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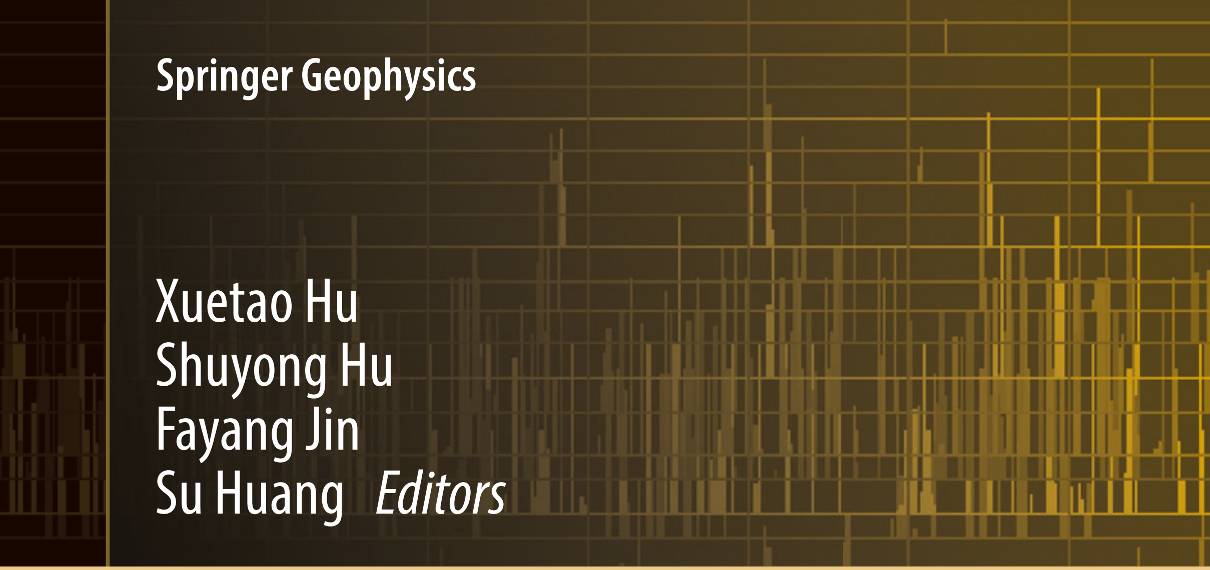

Xuetao Hu
Shuyong Hu
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Su Huang *Editors*

Physics of Petroleum Reservoirs

Second Edition

石油工业出版社
PETROLEUM INDUSTRY PRESS

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Foreword

With the acceleration of economic globalization, worldwide competition is intensifying, which brings significant changes in the talent demand of China. Professionals, with strong expertise as well as proficiency in English, are in urgent need. Bilingual teaching, in such case, is an effective way of cultivating application-oriented talents with an international vision. Therefore, it has been widely promoted in colleges and universities across China, taking a higher and higher proportion in the curriculum systems.

Southwest Petroleum University and some other Universities have offered bilingual teaching for petroleum-related majors in succession recent years. Teachers are encouraged to teach both fundamental and compulsory courses using foreign language (English mainly). Some Universities even setup international-talents-training classes. Bilingual teaching has been considered as the major method of cultivating international and inter-disciplinary talents, which helps the students to improve their international awareness as well as communication and cooperation abilities, at the same time, makes them more competitive in the job market.

Physics of Petroleum Reservoirs, as one of the most important fundamental courses in petroleum engineering and related majors, has been taught bilingually in many colleges and universities. However, there are currently too few bilingual textbooks for the teachers and students to choose from; existing teaching materials from abroad, on the other hand, can hardly match with the Chinese materials, be understood or accepted by students, nor keep up with the latest developments of this discipline. Bilingual teaching can only reach its best effect when there are suitable bilingual textbooks, otherwise it cannot even be carried on.

The authors, led by Editor Xuetao Hu, write this textbook based on their years' experience of bilingual teaching in Physics of Petroleum Reservoirs. Not only did they carefully research into massive original teaching materials abroad, but also took the students' levels and capacities into fully consideration. It is a textbook that covers the basic knowledge this course requires, at the same time, illustrates part of the frontier theories and latest developments related. This textbook timely provides bilingual teaching materials in accordance with the current teaching situation. Notably, it also matches well with the Chinese textbook of this course in SWPU, edited by Prof. Gengshen He and Prof. Hai Tang, which has been used for a long time in many colleges and universities. It is believed that the publication of this textbook can help to further improve the effect of bilingual teaching in this course, and play a key role in the education of application-oriented international talents needed by China's petroleum industry; in the meantime, it is expected to benefit to both engineers and technicians in related fields.

Chengdu, China
March 2016

Shilun Li

Preface

Physics of Petroleum Reservoirs, as one of the fundamental courses in petroleum engineering and related majors, is widely used in many fields, such as geological research, geophysical exploration, drilling engineering, oil/gas production and so on. To promote the development of such an important course, bilingual teaching is indispensable so as to help students quickly master the basic technique vocabulary, improve their English application ability, and lay a foundation for their study on the subsequent bilingual courses. For further consideration, bilingual teaching on this course can also broaden the students' horizon on the international trend of this subject and guides them to enter the related research fields as early as possible, therefore in accordance with the urgent need in China's petroleum industry for large numbers of internationalized application-oriented professionals.

However, in the practice of bilingual teaching in this course, there are too few bilingual textbooks for teachers and students to use at present. The lack of an appropriate bilingual textbook of this course has been suffered for years in Southwest Petroleum University. In view of this, the authors, based on their years' experience engaging in the bilingual teaching of this course, come out with this bilingual textbook specially. When composing this textbook, authors not only consult some original teaching materials abroad, but also take the students' knowledge levels and capacities into fully consideration. Besides the basic knowledge, this course requires, the textbook also covers some frontier theories and latest developments in this subject; hence, its strong practicability and pertinence can well satisfy the demands in bilingual teaching. This book is written to be a textbook for undergraduates who major petroleum engineering, resources exploration engineering and other relevant majors, or a reference book for oilfield engineers.

The book focuses the attributes of petroleum reservoirs, the important physical and chemical phenomena, and physical processes occurring in petroleum production. To specify, there are four chapters in this book. Chapter 1 addresses the physical properties of reservoir rocks. Chapter 2 discusses the physical properties of reservoir fluids. Chapter 3 presents the microscopic mechanism of multiphase fluids flowing through rocks. And Chap. 4 is a simple introduction to the principles of enhanced oil recovery. Considering the depth and breadth, the book mainly introduces the basic concepts, primary theories, common test items and methods in oilfield development. Through the book, students can understand the important properties of petroleum reservoirs with their applications on petroleum engineering, at the same time learn the principles and methods of measuring these physical properties as well as the required experimental skills; ultimately, lay a solid foundation for their following courses and practical work in the future.

The textbook is arranged to meet the need of 48–56 class hours. Due to the limitation of space and the adaptability for undergraduates, some topics in this subject cannot be deeply discussed. Interested readers may refer to related literatures and books.

This textbook is organized into five chapters. Xuetao Hu writes most of the book, mainly including the Preface, Chaps. 1, 2, 3 and Sect. 4.1 of Chap. 4. The rest of Chap. 4 is written by Shuyong Hu and Chap. 5 by Fayang Jin. Su Huang (from Southwest Oil and Gas Field Company, CNPC) participates in the writing of the Preface, Chap. 1 and sections of Chap. 2; and help to translate the Foreword and review the whole book in English. Xuetao Hu edits all the drafts.

We are especially indebted to Prof. Shilun Li for taking time to carefully review this book and write the Foreword, also to the leaders and teachers from Southwest Petroleum University and the School of Oil & Natural Gas Engineering, who offered strong support and great assistance in the completion of this book. As the textbook of a vital fundamental course, it inherits the advantages and absorbs the essence of various related textbooks published in different times both at home and abroad; numerous references including published and unpublished are cited, and some of them failed to be listed for some reason. Great appreciation goes to all of them.

International System of Units (SI system) is dominating in this book, whereas the system of imperial units is customarily used in the world. This book retains imperial system in some parts as well, wishing to help readers gain an international view. Therefore, it is advised that readers pay more attention to the units.

The study on Physics of Petroleum Reservoirs is ever developing. While this book is being written, innovations may take place in laboratories and oilfields throughout the world. Limited by time and the authors' level, the latest technologies and methods may not be presented completely, and omissions and shortcomings inevitable. Criticism and suggestions are always welcome.

Chengdu, China Xuetao Hu
June 2016

Contents

Chapter 1
Introduction

Xuetao Hu and Su Huang

1.1 Importance of This Course

As the power source of social developments, energy is of decisive importance to a country's economic performance, competition ability and overall national strength. Among all kinds of energy, petroleum and natural gas, functioning as the key resources, high-quality chemical raw materials and indispensable war materials, are capturing more and more attention nowadays by counties all around the world, that is why they are also called the *black gold*.

During the past decades, China's annual output of oil has been increasing all the way from less than 90,000 tons before liberation, exceeding 100 million tons in 1978, to 160–170 million tons in recent years, ranking into the world's top four major oil producing countries. However, it should not be neglected that, China has become a net importer of crude oil ever since 1997, and now imports more than 100 million tons each year since the beginning of the twenty-first century, making itself the world's second largest oil consumer. According to the national socioeconomic development plan, the future demand for oil and gas resources will continue to rise in China.

Therefore, in order to meet the resources needs for national economy modernization and sustainable development, it is necessary that

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(a) find out new oil and gas reservoirs to increase resources backup reserves;
(b) apply advanced technologies to maximize the reasonable development of hydrocarbon reservoirs;
(c) enhance the recovery of existing oil and gas fields to increase petroleum production;
(d) develop international cooperation and participate in the development of international oil and gas resources, to satisfy the requirement of China's petroleum industry in exploiting domestic and international resources facing domestic and international markets;
(e) utilize adequately various energy-saving measures, alternative energy, and new energy to reduce the pressure in petroleum demand.

For those who are going to be or already engaged in this career, proficiency in the theories and practices of petroleum exploration and exploitation is highly required, so as to make better contributions to China's oil industry in the future.

Physics of Petroleum Reservoirs studies the physical and physical-chemical phenomena in petroleum geology and petroleum production from the viewpoint of physics and physical chemistry. It is one of the required courses in both petroleum engineering and resources exploration engineering majors. It develops based on the experiments, and is a highly practical course. Meanwhile, it is fundamental to the subsequent major courses in petroleum areas, such as fluid mechanics in porous media, reservoir engineering, reservoir simulation, reservoir production engineering, well test analysis, reservoir protection technology, nature gas engineering, and enhanced oil recovery and so on.

The chief objectives of learning this course are the following:

(a) to understand the basic physical properties of reservoir rocks and reservoir fluids; as well as the mechanism of multiphase fluids flowing through reservoir rocks;
(b) to catch the point of the latest EOR methods and technologies;
(c) to learn the basic skills of experiments related with the attributes of reservoir rocks;
(d) to develop students' ability of analyzing and solving the problems encountered in reservoir production.

1.2 History and Developments of the Discipline

Physics of Petroleum Reservoirs is a relatively young subject. The earliest research related to this area can be dated back to the 1930s. At that time, these engineers, who were engaged in the petroleum production in the United States, the former Soviet Union, and some other countries, noticed the influence of reservoir fluids' properties on the production and started the preliminary studies on the fluid properties and the related determination methods.

Before 1930s, the former Soviet Union experts had the publications on this area. However, this subject came into being from the publication: *Physical Principles of Oil Production* written by Muskat in 1949 [1], U.S. that turned the researches in production data (oil, gas and water) into a subject. Aimed at the properties of reservoir rocks and fluids, this book collected various researches and production data in the first half of the twentieth century, and summarized them to give explanations from a physical view. Another breakthrough took place in the 1950s, when the former Soviet Union professor Kotyakhov from Moscow Petroleum Institute published *Основы физик0438 нефтяного пласта* (*Foundation of Reservoir Physics*) [2], which marks the beginning of Physics of Petroleum Reservoirs as an independent branch of petroleum production engineering.

The following years witnessed extensive and in-depth developments of the subject. A variety of books reflecting the research results related with Physics of Petroleum Reservoirs had been successively published in China and other countries in the world, such as the United States, Soviet Union, Canada, and so on. Despite the different names of these books (e.g., *The Basic Principles of Reservoir Engineering*), their contents are broadly consistent. Some iconic publications at abroad are

(a) In the 1970s, Chilingar et al. [3] published *Oil and Gas Production of Carbonate Reservoirs*, which describes the characteristics of carbonate reservoir from the exploitation point of view, and gives a more systematic and comprehensive depiction of the carbonate reservoir and its physical properties. The book, *The Properties of Petroleum Fluids* written by William et al. [4], explains systematically on the physical and chemical properties of oil and gas with related calculations. In 1977, a new book, *Physics of Oil and Gas Reservoirs*, was created by F.I. Kotyakhov and his assistant, in which the properties of oil and gas reservoirs and the pore structure of the reservoir rocks were reconsidered.

Физико—Химическая Механика Нефтянотo пласта (*The Physical and Chemical Mechanism of Oil-Bearing Reservoir*) by Markhasin (1982) [5] described the physical-chemical processes of crude oil seepage and migration from the physical and chemical point of view for the first time. His book highlights that the oil recovery can only be enhanced through elaborate studies of the physical and chemical properties of oil-bearing reservoirs based on the traditional reservoir physics.

(b) The studies in the 1980s mainly focused on the characteristics of carbonate reservoirs, clastic rocks, and secondary pores; the non-Newtonian nature of hydrocarbon fluids, the application of phase-equilibrium equation, and so on. At that time, experimental testing techniques and computer technology also made remarkable progresses.

(c) Since the 1990s, the study on Physics of Petroleum Reservoirs has stepped into a new stage. Various research findings and literatures prospered.

In China, Physics of Petroleum Reservoirs was noticed as an individual subject around the 1950s. The signal event was that a former Soviet Union expert being invited to have, for the first time, a lecture on this subject in our first petroleum school (Beijing Petroleum Institute), and to tutor graduate students. Since then, there had been more and more professionals engaged in teaching and researching of this area in step with the increasing numbers of oilfields in China. At the same time, the successive discoveries and developments of the giant oilfields in eastern China also promoted further development of this subject in China. Institutes and laboratories for the research in this area were established one after another in Beijing and the major oilfields in China. Various experiments and pilot tests on petroleum reservoir development and EOR technologies were also carried out. As a result, numerous research achievements were made, and the professional teams have thus been better developed. The study on Physics of Petroleum Reservoirs in China study has progressed significantly. Since the 1960s, many iconic works reflecting the latest research results on this area have been published. To name a few: *Reservoir Physical Basis* by Shiduo Hong (1985) [6], *Reservoir Physics* by Zhetan Luo (1985) [7], *Physics of Oil-gas Reservoir* by Boqun Zhang et al. (1989) [8], *Reservoir Physics* by Gensheng He (1994) [9], *Fundamentals of Petrophysics* by Shenglai Yang (2004, 2011) [10, 11], *Reservoir Physics* by Yuncheng Wang (2006) [12], etc. In addition, a growing number of articles published in a variety of magazines.

Through the constant efforts of generation after generation of scholars both at home and abroad, following achievements have been made in this subject:

(a) A relatively complete theoretical system;
(b) Standardized experimental technologies;
(c) Wide test contents: various physical properties of reservoir rocks and reservoir fluids;
(d) Updated research areas and method: pore structure, multiphase flow, surface properties, capillary pressure, and so on;
(e) Increasing test items: conventional core analysis, special core analysis, EOR tests, flow tests for formation sensitivity, and so on.

In a word, more and more normative and mature research methods have developed, and a number of industry standards have established.

However, we should notice that, due to the heterogeneity of reservoir rocks and fluids, and the complicated physical phenomena and processes occurring in reservoirs, we are not able to fully understand, explain, and describe all phenomena in petroleum reservoirs at present. Some understandings may be relatively immature.

However, the needs of oil-gas production always promote the development of this subject. New problems emerging in petroleum production bring about new research targets. Physics of Petroleum Reservoir will continue to grow, blossom, and evolve with the following features:

(a) Integration: mutual penetration and cooperation between disciplines forms new edge theories;
(b) Innovation: the application of new theories accelerates the innovations in research methods and test technology to solve new problems occurring in petroleum production;

(c) Reproducibility: tests and experiments will be more reliable to simulate actual conditions and development process of reservoirs.

Nowadays, it enters a brand-new research stage of Physics of Petroleum Reservoirs, in not only the breadth and depth of theoretical research, but also the contents of experimental tests and the service areas for oil-gas production. It has become an indispensable theoretical basis for oilfield development in China. With the development of deep hydrocarbon reservoirs, high water-cut oil reservoirs and low-permeability oil/gas reservoirs, increasing difficulties may occur in petroleum production. Physics of Petroleum Reservoirs, offering the indispensable fundamental data, theories and research methods for oil-gas production, will no doubt play a more important role in the future.

1.3 Description and Targets of This Course

The English word *petroleum* is derived from the combination of Greek word *petro* (rocks) and Latin word *Oleum* (fuel oil), meaning the fuel oil that comes from rocks. Physics of Petroleum Reservoirs is here focused on the properties of reservoir rocks and reservoir fluids (oil, gas, and water), as well as the microscopic mechanism of reservoir fluids flowing through rocks. The main contents include the following:

(a) The physical properties of reservoir rocks
Underground reservoir space refers to the void space within the rocks. The physical properties of a rock include the properties of matrix and pores in the rock. The unique properties of reservoirs make them fundamentally different from ordinary liquid containers on the ground. As porous media, the unique properties of rocks determine the distribution and flow patterns of reservoir fluids in rocks. Therefore, the properties of reservoir rocks are the basis of petrophysics for petroleum production, and are the important issues of oilfield development theories.

(b) The physical properties of reservoir fluids
Different from the oil on the ground, the crude oil in reservoirs is under high pressure and temperature, with a large number of dissolved gas in it. The physical properties of reservoir fluids and the phase behavior of oil-gas system are the basis of fluid investigations in petroleum production, and are the important issues of oilfield development theories as well.

(c) The microscopic mechanism of fluids flowing through rocks
This part explains essentially the mechanism of the distribution, flow, and remaining of oil and gas in reservoirs, which lays a solid foundation for the research of EOR and the implementation of EOR measures.
In a word, the knowledge of the physical properties of reservoir rocks and fluids, and the interaction between rock and fluids is always involved in the whole life of reservoir production. At the early stage of a reservoir's life, it can

be used for the determination of oil/gas reservoir types, and serves for the design of development plan. During the reservoir development, it is indispensable for performance analysis and reservoir management. When it comes to the late life of a reservoir, it serves as a vital groundwork of studies on the distribution of remaining oil, EOR methods and so on. Therefore, the main targets of this subject are to provide reliable basic parameters for accurately recognizing, actively reforming and effectively developing hydrocarbon reservoirs.

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Chapter 2
Physical Properties of Reservoir Rocks

Xuetao Hu and Su Huang

A rock capable of producing oil, gas, or water is called *reservoir rock*. A reservoir rock may be any rock with sufficient porosity and permeability to allow oil and gas to accumulate and be produced in commercial quantities [1]. Petroleum generally occurs in sandstones, limestones, dolomites, conglomerates, and shales, but sometimes it is also found in igneous and metamorphic rocks. As a whole, sandstone and carbonate rocks are the most common reservoir rocks. However, reservoir rocks are quite variable in composition and physical properties [2]. The physical properties of reservoir rocks are the vital information for producers to estimate the geological reserve and ultimate recovery of an oilfield and determine the most efficient method of petroleum production.

Reservoir rocks may be investigated from two points of view, namely, microscopic and megascopic. If we study a core or a sample of a reservoir rock containing petroleum and place it under a magnifying glass (binocular or microscope), we can observe that the reservoir rock is made of a framework of minerals (rigid or friable) which fills but part of the void space. The void space in the rock is broadly known as *pore*. Oil, gas, or/and water can enter and fill in the pores if they are interconnected. In general, interconnected pores are interlaced within the mineral framework. The size, quantity, and shape of the interconnected pores in a reservoir rock determine the ability of the rock storing and transmitting fluids. Therefore, the physical properties of reservoir rocks are in essence dependent on the mineral framework of the rock, namely on the mineral composition and the texture of the rock.

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2.1 Matrix Features of Reservoir Rocks

Although we find oil and gas occasionally in igneous rocks, most of reservoir rocks are sedimentary in origin. Sedimentary rocks that contain oil and gas are generally divided into two categories: clastic sedimentary rocks and carbonate sedimentary rocks. The former chiefly includes conglomerate, sandstone, and mudstone, while the latter usually refers to limestone and dolomite. Sandstone is one of the most common and important petroleum reservoirs. Sandstone is a clastic sedimentary rock composed of more than 50 % sand-sized minerals or rock grains.

Sandstone is an aggregate of various particles. The size and nature of these particles in sandstone determine the characteristics of the rock. Actually, all clastic rocks have two basic properties: composition and texture. Rock texture indicates the way the particles or minerals are put together to constitute the rock. Some other properties, like structure, density, color, electrical properties, porosity, and permeability, are only second- or third-order derivatives of the two basic properties (composition and texture). In order to find the best way to exploit petroleum from underground rocks, it is necessary for the producers to know what a rock is composed of and how it is formed because the knowledge of the mineral composition and rock texture can give people an idea of how easy the petroleum may get into the rock.

In the description of sedimentary rocks, texture is a key content. It can help to interpret the mechanisms and environments of deposition. The texture of clastic sediments includes external characteristics of sediment grains, such as size, shape, and orientation [3]. Sediment texture is dependent on the grain morphology, surface features, and the fabric of the sediment.

Generally, rock's texture can be adequately studied by means of casting thin section and scanning microscope. For sand and silt-sized sediments, the analysis of rock's texture mainly focuses on the size, sorting, shape, and roundness of particles (grains). The grain-size of clastic rocks may vary from clay in shales; silt in siltstones; sand in sandstones; and gravel; cobble; to boulder-sized fragments in conglomerates and breccias (Fig. 2.1). Different rocks consist of different particles. As a result, the size, distribution, and nature of particles in a rock are responsible for many important physical and chemical properties of the rock, such as porosity, permeability, wettability, and so on. The grain-size composition and distribution of a reservoir rock are thus very important information for petroleum engineers to understand the properties of the rock.

2.1.1 Grain-Size Distribution of Rocks

Grain-size is one of the most important characteristics of rock particles. It is customarily defined as the average diameter of grains in sediments or lithified particles in clastic rocks, expressed in millimeter. It is a measure of the particle size of a rock.

Fig. 2.1 A display of grains ranging in size from silt to very coarse sand

Table 2.1 Grain-size classes for sediments and clastic rocks (Zhu [4])

Grain-size (mm)	Class	Sediment	Rock
>1000	Boulder	Gravel	Conglomerate and breccia
100–1000	Cobble		
10–100	Pebble		
2–10	Granule		
1–2	Huge sand	Sand	Sandstone
0.5–1	Coarse sand		
0.25–0.5	Medium sand		
0.1–0.25	Fine sand		
0.05–0.1	Coarse silt	Silt	Siltstone
0.005–0.05	Fine silt		
<0.005		Clay	Claystone (mudstone)

According to grain-size, the grains of clastic rocks can be classified into several broad groups: gravel, sand, silt, and clay (Table 2.1), which are generally called as grain-size classes. The rocks corresponding to each grain-size class above are known as conglomerate/breccia, sandstone, siltstone, and mudstone, respectively. In China, the accepted grain-size scale is classified with decimal system (Table 2.1). However, the common parameter is crystal size rather than grain-size in the description of chemical rocks, such as evaporates, recrystallized limestones, and dolomites.

2.1.1.1 Grain-Size Composition (Granulometric Composition)

A grain-size composition means the constitution of various size particles in a rock. It is customarily defined as the percentage of different size particles in a rock (e.g., sandstone), in weight. Mathematically, it can be expressed as

$$G_i = \frac{w_i}{\sum w_i} \times 100\ \% \tag{2.1}$$

where G_i is the weight percent of ith group of rock particles, %; w_i is the weight of ith group of rock particles, g.

Using the grain-size composition of a rock, the size and distribution of particles in the rock can be quantitatively described. It is helpful to the understanding of the rock texture.

2.1.1.2 Grain-Size Analysis

The measurement of the grain-size distribution of a rock is called *grain-size analysis*. In general, there are various laboratory techniques available for grain-size analysis. However, what technique can be used in the analysis mainly depends on the size of grains, the volume of the rock, and the consolidated degree of the rock. Generally, a systematic method of grain-size analysis includes the following techniques: sieve analysis, sedimentation method, direct measurement, and other methods.

In grain-size analysis, direct measurement is a subsidiary method, just suitable for the samples consisting of larger size particles, e.g., cobble, boulder, etc. Other methods mainly include optical method, electrical method, thin section analysis, image and analysis. These methods are often used for special samples, such as tiny samples and tightly cemented samples. Sieve analysis and sedimentation method are the routine methods in grain-size analysis. The principles of the two methods are simply described as follows.

Sieve analysis

Sieve analysis is a quick method and can provide a reliably and relatively broad grain-size spectrum. It is thus a main method of grain-size analysis and often used for determining the grain-size distribution of conventional sandstones.

In this method, a rock sample should be first broken into dispersed grains or particles. Then the grains are separated into several fractions with a stack of sieves on a shaker (Fig. 2.2). Each fraction of the grains has different average grain-sizes. After that, each fraction of grains is weighed and the grain-size composition of the sample can then be calculated according to the weight of each fraction of grains.

A typical sieve analysis involves a nested column of sieves with wire mesh cloth (screen) which has different mesh sizes (opening size) (Figs. 2.2 and 2.3). The opening size of the nested sieves should be suitable for the grain size of the sample. The nested sieves should be placed in the order of decreasing opening size from top to bottom on a mechanical sieve shaker (Fig. 2.2). A pan should be placed below the stack of sieves to collect the aggregate that passes through the last sieve.

The mesh size of sieves is expressed in two ways. One is the number of openings per inch (linear) of mesh cloth, called mesh, e.g., 200 mesh means 200 openings per inch of mesh cloth. The other one is the size (diameter) of openings of mesh cloth

Fig. 2.2 A shaker used in sieve analysis

Fig. 2.3 Sieves used in sieve analysis

expressed in millimeter. In general, the opening size of a sieve is approximately $1/\sqrt{2}$ or $1/\sqrt{4}2$ increase than that of the next sieve. The opening size of sieves used in China and USA is listed in Table 2.2. The series of 9, 10, 14, 20, 27, 35, 40, 60, 80, 100 mesh sieves are commonly used for the grain-size analysis of conventional sandstones.

The routine procedure of sieve analysis includes the following steps:

(a) *Sample preparation*: first, select a representative sample from rock cores. Then let the sample be crumbled in a pulverizer to dispersed grains.
(b) *Sieving*: put the dispersed grains of the sample into the top sieve of the stack of sieves on a shaker shown in Fig. 2.2. Turn on the shaker and let it run for enough time for the separation of the grains. During the process of shaking, the grains pass through each sieve from top to bottom. Each of the sieves

Table 2.2 Typical sieve no. and corresponding opening sizes in sieve analysis

Sieve size (China) [5]		Standard sieve size (U.S.) [6]	
Sieve no. (mesh)	Opening (mm)	Sieve no. (mesh)	Opening (mm)
4	4.599	4	4.760
5	3.962	5	4.000
6	3.327	6	3.360
7	2.794	7	2.830
8	2.362	8	2.380
9	1.981	10	2.000
10	1.651	12	1.680
12	1.397	14	1.410
14	1.165	16	1.190
16	0.991	18	1.000
20	0.833	20	0.840
24	0.701	25	0.710
27	0.589	30	0.590
32	0.495	35	0.500
35	0.417	40	0.420
40	0.350	45	0.354
60	0.245	50	0.297
65	0.220	60	0.250
80	0.198	70	0.210
100	0.165	80	0.177
110	0.150	100	0.149
180	0.083	120	0.125
200	0.074	140	0.105
250	0.061	170	0.088
270	0.053	200	0.074
325	0.047	230	0.063
425	0.033	270	0.053
500	0.025	325	0.044
625	0.020	400	0.037

retains part of the grains due to larger grain-size than the opening size of the sieve. The dispersed grains of the sample are thus separated into several fractions.

(c) *Determine the weight of each fraction*: measure weight of the grains retained on each sieve with a balance. The weight of each fraction of grains is expressed as w_1, w_2, …, w_n. w_n is the weight of the grains in the pan. The cumulative weight, W of all fractions is then calculated by the weight of each fraction. Namely, $W = w_1 + w_2 + \cdots + w_n$.

(d) *Determine grain-size distribution*: the percentage of each grain fraction retained on each sieve can be determined by Eq. (2.1), expressed as G_1, G_2, … G_n.

Sieve analysis has been used for decades to monitor the particle size of different particle materials [7]. For coarser materials, the sizes may range down to 0.150 mm; sieve analysis is accurate and the particle size distribution is consistent. However, for materials finer than 0.150 mm, this method is significantly less accurate. For finer particles or grains, it could be harder to make the particles pass through the openings of sieves because of the increasing mechanical energy required as well as effects of interfacial adsorption between particles and between particle and the mesh cloth.

This method assumes that all particles are orbicular or nearly so, and one particle can only pass through the square-shaped openings with larger sizes than its own diameter. For elongated and flat particles, sieve analysis can give a less reliable result because an elongated particle may pass through the screen from end-on, but would be prevented the other way (e.g., if it is side-on). For example, a needle-shaped particle can either pass through a mesh or be retained on the screen, depending on its orientation during sifting. Even so, the density of particles has no effect on the analysis results. Sieve analysis is a favorite method for loose or weakly cemented rocks, but it may not be suitable for soft or tight rocks. Such kind of rocks may generate size-distorted particles during the process of breaking the sample.

In addition, the precision of sieve analysis is also affected by the following factors: the number of sieves used in the analysis and their quality, moisture of grains, and sieving time. Experience of the user is also reflected in the measuring results.

In a word, this method is simple, easily available, and relatively reliable. It is widely used in grain-size analysis of particle materials and reservoir rocks. Sieve analysis can also provide useful information and materials for the study on mineralogy and particle shape in the future.

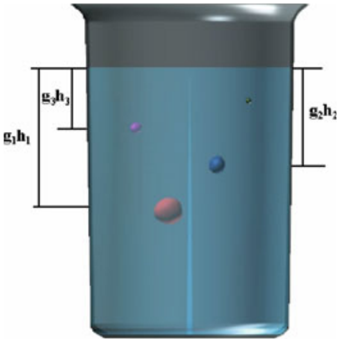
Sedimentation method

Sedimentation analysis appeared more than a century ago [8]. It was used in laboratories at the end of the nineteenth century and served as the most common method of soil and sediment particle size analysis.

Sedimentation method is a subsidiary method for the grain-size analysis of conventional sandstones. It is awfully appropriate for the grain-size analysis of tiny particles retained in the pan in sieve analysis. It is accurate for particles ranging between 0.053 and 0.074 mm, but it is less accurate for particles in sub-micrometers due to the effects of Brownian motion.

This method is based on the application of Stokes' law. Stokes' law describes the settling velocity of spherical particles in a viscous fluid under gravity (i.e., free falling). Under the conditions of low Reynolds numbers (i.e., laminar flow), the settling velocity of particles depends on the ratio of the particle density to the fluid density, the viscosity of the fluid, and the size of particles. Therefore, different particles have different settling velocities when subsiding in a viscous liquid (Fig. 2.4).

Fig. 2.4 Sketch map of particle settling



g_i: acceleration of gravity; h_i: distance

In the simplest case, the settling velocity of a particle is proportional to its size. According to the particle's velocity measured, the diameter of particles can be determined according to the Stokes equation of fluid mechanics:

$$d = \sqrt{\frac{18\gamma v}{g(\rho_s/\rho_L - 1)}} \tag{2.2}$$

where γ is the kinematical viscosity of suspension liquid, cm^2/s; v is the terminal settling velocity of a particle in the liquid, cm/s; g is gravity acceleration, cm/s^2; ρ_s is particle density, g/cm^3; ρ_L is liquid density, g/cm^3; d is particle's diameter, cm.

Equation (2.2) is valid for single spherical particle subsiding slowly in a fluid without the interference of other forces or motions. The concentration of particles in the liquid should be low enough to ensure that particles are adequately dispersive in the liquid and no appreciable interaction and interference between particles occur during the experiment. Therefore, the maximum mass concentration, commonly accepted, is usually less than 1 %. In addition, In order to reduce the interference of vessel wall to particle settling, the distance of a particle to the vessel wall should be at least 0.5 cm. In this situation, however, some particles may dissolve partially or fully in the fluid altering the grain-size distribution.

Mean size of particles

In clastic reservoir rocks, the particle size varies greatly in nature. In sieve analysis, each sieve actually retains an aggregate of different size particles. We thus know the size range of particles between the opening sizes of two adjacent sieves but grain-size of each particle. Therefore, it is very necessary to know the mean size of particles in each sieve for the study of rock texture. In an ordinary way, the mean size of particles in each sieve/fraction can be determined by the following formula:

$$\frac{1}{\bar{d}_i} = \frac{1}{2}\left(\frac{1}{\bar{d}_i'} + \frac{1}{\bar{d}_i''}\right) \tag{2.3}$$

where $\bar{d}_i$ is the mean diameter of particles retained on *i*th sieve, μm; d_i' is the opening size of last sieve (*i*-1th), μm; d_i'' is the opening size of *i*th sieve, μm.

2.1.1.3 Grain-Size Distribution

To display the results of the grain-size analysis of a rock, first find the percent of each fraction of grains. To do so, Eq. (2.1) can be used. Next, find the cumulative percent of all grains till *i*th fraction. The percentage of cumulative grains to *i*th fraction is determined by Eq. (2.1) using the total weight of all grains to *i*th fraction.

The result of grain-size analysis can be represented using either a table or a diagram. Table 2.3 shows the result of a grain-size analysis for a typical sandstone sample. Generally, the graphical method is more popular in oilfields, normally including grain-size distribution curve, cumulative grain-size distribution curve, grain-size frequency histogram, etc.

The curve of the weight percent of grains to their diameter is referred to as *grain-size distribution curve* or *grain-size frequency curve* (Fig. 2.5). A curve with cumulative weight percent on the *y* axis and grain-size (grain diameter or phi value) on the *x* axis is called *cumulative grain-size distribution curve* or *grading curve* (Fig. 2.6).

The two curves can visually display the grain-size distribution of a rock. Generally, a sharper peak of grain-size distribution or a steeper curve of cumulative grain-size distribution reflects more uniform grain-sizes (good sorting) of a rock; a flat peak or less steep curve reflects less uniform grain-sizes (poor sorting) in opposite manner. Different locations of the curve in the diagram indicate different average grain sizes of rocks (Fig. 2.7). From here we see that both the two curves can characterize illustratively the size and distribution of rock particles.

Table 2.3 The results of a grain-size analysis for a typical sandstone

Opening size of sieve (mm)	0.833	0.701	0.589	0.495	0.417	0.35
Weight percent (%)	2.10	13.11	54.15	18.50	7.44	4.70
Cumulative weight percent (%)	2.10	15.21	69.36	87.86	95.30	100.0

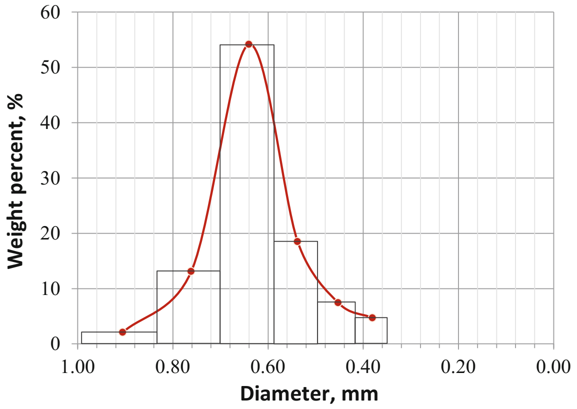


Fig. 2.5 Grain-size distribution curve

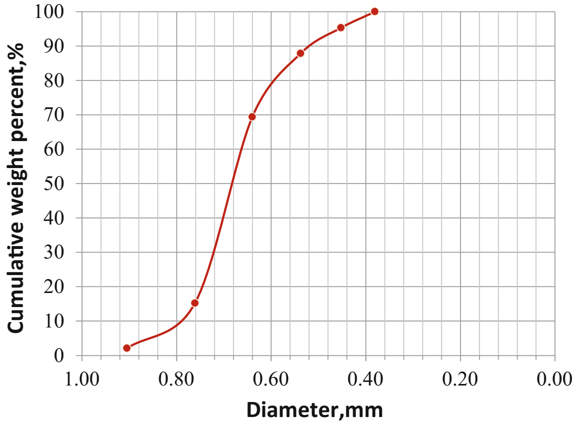


Fig. 2.6 Cumulative grain-size distribution curve

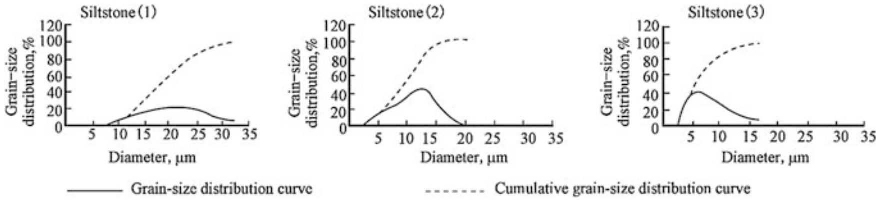


Fig. 2.7 Grain-size distribution curves of different siltstones

2.1.1.4 Grain-Size Statistical Parameters

Sorting of a grain population is a measure of the range of grain-sizes present and the magnitude of the spread or scatter of these sizes around the mean size [9]. It indicates the uniformity of grain-size distribution within a sedimentary rock. In well-sorted sediments, the grain-size of particles is very similar, while the particles consisting of poorly sorted sediments usually are distributed in a wide range of grain-size (Fig. 2.8). In the same way, a rock having a wide range of grain-size is said to be poorly sorting, whereas a well-sorted rock has a relatively narrow grain-size range. Well-sorted rocks are generally porous and have high permeability, but poorly sorted rocks have lower porosity and permeability.

Describing the significant feature of grain-size distributions, grain-size parameters can be used to evaluate the grain-size distribution or sorting of rock particles. Grain-size parameters can be determined in terms of different mathematical methods. Most grain-size parameters are defined based on graphical-statistical method, such as median, mean, standards deviation, skewness, kurtosis, etc. This is to say that these parameters are calculated with the grain diameters read from a graph (cumulative grain-size distribution curve). At present, the common parameters are customarily calculated with the method proposed by Folk and Ward. Here are several common grain-size parameters.

Standard deviation

Standard deviation is widely used to evaluate the sorting of rock particles. It describes the uniformity of grain-sizes in a rock. Folk and Ward (1957) proposed the following expression for calculating graphic standard deviation [10]:

$$\sigma = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \tag{2.4}$$

where phi (ϕ) is a logarithmic transformation: $\phi_i = -\log_2 d_i$; d_i is grain diameter in millimeters; The subscript of 5, 16, 84, and 95 denotes separately the 5, 16, 84, and 95 % by cumulative weight of a cumulative grain-size distribution curve. So, ϕ_5, ϕ_{16}, ϕ_{84}, and ϕ_{95} represent the phi values at 5, 16, 84, and 95 cumulative percentage (Fig. 2.9).

The standard deviation of grain-size distributions of rocks ordinarily ranges from <0.35 to >4.00. Based on the statistical results of a lot of samples, a verbal

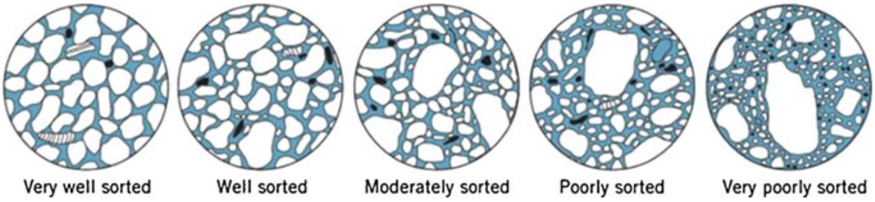


Fig. 2.8 Schematic diagram of sorting levels of sediment particles

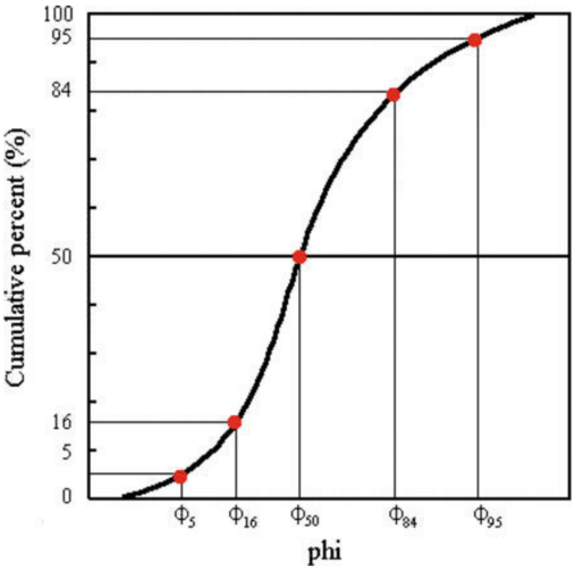


Fig. 2.9 Schematic diagram for determining the values of ϕ_5, ϕ_{16}, ϕ_{84} and ϕ_{95} on the curve of cumulative grain-size distribution

Table 2.4 Classification scale of standard deviation

Standard deviation	<0.35	0.35–0.50	0.50–0.71	0.71–1.00	1.00–2.00	2.00–4.00	>4.00
Scale	Very well sorted	Well sorted	Moderately well sorted	Moderately sorted	Poorly sorted	Very poorly sorted	Extremely poorly sorted

classification scale for sorting corresponding to various values of graphic phi standard deviation is presented by Folk and Ward (1974) (Table 2.4) [10, 11]. Obviously, the smaller the standard deviation is, the more the uniform rock particles are.

Skewness

Skewness is an additional measure of grain-size sorting. Actually, two samples may have the same average grain-size and sorting but may be quite different to their degrees of symmetry. Skewness measures the degree to which a grain-size distribution curve approaches symmetry. The grain-size distributions of most clastic sediments do not yield a perfect normal, or lognormal, distribution curve. Instead, they display an asymmetrical distribution. Folk's inclusive graphic skewness (1957) is calculated by the equation [10]:

$$S_{\mathrm{kp}} = \frac{\phi_{84} + \phi_{16} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_{95} + \phi_5 - 2\phi_{50}}{2(\phi_{95} - \phi_5)} \quad (2.5)$$

where S_{kp} is skewness of grain-size distribution. The phi values (ϕ_i) represent the same percentages as those for standard deviation, namely ϕ_5, ϕ_{16}, ϕ_{50}, ϕ_{84}, and ϕ_{95} represent the phi values at 5, 16, 50, 84, and 95 cumulative percentage.

In general, the skewness of a grain-size distribution varies between −1 and 1, as $-1 < S_{kp} < 1$. Symmetrical grain-size curves (normal distribution) have a skewness equal to 0; those with a large proportion of fine particles are said to be fine skewed, or positively skewed (fine sediment has positive phi values, $S_{kp} > 0$) (Fig. 2.10a); those with a large proportion of coarse particles are said to be coarse skewed, or negatively skewed ($S_{kp} < 0$) (Fig. 2.10b). A verbal classification scale proposed by Folk (1966) [4] is listed in Table 2.5. Obviously, the more the value of the skewness deviates from zero, the greater the skewness of grain-size distribution.

Kurtosis

Kurtosis is a measure of the *sharpness* of a grain-size distribution curve. The sharpness or peakedness of a grain-size distribution curve is known as Kurtosis. Kurtosis describes the concentrative degree of grain-size distribution in a rock. Generally, a normal distribution curve is mesokurtic; a sharp-peaked curve is said to be leptokurtic; and a flat-peaked curve is platykurtic. Sharp-peaked curves indicate better sorting in the central portion of the grain-size distribution than the tails, and flat-peaked curves indicate the opposite.

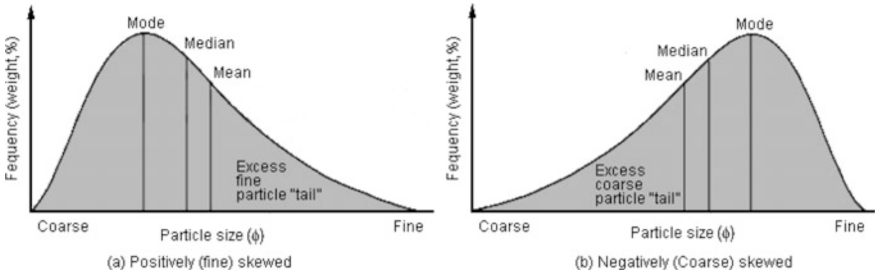


Fig. 2.10 Skewed grain-size frequency curves, illustrating the difference between positive (fine) and negative (coarse) skewness (Sam [9])

Table 2.5 Gradation of skewness (Folk 1966)

Skewness	<−0.30	−0.3 to −1	−0.1 to +0.1	+0.1 to +0.30	>+0.3
Scale	Strongly coarse skewed	Coarse skewed	Nearly symmetrical	Fine skewed	Strongly fine skewed

Folk's formula (1957) for calculating graphic kurtosis is as follows [10]:

$$K_p = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})} \tag{2.6}$$

where K_p is the kurtosis of a grain-size distribution; the phi values represent the same percentages as those of standard deviation.

In general, normal distribution curves have a kurtosis equal to 1; leptokurtic curves have a kurtosis higher than 1, and platykurtic curves have a kurtosis lower than 1. If a curve is very flat or double-peaked, K_p may be less than 0.6; A much sharp-peaked curve may have a K_p ranging from 1.5 to 3.

Mode

Mode (Mo) is the most frequently occurring grain-size in a population of rock particles. The modal diameter is the diameter of grains represented by the peak of a distribution curve or the steepest point of a cumulative curve, as shown in Fig. 2.10.

To a certain extent, it represents the grain-size of the majority and the sorting of rock particles.

Median

Median (Md) is the grain-size corresponding to the 50 % cumulative weight of a cumulative grain-size distribution curve. It represents the midpoint of a grain-size distribution. In a rock sample, half of the grains by weight are coarser than the median, and half are finer.

Mean

Mean of a grain-size distribution refers to the arithmetic mean of all grain-sizes in a rock sample. Actually, a graphic mean can be obtained according to the typical diameters determined from a cumulative distribution curve. The following expression is the commonly used algorithm:

$$M_z = \frac{d_{16} + d_{50} + d_{84}}{3} \tag{2.7}$$

where d_{16}, d_{50}, and d_{84} are particle diameters separately corresponding to 16, 50, and 84 % cumulative weight of the cumulative distribution curve, μm.

2.1.2 Specific Surface Area of Rocks

Specific surface area, or SSA for short, is an essential property of reservoir rocks. It is a measure of the total surface area of grains in a rock. The SSA of reservoir rocks has a particular importance for the study of adsorption and reactions on surfaces in petroleum engineering.