs, even accounting for the marked increase in energy use from the rapidly expanding economies of the developing world. Thus, the critical questions concern how to develop the use of these resources in a manner that produces the maximum economic benefit with the least environmental, social and climate impacts.

Types of Unconventional Reservoirs

The unconventional reservoirs that are contributing to significant oil and gas production (those listed in Fig. 1.2 and others) are geologically different in significant ways, thus necessitating different approaches for how they should be optimally exploited. While these differences will be highlighted throughout this book, it is important to recognize that there are generally three basic types of unconventional reservoirs successfully being exploited with horizontal drilling and multi-stage hydraulic fracturing.

Organic-Rich Source Rocks and Maturation – The first basic type of unconventional reservoirs are organic-rich source rocks, sometimes called *resource* plays. These are exemplified by the Barnett shale, the first unconventional formation to be extensively developed with horizontal drilling and multi-stage hydraulic fracturing. Conventional oil and gas are produced from relatively permeable reservoirs into which oil and gas have migrated from organic-rich source rocks. In contrast, resource plays refer to producing zones that are organic-rich (and often clay-rich) source rocks themselves, which are characterized, as mentioned above, by ultra-low permeability. While hydrocarbon source rocks have been recognized and studied for over a century, the potential for economic production from source rocks was considered impossible until successful development of the Barnett shale around 2004, by Mitchell Energy. Figure 1.5 (from Loucks & Ruppel, 2007) illustrates the depositional environment of the Barnett shale, where various types of organic matter were deposited in an anaerobic, relatively deep-water coastal environment, leading to preservation of the organic matter in clay-rich sediments during Mississippian time (~325 Ma).

As is the case in most unconventional reservoirs, different lithofacies comprise the Barnett shale which are defined on the basis of mineralogy, fabric, biota and texture. An example is shown in Fig. 1.6 (Sone & Zoback, 2014a) in which three distinct Barnett lithofacies are defined on the basis of mineralogy and a gamma ray log. Most production has come from the lower "hot" part of the Barnett. Notice that even within the lower Barnett, sub-units have been defined and even within the sub-units, there are individual bedding units or lithofacies with distinct composition at relatively fine scale. This multi-scale heterogeneity is discussed in detail later in this chapter.

Peters et al. (2005) discuss the organic content of hydrocarbon source rocks and maturation in great detail. It is obvious that the amount of organic matter that is present

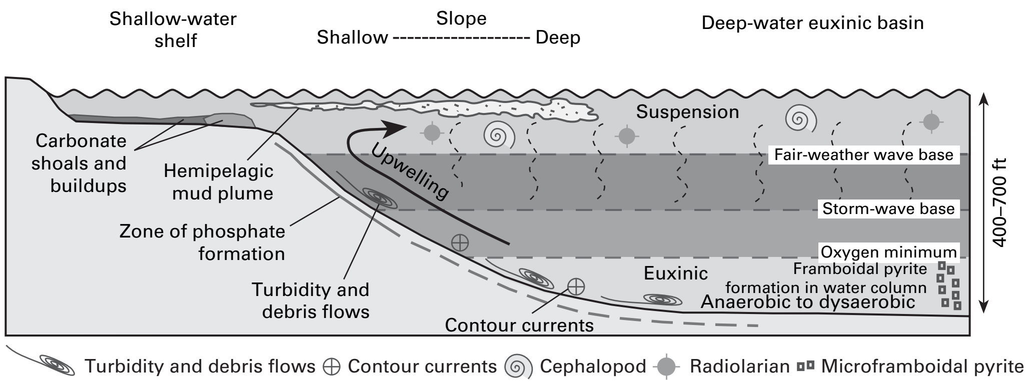

Figure 1.5 Schematic illustration of the manner in which various types of organic material were deposited and preserved in a deep water euxinic basin to produce the Barnett shale. From Loucks and Ruppel (2007). *Reprinted by permission of the AAPG whose permission is required for further use.*