"This excellent text book provides much-needed reference on reservoir rock properties. Prof. Nayef Alyafei has based this work on his own popular lecture courses and his extensive research in multiphase flow in porous media. A wide range of topics is presented clearly with excellent illustrations and explanations throughout. The approach follows an easy-to-follow coherent progression of ideas and is pedagogical in its presentation, making this work ideal as a textbook for undergraduate or post-graduate studies in petroleum engineering, hydrology or related disciplines. The book provides a much needed reference on petrophysics which is also valuable for researchers and professionals working in the oil industry. It is also of interest to the growing body of students, researchers, scientists and engineers working on flow in porous media with a variety of applications from hydrocarbon recovery to carbon dioxide storage. I will certainly recommend this work to my own students and colleagues, and use it in my teaching."

Martin Blunt, Professor of Reservoir Engineering, Imperial College London

This book covers the essential concepts of rock properties aiding students, petroleum geoscientists, and engineers to understand petroleum reservoirs.

Key Features:

- Explains the fundamental concepts with great clarity and a step-by-step approach.
- Provides numerous examples and problems on each covered topic.
- Written in clear English language to appeal to global students.
- Summary highlighting the main points of each chapter.
- Numerous illustrative figures to solidify the understanding of the concepts.

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Fundamentals of Reservoir Rock Properties

Nayef Alyafei

Conversion of Units

Length:

1 ft = 0.3048 m = 12 in

1 m = 3.281 ft = 39.37 in = 100 cm

Area:

1 ft^2 = 0.092903 m^2 = 144 in^2

1 m^2 = 10.7649 ft^2 = 10000 cm^2

Mass:

1 lbm = 0.45359 kg

1 kg = 2.2046 lbm = 1000 g

Force:

1 lbf = 4.44822 N = 32.2 lbm.ft/s^2

1 N = 0.2248 lbf = 1 kg.m/s^2

Interfacial Tension:

1 N/m = 1000 mN/m = 1000 dyne/cm

Permeability:

1 D = 1000 mD = 9.869233 x 10^{-13} m^2

Volume:

1 ft^3 = 0.02831 m^3 = 28.3168 L = 0.178 bbl = 0.178 RB

1 m^3 = 35.29 ft^3 = 1000 L

Pressure:

1 atm = 101.3 kPa = 1.013 bar = 14.696 lbf/in^2 (psia)

1 psia = 6.89 kPa = atm/14.696

1 Pa = 1 N/m^2 = 1 kg/m.s^2 = 10^{-5} bar = 1.450 x 10^{-4} lbf/in^2 = 10 dyne/cm^2

psia = psig +14.7

Density:

1 g/cc = 1000 kg/m^3 = 62.427 lb/ft^3 = 8.345 lb/gal = 0.03361 lb/in^3

Viscosity:

1 cP = 0.01 poise = 0.01 g/cm.s = 0.001 kg/m.s = 0.001 n.s/m^2 = 0.001 Pa.s

= 0.01 dyne.s/cm^2 = 6.72 x 10^{-4} lbm/ft.s = 2.09 x 10^{-5} lbf.s/ft^2

Metric Prefixes:

Prefix	Symbol	Multiplication Factor
giga	G	10^9
mega	M	10^6
kilo	k	10^3
centi	c	10^{-2}
milli	m	10^{-3}
micro	µ	10^{-6}
nano	n	10^{-9}

Oilfield Prefixes:

Prefix	Symbol	Multiplication Factor
Thousand	M	10^3
Million	MM	10^6
Billion	MMM or B	10^9
Trillion	T	10^{12}

Index

Chapter 1

Introduction

Prior to the discovery of petroleum, mankind used coal as the main source of energy to operate their machines. Since the first commercial well drilled in the United States in 1859, the dependence on petroleum as a source of energy has increased tremendously. From that point onwards, **petroleum has been and will continue to be the main source of energy for decades ahead** due to its availability, efficiency, and low price. In addition, hydrocarbons are not only used as fuel for our machines, but also as lubricants and raw materials for many modern industrial products such as plastics, paints, and rubber.

1.1 What is Petroleum?

Petroleum is a naturally occurring hydrocarbon (composed of hydrogen and carbon atoms) that can exist as a solid, liquid, or gas. The physical state of the hydrocarbon is a function of the pressure and temperature to which it is exposed as well as the structure (chain length/molecular weight). However, most of the hydrocarbons found within the ground are either liquid or gas, and are referred to as crude oil and natural gas, respectively.

1.2 Origin of Petroleum

There are two theories for the origin of petroleum. They are the **organic** and **inorganic** theories, as stated in **Table 1.1**.

Table 1.1: Theories for the origin of petroleum.

Organic (derived from living matter, usually carbon atoms)	**Inorganic** (not derived from living matter)
States that petroleum evolved from the decomposition of animals and plants that lived during previous geological times.	States that petroleum was formed through chemical reactions between water, carbon dioxide, and several inorganic substances such as carbonates in the earth.

The organic theory is the commonly accepted theory.

1.3 Petroleum System

A petroleum system consists of different geological components needed to generate and store hydrocarbons. These components are source rock, migration path, reservoir rock, trap, and seal. **Source rock** is the rock containing organic matter in sufficient quantity, and is under suitable conditions for the formation of hydrocarbons. **Migration path** is the pathway that the hydrocarbons take to move away from the source rock to the point where they can find a suitable trap. The forces driving the movement of hydrocarbons out of the source rock come from tectonic stresses, which are coupled with capillarity (this topic is explained further in Chapter 8) and buoyancy (density difference); since hydrocarbons are lighter than water, they move upward. **Reservoir rock** is the rock that is able to store hydrocarbons in its pores. The hydrocarbons will continue migrating upward until they reach a **seal**. This is an impermeable layer of rock that blocks the hydrocarbons from further migration. Finally, a **trap** is a configuration of rocks, ensuring that the hydrocarbons are stored in it. Traps can be structural, stratigraphic, or a combination of both. **Figure 1.1** shows the components and processes in a petroleum system.

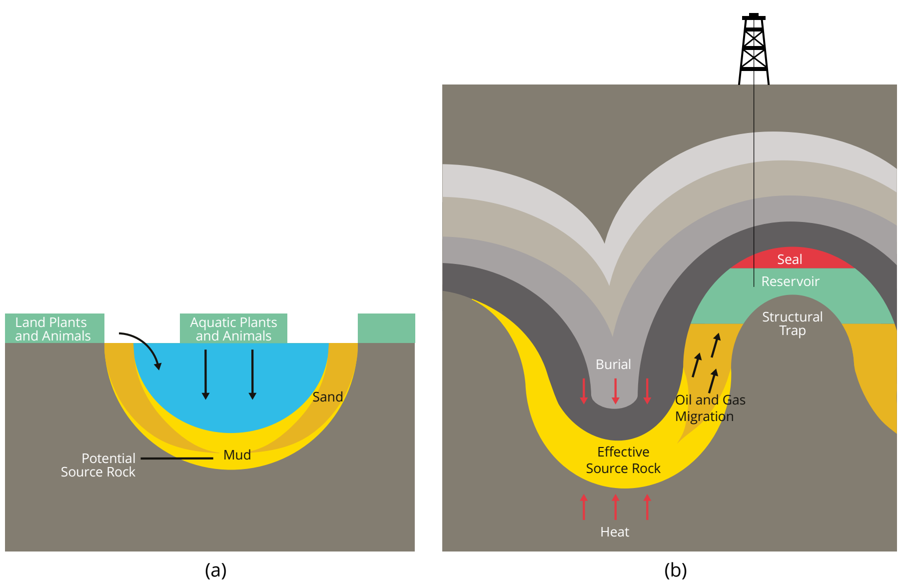


Figure 1.1: Schematic showing (a) the process of hydrocarbon formation and (b) the migration of matured hydrocarbon until it reaches an impermeable seal and attains static equilibrium.

1.4 What is a Reservoir?

In petroleum engineering, a reservoir is the place where the hydrocarbons reside. Our job as petroleum engineers is to access reservoirs and extract the hydrocarbons (natural gas and/or crude oil) in an economical and environmentally safe manner. Reservoirs can be classified into three types: oil, gas, and gas-oil

reservoirs, as shown in **Figure 1.2**. Natural gas, if present in a reservoir, is always on top because it has the lowest density, while water is always at the bottom because it has the highest density among the three reservoir fluids (gas, oil, and water).

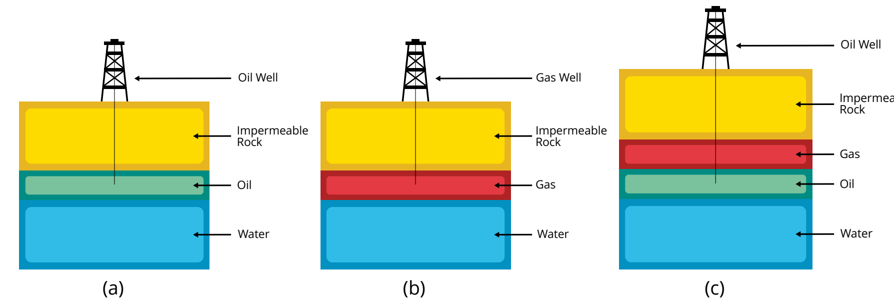


Figure 1.2: Schematic showing typical hydrocarbon distributions in (a) an oil reservoir, (b) a gas reservoir and (c) a gas–oil reservoir.

1.5 Lithology of Petroleum Reservoirs

Lithology is the general physical characteristics of a rock. Reservoir rocks can be divided into two types: **sandstone** and **carbonates**. Sandstones are formed from grains that have undergone sedimentation, compaction, and cementation. Carbonates are principally formed on carbonate platforms by a combination of biogenic and abiogenic processes.

The major characteristics of both sandstone and carbonate rocks are shown in **Table 1.2.**

Table 1.2: Geological comparison between sandstone and carbonate rocks.

Sandstone	**Carbonate**
• Usually composed of silica grains (mainly quartz and some feldspar). • Consolidated (the rock is combined as one unit) or loosely consolidated. • May contain swelling clays (clays have negative impact on reservoir quality).	• Two major types are limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). • Pore space consists of inter- or intragranular porosity as well as areas of dissolution (vugs) and fractures.

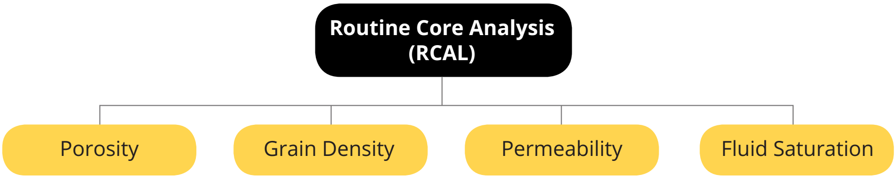
1.6 What is Petrophysics?

Petrophysics is the study of rock properties and rock-fluid properties. These properties, which we will study extensively in the following chapters, include: **porosity, rock compressibility, single-phase permeability, fluid saturation, electrical properties of reservoir rocks, wettability, capillary pressure,** and **relative permeability.** Petrophysics can be divided into core and wireline petrophysics. In this book, we will mainly cover **core petrophysics** that requires conducting laboratory experiments on core samples brought from the reservoir to the surface. **Wireline petrophysics,** which involves using logs to determine properties, will also be briefly covered in this book.

Rock samples are extracted from the reservoir through coring and can be subjected to two categories of laboratory analysis: **routine core analysis** and **special core analysis.**

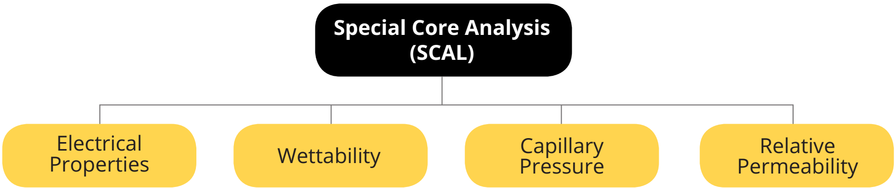
1.6.1 Routine Core Analysis (RCAL)

Routine core analysis attempts to find the basic properties of the reservoir rock such as porosity, grain density, permeability, and fluid saturation, as shown below:



1.6.2 Special Core Analysis (SCAL)

Special core analysis is an extension of RCAL, and attempts to measure data that is more representative of the reservoir conditions. These measurements include electrical properties of reservoir rocks, wettability, capillary pressure, and relative permeability, as shown below:



1.7 Why Do We Need to Understand Petrophysics?

Petrophysics is a fundamental science for petroleum engineers. Most of the petroleum engineering topics branch out from petrophysical concepts. An understanding of petrophysical properties helps us in:

- Estimating the quantity of hydrocarbons present in the reservoirs (e.g. porosity and fluid saturation).
- Understanding how the hydrocarbons will flow from the reservoir to the well during production (e.g. permeability, wettability, and relative permeability).

In this book, we will study each petrophysical property extensively.

Chapter 2

Porosity

Porosity is the ratio of void volume in a porous medium to the total volume of that medium. Let us assume that we have an empty 350 ml glass, and we fill the glass to the brim with water to cover the entire volume. Now consider another identical glass with four ice cubes in it, with each ice cube having a volume of 50 ml. The total volume of ice in the glass will be 200 ml, given that it is not melting. If we now want to pour water to the glass, we know that there will be room for just 150 ml of water, since the rest of the volume is occupied by ice. Hence, the porosity of the glass with the ice cubes will be 150 ml (pore volume, the volume of water filling the pore space) divided by 350 ml (total volume) and the resulting porosity will be 0.43. This scenario is shown in **Figure 2.1**. Basically, porosity means storage capacity that can indicate the amount of fluid that the porous medium can store. Porosity can be calculated using the following equation:

$$\phi = \frac{V_p}{V_t} \tag{2.1}$$

where ϕ is the porosity [dimensionless since we are dividing two volumes], V_p is the pore volume [cm^3], and V_t is the total volume [cm^3].

Alternatively, we can subtract the matrix volume (in this case, the ice cubes) from the total volume and divide it by the total volume to obtain the porosity, as shown in the following equation:

$$\phi = \frac{V_t - V_m}{V_t} \tag{2.2}$$

where V_m is the matrix volume [cm^3].

Overall, we can say that:

$$\phi = \frac{V_p}{V_t} = \frac{V_t - V_m}{V_t} \tag{2.3}$$

$$V_t = V_p + V_m \tag{2.4}$$

Therefore, if we know any two of the volumes, we can calculate the porosity.

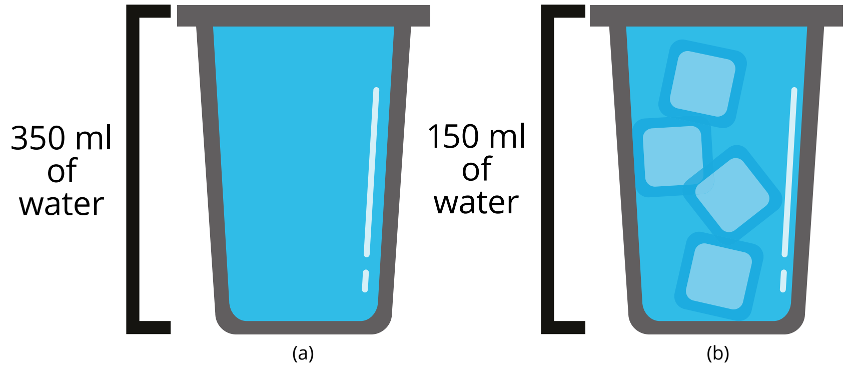


Figure 2.1: Schematic showing (a) a glass filled with 350 ml of water and (b) a glass filled with water and four ice cubes. As shown, the volume of water in the glass with ice cubes is less since a matrix volume is present.

Example 2.1

A core sample has a total volume of 24.5 cm³ and a matrix volume of 18.9 cm³.

(a) What is the pore volume of this sample?
(b) What is the porosity of this sample?

Solution

(a) **Equation 2.4** can be used to find the pore volume:

$$V_t = V_p + V_m$$
$$24.5 = V_p + 18.9$$
$$V_p = 5.6\ \text{cm}^3$$

(b) **Equation 2.1** can be used to find the porosity:

$$\phi = \frac{V_p}{V_t} = \frac{5.6}{24.5} = \mathbf{0.229} \text{ or } \mathbf{22.9\%}$$

Reservoir rocks are porous and contain fluids in their pores, as shown in **Figure 2.2**. Porosity measurement from a core is part of RCAL. When we use the term "core," we usually refer to a cylindrical rock sample with a width and length of a few centimeters.

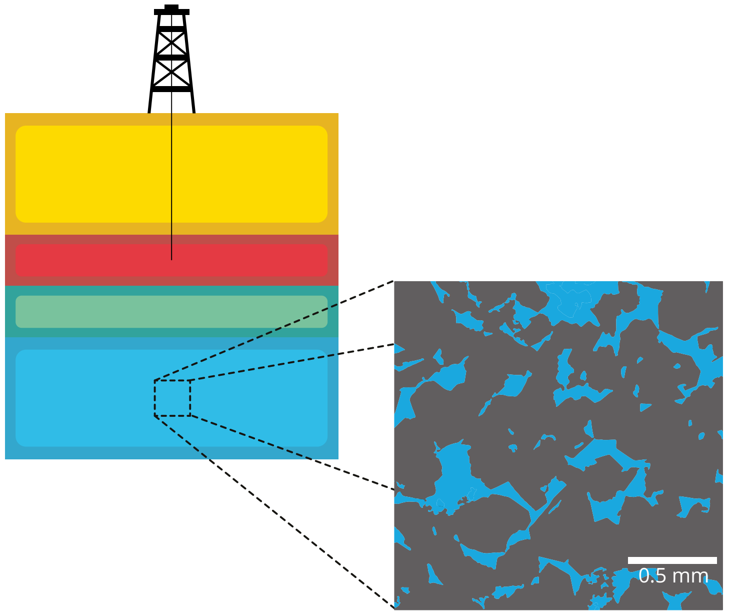


Figure 2.2: Schematic showing the pore spaces in a reservoir rock at a micro-scale from a giant reservoir field. The blue color in the figure represents the water while the black color represents the matrix.

In addition, when dealing with rocks, we often refer to the matrix volume as the grain volume (V_g) and the total volume as the bulk volume (V_b). **Note that the fractional porosity value is often multiplied by 100 to make it a percentage; however, it should always be a fraction when used in calculations**. The porosity of reservoir rocks usually ranges from 5% to 40%. **Table 2.1** shows typical porosity values for different reservoir rocks. The porosity of rocks within a reservoir indicates how much oil and/or gas is stored in that reservoir. Therefore, finding the porosity of the reservoir beforehand is important for engineers because it helps them estimate how economically viable that reservoir is and how many resources should be invested in it.

Table 2.1: Typical porosity values in reservoir rocks.

Rock Type	**Range**
Loosely consolidated sands	35–40%
Sandstones	20–35%
Well-cemented sandstones	15–20%
Limestones	5–20%