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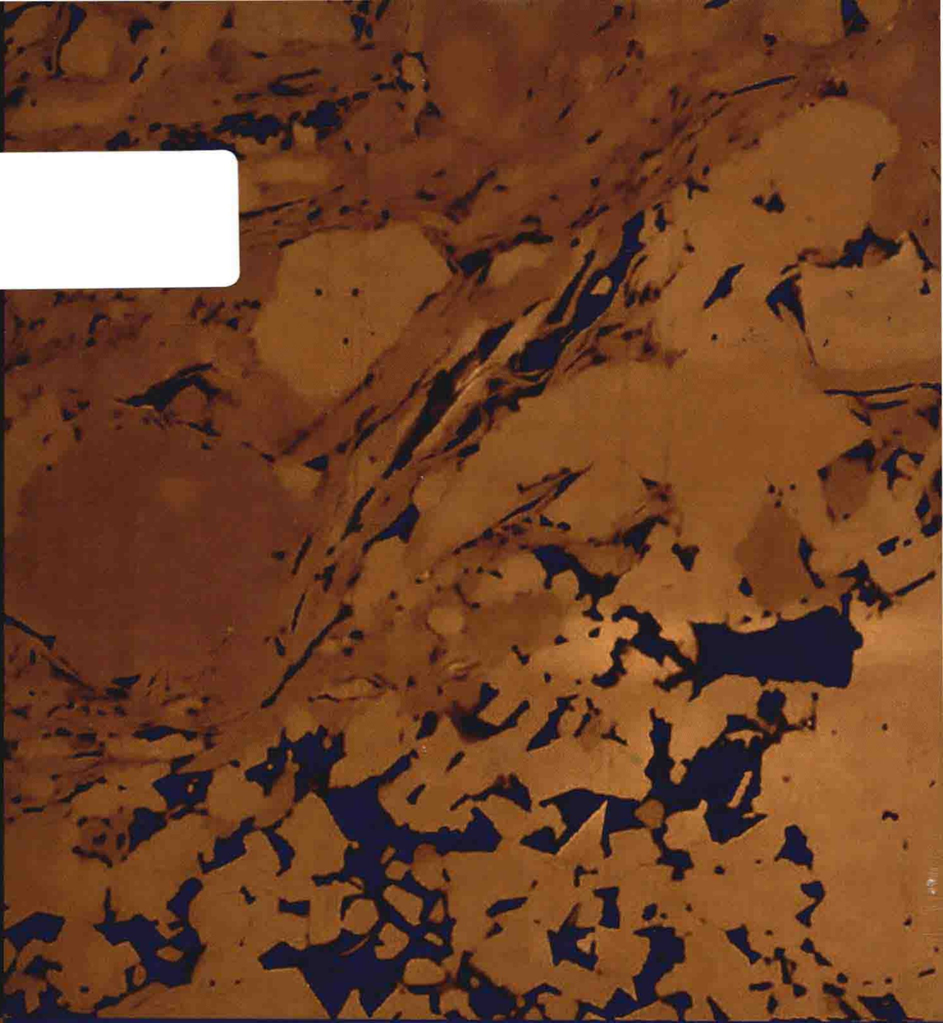

# Pore Scale Phenomena

## Frontiers in Energy and Environment

**John Poate • Tissa Illangasekare**
**Hossein Kazemi • Robert Kee**
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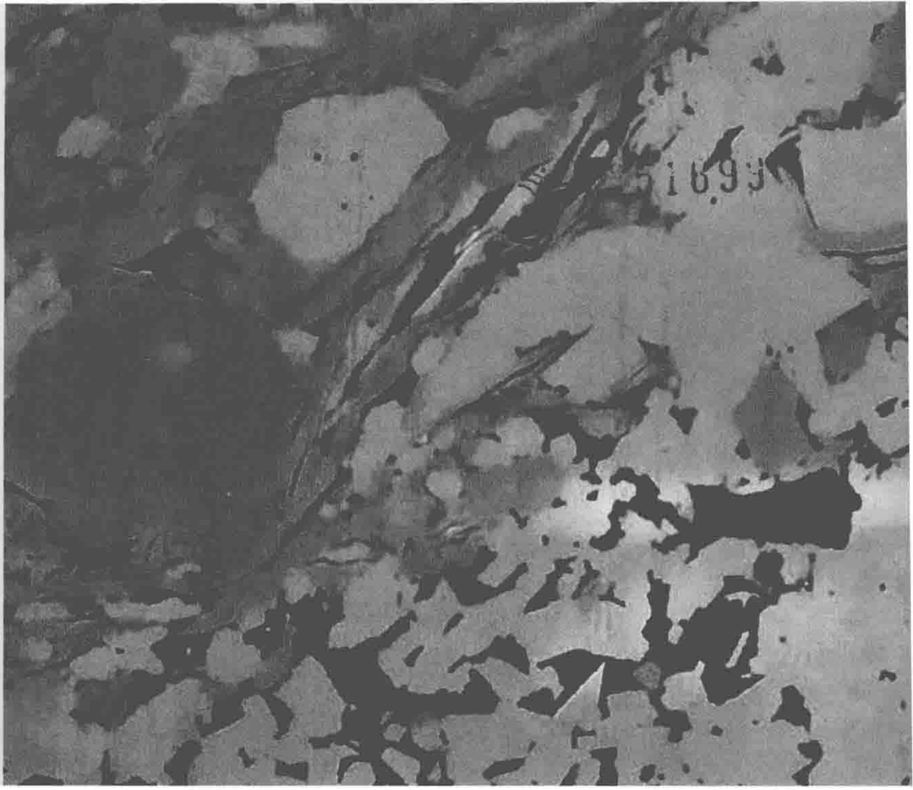

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Vol. 10 Pore Scale Phenomena: Frontiers in Energy and Environment
*edited by John Poate (Colorado School of Mines, USA), Tissa Illangasekare (Colorado School of Mines, USA), Hossein Kazemi (Colorado School of Mines, USA) and Robert Kee (Colorado School of Mines, USA)*

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# Preface

This monograph consists of a series of chapters devoted to understanding the physical and chemical properties of pore scale phenomena primarily in the energy and environmental worlds. The properties of these phenomena range across length scales from the atomic to the geographic and have large economic and societal implications. The genesis of this endeavor rose through a series of meetings at the Colorado School of Mines where we realized that the school had a critical mass of faculty addressing key pore scale research issues. We have tried to capture the essence of this research in this monograph. The chapters reflect the heterogeneity of the research. Mines has a proud record in applied research and engineering from its founding days and its impact on the mining industry in the US and the world. We are now contributing in many areas of energy and environmental research and trust that this monograph demonstrates this diversity.

We would like to thank and acknowledge our colleagues at Mines and the authors from our collaborating universities, national laboratories, and companies who tackled this endeavor with real enthusiasm. In particular we could not have pulled this off in a timely fashion without the expert assistance of Luis Zerpa, Giovanny Grasso, Jeff Brown and Lisa Kinzel.

*John Poate, Hossein Kazemi, Tissa Illangasekare, Robert Kee*
*Colorado School of Mines*
*Golden, Colorado*
*September 2014*

## Contents

# Chapter 1

# Overview

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Pore scale phenomena and their connected networks are pervasive in many areas of science. This monograph primarily focuses on those areas pertinent to energy and the environment in terms of oil and gas reservoirs, geohydrology and energy conversion. Transport properties are considered in detail. This chapter introduces the contents of the monograph.

## 1.1. Introduction

What are pore scale phenomena and why is there so much current interest? The answer is convoluted with a fascinating history of the earth, materials and biological sciences. Natural porous materials abound in the earth, such as expansive bentonite clays and porous limestone and in living organisms, such as the mastoid bone with its porous air cavities. Moreover many fabricated materials and structures now have complicated porous structures. Understanding the properties of these pores in terms of their structure and transport properties is now emerging as a grand challenge in terms of the scaling from the microscopic or nanoscale regime to the macroscopic world. This transition from the nanoscale to a macroscopic world is known as mesoscale science.

Undoubtedly the driver for much of this interest in the earth sciences has been the shale gas revolution. Extraction of natural gas from nanoscale pores in shale or rocks by hydraulic fracturing has transformed the energy agenda of the US. Many fundamental questions remain regarding the fluid flow mechanisms and opportunities for improving flow. There is now a burgeoning interest in similar processes with regard to water extraction and conservation. The fundamental challenges of understanding atomic and molecular transport in the porous structures of energy-conversion devices are profound. The performance of such devices is critically dependent on the transport phenomena.

This is a very large field of science and technology. This monograph primarily concentrates on three areas of the earth and materials sciences that are driving the research and engineering agendas. The opportunities for cutting edge and interdisciplinary research are large. Take, for example, the fields of physical and chemical analysis of surface and bulk properties of materials. Analyzing pores and their characteristics is opening up a new field of physical and chemical analytical techniques. The possibilities of collaboration and synergies between the traditional materials, earth and biological science disciplines could lead to new discoveries and understanding.

## 1.2. Oil and Gas Reservoirs

The first section of this monograph is introduced by H. Kazemi with a discussion of the physics of flow in petroleum reservoirs. Figure 1.1 shows the dramatic increase in US shale gas production in recent years. As discussed by H. Kazemi, this increase would not have occurred without seminal engineering and scientific advances. The societal and economic impact of this energy source is profound. To quote Daniel Yergin [1], one of the world's leading energy economists and analysts,"Shale gas, the biggest energy innovation since the start of the new century, has turned what was an imminent shortage in the United States into what may be a hundred year supply and may do the same elsewhere in the world. It is dramatically changing the competitive position for everything from nuclear energy to wind power. It has also stoked, in a remarkably short time, a new environmental debate".

This remarkable US revolution was charted and predicted by the Potential Gas Committee [2] which is comprised of 100 volunteer geoscientists and petroleum engineers from industry, academia and state and federal government organizations. The committee functions independently but with technical and administrative assistance from the Potential Gas Agency of the Colorado School of Mines. The committee has been assessing the technically recoverable US natural gas resource since 1964. Prior to 2008 the committee assessed relatively small volumes of gas in shale formations. However, with the increase in shale drilling and production from 2006-2008

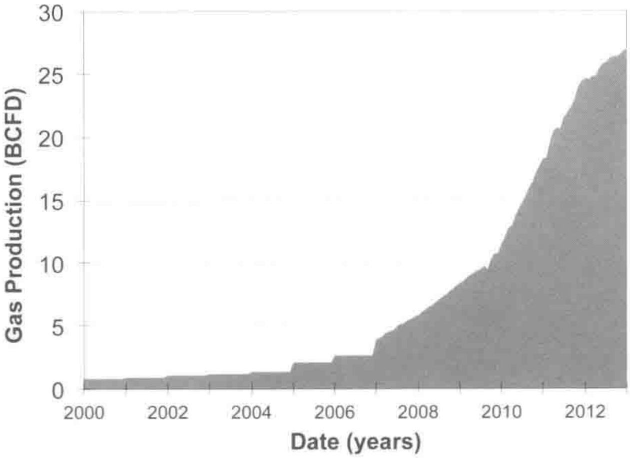


Fig. 1.1. U.S. total shale gas production comprises about 40 percent of total U.S. dry gas production (www.eia.gov/energy in brief/article/about shale gas.cfm).

due to horizontal drilling and multistage hydraulic fracturing, the committee members used private and public data to expand their evaluation of shale reservoirs. While some skepticism was voiced at the time regarding this substantial increase in recoverable resources, shale gas production since 2008 has validated the committees assessments. Indeed the work of US scientists has led to an assessment of the worlds oil and shale gas formation. The technically recoverable resources are ubiquitous throughout the world as shown in Fig. 1.2.

The flow of oil, water or gas through a petroleum reservoir is described by Darcy's Law. The Darcy (D) is a measure of the discharge rate or fluid flow corrected for the viscosity of the fluid and driving pressure gradient. Sandstone and carbonate reservoirs typically have permeabilities in range $10^{-1}$–$10^{3}$ mD. These are, for example, the easily accessible and high production reservoirs of the Middle East. Tight shale, for example the Marcellus basin, of the US, is the rock equivalent of mud with permeabilities in the range $10^{-6}$–$10^{-3}$ mD. Figure 1.3 shows the inherent permeabilities of accessible and inaccessible reservoirs as a function of rock type. Lateral drilling and hydraulic producing can increase the permeabilities of the tight sandstones and shales by many orders of magnitude for oil and gas production. Numerous examples are shown in this monograph of such shales where the carbonaceous material (oil, gas) and water is contained in pores embedded in the shale matrix.

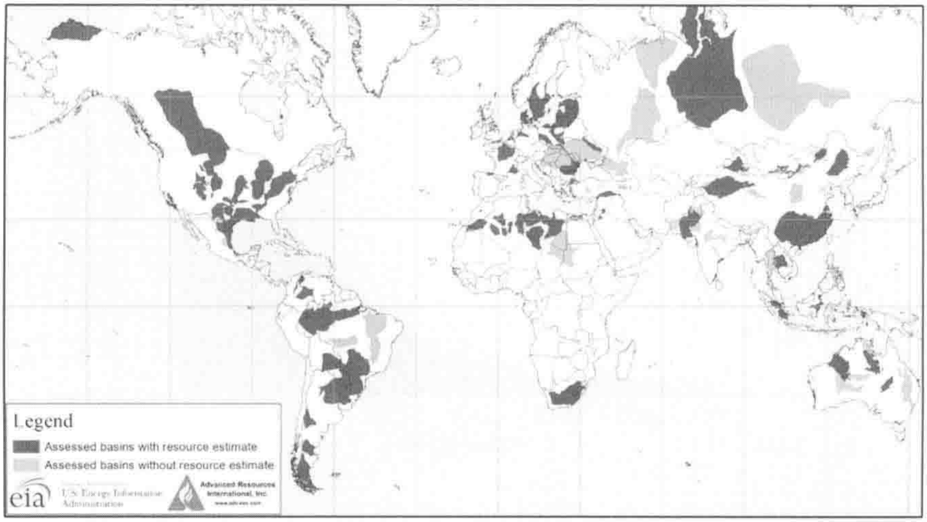


Fig. 1.2. Map of basins with assessed shale oil and shale gas formations (www.eia.gov/analysis/studies/worldshalegas/).

The challenges in simulating, modelling and understanding the behavior of the shales before and after fracturing are daunting. The chapters in this section deal with virtually all aspects of this science and engineering. Figure 1.4 shows an example of the convergence of theory and experiment in modelling fluid flow in fractured networks [3, 4] that are constructed in a two dimensional polymer matrix. These transparent micromodels give beautiful visual progressions of fluid flow in networks that can be artificially configured. In the field, additives are added to hydraulic fracturing fluids to decrease viscosity and increase permeability. In this experiment water flooding is substantially increased by additions of surfactants that decrease viscosity. Such work is allowing the development of models to predict multiphase flow in the field.

A fascinating aspect of the gas reservoir and energy story is that of the methane hydrates. These crystalline solids of water and gas were first documented by Sir Humphrey Davy in 1811 [5]. They were first regarded as a scientific curiosity. Then industry recognized their importance when natural gas pipelines, at high pressures and low temperatures, were blocked by solidifying gas and water. Global studies now show enormous quantities of naturally occurring gas hydrates in porous media. The question is whether these gas resources can be recovered in an efficient and economic fashion.

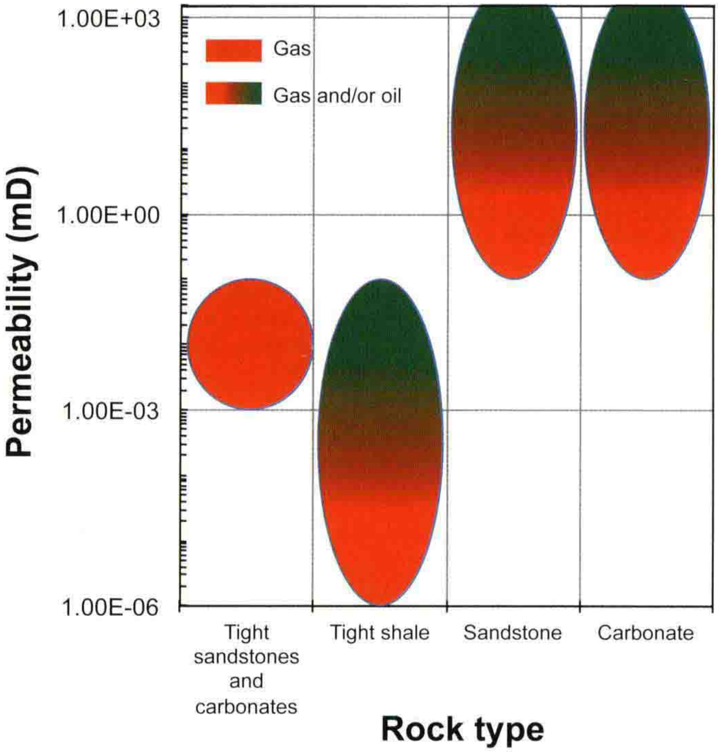


Fig. 1.3. Permeability vs. rock type.

These issues are addressed in the chapters which concern the dissociation and transport mechanisms. These studies bear directly on the environmental concerns of the release of methane under global warming and other geologic events. An environmental consequence of the increase in natural gas production from shale reservoirs has been the substantial decrease in $CO_2$ production. Gas-fired power stations produce 50% of the total produced $CO_2$ from coal-fired stations. Whatever the source, there is a need to sequester $CO_2$. One very novel suggestion [6] is illustrated in Fig. 1.5 showing that $CO_2$ can form clathrate hydrates, which thermodynamically is favored to displace methane from the hydrate cage. Experiments are underway to inject $CO_2$ to displace methane from hydrates; thus producing fuel and sequestering the $CO_2$.

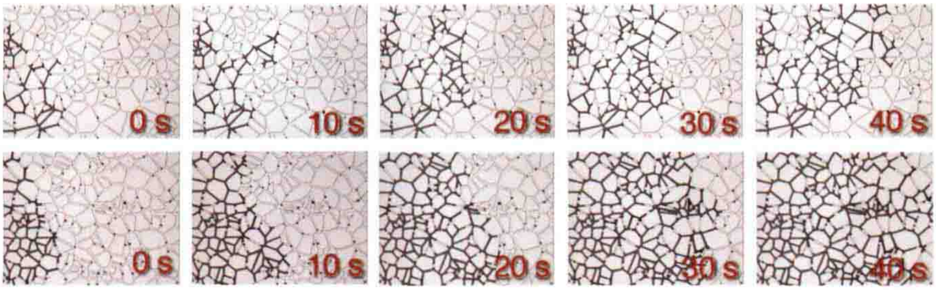


Fig. 1.4. Progression of water flooding (top) and surfactant flooding (bottom) in polymeric organosilicon compounds (PDMS) microfluidic channels. The network contains microchannels that are 4-8 $\mu m$ wide and 15 $\mu m$ deep. From Xu et al. [3, 4].

## 1.3. Hydrology

This section of the monograph is introduced by T. Illangasekare, K. Smits, R. Fucik and H. Davarzani. The first section of the monograph dealt with the accessibility of oil and gas reservoirs and their production which drives the worlds energy economy. An area of equal societal concern in terms, for example, of sustainability and food production is that of water. While the economic driver there is small, in comparison, to the oil and gas industry, the situation is changing. Erratic weather patterns are becoming evident with increased periods of drought. As Ben Franklin [7] remarked in 1746,"When the well is dry, we know the worth of water". Governments and agencies are now addressing with increasing urgency, the research challenges of coupling the earth and meteorological systems for the hydrological cycle.

The hydrological cycle is shown (Fig. 1.6) in the classic figure of Trenberth et al. [8]. The driving forces are radiation and energy. The atmospheric processes cause precipitation for example and the surface and sub-surface processes complete the water cycle. The chapters in this section deal with the many issues of scaling water transport from the nano or small scale to the field scale in the sub surface. The latest modelling and experimental techniques are discussed. An area of particular interest to pore scale studies is that of geochemical reactivity. Injection of $CO_2$ for sequestration purposes or injection of a working geothermal fluid can be severely impacted by the chemical reactivity of the pores.