Fundamentals of the Petrophysics of Oil and Gas Reservoirs

Leonid Buryakovsky, George V. Chilingar, Herman H. Rieke, and Sanghee Shin

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This volume is dedicated to Dr. Chengyu Fu for his important contributions to World Petroleum Industry and World Economy
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Preface

Petrophysics (rock physics) is a branch of applied geology relating to the study of reservoir and caprock properties and their interactions with fluids (gases, hydrocarbons, and aqueous solutions) based on fundamental methods of physics, chemistry, and mathematics. The geologic material forming a reservoir for the accumulation of fluids (oil, gas and water) in the subsurface must contain a three-dimensional network of interconnected voids (pores, vugs and/or fractures) to store the formation fluids and allow their movement within the reservoir during hydrocarbon recovery. Petrophysical applications are widely used in petroleum geology, economic geology, seismic interpretations, hydrocarbon reserve estimation, reservoir description and simulation, field development planning, and reservoir production management.

The goal of petroleum geology is to perform the exploration and to provide, if a discovery is made of a commercial oil and gas accumulation, a geological/geophysical description of the reservoir. This includes preparing an estimate of the initial reserve hydrocarbon volume. The application of petrophysics in both hydrocarbon exploration and recovery is to minimize financial risk.

The goal of economic geology is the study and analysis of geologic bodies and materials that can be utilized profitably, including carbon fuels, metals, nonmetallic minerals, and water. The application of geoscience knowledge and theory is foremost for understanding of the origin of deposits and, most importantly, how to exploit them.

The goal of reservoir engineering is to produce an integrated reservoir study in order to support a computer model of the reservoir that can implement the integration of the total reservoir database. The model must include: (1) production forecasts; (2) results of operational consequences based on management decisions, and (3) how to maintain a current reservoir model by using newly-acquired performance and field data.
Theoretical and applied petroleum geology encompasses the exploration, discovery, and integration of information to be applied to the appraisal of oil and gas basins, provinces, regions, areas, and fields that are considered as integral geologic systems. Owing to the absence of distinct boundaries, geologic systems are mostly the so-called open systems, the geologic properties of which are modified over time and space. Considering these comments, a geologic system can be defined as follows:

*A geologic system is an organized natural assembly of interconnected and interacting elements of lithosphere having common development history and comprising a single geologic body with properties that are not inherent in its individual elements.*

In this regard the petrophysical system may be defined as a:

*Petrophysical system is the well-organized natural assembly of interacting solid, liquid, and gaseous elements having common development history and a distinguishing set of physical and chemical properties, which manifest themselves both individually and jointly.*

In addition to the above-mentioned statement, we have to indicate also the basic principle of geological investigations, which states, "the present is the key to the past". This concept means that processes, which acted on the Earth in the past, are very similar to or are the same as those operating today. That is why the petrophysical study of reservoir and sealing-rock (caprock) properties by laboratory core analysis and/or well logging and well testing is very important to understand the origin, composition, and behavior of oil and gas reservoirs.

The study of fluid flow through porous rocks as well as rock properties themselves had begun by Austrian scientist Kozeny (1927). He solved the Navier-Stokes equations for fluid flow by considering the porous medium as an assembly of capillary tubes (pores) of the same length. Kozeny obtained relationship among permeability, porosity, and specific surface area of porous media (Kozeny, 1927). At about the same time, the Schlumberger brothers in France introduced the first well logs. These early developments led to rapid improvements of equipment, production operations, formation evaluation, and hydrocarbon recovery efficiency (Schlumberger, 1972, 1987). Therefore, in the decades following, the study of rock properties and fluid flow was intensified and became a part of the research endeavors of petroleum institutes and major oil companies. Today, most of the oil and gas companies rely on
research and the application of the obtained results to the field by service companies.

A first experimental study of petrophysical properties using rock samples was by Bridgman (1918). He conducted the stress–strain testing under atmospheric pressure and at room temperature. Comparison of his experimental results with well-logging data showed a discrepancy between the two owing to the influence of formation pressure and temperature on the petrophysical properties in-situ. Bridgman was the first investigator who established deviation of physical parameters of sandstones determined at room temperature and atmospheric pressure from those obtained under elevated pressures and temperatures (Bridgman, 1936; Bridgman et al., 1966).

In 1942, G.E. Archie discussed the relationship between electrical resistance of fluids in porous media and porosity and proposed an equation relating porosity and electrical resistivity. He reviewed and discussed the relationships among the types of rocks, sedimentary environments, and petrophysical properties, and suggested that specialized studies of reservoir properties of reservoir rocks and caprocks should be recognized as a separate geologic discipline called petrophysics (Archie, 1950, 1952).

The influence of overburden pressure on porosity was studied by Archie (1950), who established that porosity of argillaceous sediments at the Earth's surface is about 50%, whereas at a depth of 2000 m it is ten times lower. Krumbein and Sloss (1951) showed that the porosity of shale and sandstone is a function of burial depth, which influences porosity of shale more than that of sandstone. Fatt (1953, 1957a,b) was the first investigator who suggested that the physical properties of rocks are affected by the difference between the total overburden pressure and reservoir pore pressure, i.e., the net overburden (grain-to-grain) pressure.

A major contribution to petrophysical studies was made by Hedberg (1926, 1936); Athy (1930); Carman (1937, 1938, 1939); Carpenter and Spencer (1940); Klinkenberg (1941, 1951); Trask (1942); Taylor (1950); Wyllie et al. (1950, 1956, 1958a); Winsauer et al. (1952, 1953); Griffith (1952); Brooks and Purcell (1952); Fatt (1953, 1957a,b); Hall (1953); Krumbein (1955b); Weller (1959); von Engelhardt (1960); Chilingar et al. (1963); Chilingar (1964, 2005); Donaldson et al. (1969); Rieke and Chilingarian (1974), Eremenko and Chilingar (1996), Rebesco and Camerlenchi (2008), and van den Berg and Nio (2010).
Important petrophysical studies were carried out in the former USSR, e.g., Avdusin and Tsvetkova (1938); Volarovich (1940, 1960); Trebin (1945); Kotyakov (1949, 1956); Samedov and Buryakovksy (1957); Kusakov and Gudok (1958); Buryakovksy (1960, 1970, 1977); Buryakovksy et al. (1961, 1975, 1982); Vassoievich and Bronovitskiy (1962); Dobrynin (1962); Teodorovich (1965); Parkhomenko (1965); Vendelshtein (1966); Khanin (1966, 1969); Dakhkilgov (1967); Shreiner et al. (1968); Petkevich and Verbitskiy (1970); Avchan (1972); Ellanskiy (1972); Bagrintseva (1977, 1982); Chernikov and Kurenkov (1977); Marmorshtein (1975, 1985); Morozovich (1967); Proshlyakov (1974); and Dzhevanshir et al. (1986).

Generalized discussion of petrophysics were published by Krumbein and Sloss (1951); Pirson (1950, 1963); Scheidegger (1957); Dakhnov and Dolina (1959); von Engelhardt (1960); Kobranova (1962, 1986); Parkhomenko (1965); Khanin (1966, 1969, 1976); Avchan et al. (1966, 1979); Vendelshtein (1966); Romm (1966, 1985); Griffith (1967); Gudok (1970); Dobrynin (1970); Lomtadze (1972); Volarovich (1974); Pavlova (1975); Chilingar et al. (1975, 1976, 1979, 1992); Kotyakov (1977); Buryakovksy (1977, 1985a); Buryakovksy et al. (1961, 1982, 1985b, 1990a, 2001); Marmorshtein (1975, 1985); Bagrintseva (1977, 1982); Magara (1978); Ellanskiy (1978); Dakhnov (1982, 1985); Proshlyakov et al. (1987); and Tiab and Donaldson (1996).

Of major importance in petrophysical studies is the construction and investigation of petrophysical relationships. Among a large amount of contributions on the use of mathematical methods and techniques in petrophysics one should mention the following: Krumbein (1955a, 1955b); Miller and Kahn (1962); Stetyukha (1964); Krumbein et al. (1965, 1969); Sharapov (1965); Griffith (1967); Vistelius (1967); Harbaugh et al. (1970, 1977); Buryakovksy (1968, 1974b, 1982, 1985a, 1992); Buryakovksy et al. (1974a, 1979, 1980, 1981, 1982, 1990a, 1991); Ellanskiy (1978); Romm (1985); Abasov et al. (1987, 1989); Lucia (1999); Chilingar et al. (2005); and Cosentino (2006).

Seismic fluid detection, reservoir delineation, and rock physics is in the realm of the geophysicists. Because of the growing complexity of recently discovered oil and gas fields more reliance is being placed on seismic delineation of the properties of reservoir rocks, (such as porosity and permeability), fluid movement in time, fracture detection, pore pressure, mineralogy and saturation components in the formation. Well test data; well logs,
and core data are of a scale that does not match seismic spatial
detail of the variability in reservoir petrophysical properties.
Some important contributors to this science are: Fertl et al. (1976);
Gregory (1976); Nobes et al. (1986); Batzle and Wang (1992);
Berryman (1992); Guéguen and Palciauskas (1994); Mavko et al.

Various oil and gas reservoirs in clastic, carbonate and volca-
nic rocks are described in this book, taking into consideration their
depositional environments and depth of occurrence. Core analysis
and well-logging techniques, used for the determination of such
essential reservoir-rock properties as porosity (total and effective),
permeability (absolute and relative to air, water, oil, and gas), oil/
gas/water saturation, and wettability are described in detail. Well-
logging section includes electrical, radioactive, acoustic and other
tools used for subsurface investigation. Well-log analysis and inter-
pretation includes formation evaluation based on core and log data
and relationships between them. Today, the mathematical simula-
tion of petrophysical properties and relationships including core-to
core and log-to-core, and seismic-to-core-to-well-log correlation is
a common industry practice. One must be aware that the scales of
petrophysical properties in these correlations are of different mag-
nitudes, ranging from $10^{-6}$ to $10^6$ m, which covers the microscopic to
the gigascopic properties (Chilingarian et al., 1996).

This book is an essential summary of theoretical studies and
their practical applications in the field of petrophysics and some
interdisciplinary sciences, activities conducted by the authors
for more than 50 years. It represents the physical and geologi-
cal background of petrophysical investigations of subsurface
formations.

Leonid A. Buryakovksy
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Hydrocarbon exploration and exploitation technologies have made
tremendous technical progress during the past 25 years. One of
the technologies that improved success is the ability to integrate
reservoir information into a virtual three-dimensional reservoir.
Although, such spatial computer models only represent an approxi-
mation of the real hydrocarbon reservoir, simulation has facilitated
our knowledge and limitations owing to the scarcity of available data. One should consider the fact that the model is only as good as the available data, which is basically petrophysical and fluid properties of the producing formation. This book is about the background and value of having knowledge of the petrophysical properties and geological data to help maximize the hydrocarbon recovery.

The authors would also like to recommend the classical book on "Petrophysics" by D.Tiab and E.C. Donaldson, 2004, Gulf Professional Publishing, as a reference book.

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Acknowledgement

The help extended by Dr. Henry Chuang, President of Willie International Holdings Limited of Hong Kong, China, a Petroleum Engineer, was invaluable in publishing this book. He deserves the highest of praise.
1.1 Characterization of Hydrocarbon Reservoirs

Hydrocarbon accumulation requires the presence of a natural trap consisting of reservoir rocks, sealing or caprocks, and three-dimensional four-way closure. The description of reservoir rocks should include the following elements:

1. Presence of reservoir rocks
   - Depositional model (sequence stratigraphy framework)
   - Lithology
   - Structural characteristics
   - Lateral and vertical distribution

2. Quality of reservoir rocks
   - Lateral continuity and extension
   - Thickness and vertical lithological cyclicity
   - Relative heterogeneity of rock properties
   - Pore systems ranges and types
   - Transmissibility of fluids
   - Hydrocarbon potential and preservation
   - Diagenetic characteristics

The reservoir rocks are mainly sedimentary rocks, which are deposited as sediments by water, wind, or ice and made up of clastic material, chemical precipitates, and organic or biogenic debris. Sedimentary rocks have formed from sediments or debris by any of the following processes: (1) compaction, (2) cementation, and (3) crystallization. A simplified classification of sedimentary rocks is presented in Table 1.1.

Clastic rocks are the consolidated sedimentary rocks consisting principally of the debris of preexisting rocks (of any origin) or the solid products formed during chemical weathering of such rocks, transported mechanically (by such agents as water, wind, ice, and
gravity) to their places of deposition. Clastic non-carbonate rocks, which are almost exclusively silicon-bearing (either as quartz or silicates) are called the siliciclastic rocks. Siliciclastic rocks consist of sand-, silt- and clay-size particles and their combinations.

Carbonate rocks are the rocks consisting chiefly of carbonate minerals formed by the organic or inorganic precipitation from aqueous solution of carbonates of calcium (limestone), calcium plus magnesium (dolomite), or iron (siderite). These rocks may consist also of the debris of preexisting carbonate rocks (of any origin), which have been transported mechanically to their places of deposition.

Chilingar and Yen (1982) pointed out that carbonate rocks constitute only 15 to 30% of the total volume of sedimentary rocks, whereas about 65% of the total oil and gas reserves in the World reside in carbonate reservoirs. The behavior of carbonate reservoirs differs in many respects from sandstone reservoir, mainly due to the very complex pore structure of carbonate rocks. However, the percentage of in-situ oil recovered from these reservoir rocks is often very low (≤ 20%). Their origin, composition, and the diagenetic and catagenetic processes in large measure determine the petrophysical properties of carbonates and behavior of carbonate hydrocarbon reservoirs (refer to Chilingarian et al., 1996).

Chert is a hard, extremely dense or compact cryptocrystalline sedimentary rock, consisting dominantly of cryptocrystalline silica (chiefly fibrous chalcedony) with lesser amount of micro- or cryptocrystalline quartz and amorphous silica (opal).

Figure 1.1 illustrates a classification based on a tetrahedron at the corners of which are placed carbonate, clay (shale), sandstone (quartz) and chert. This figure also depicts one side of this

<table>
<thead>
<tr>
<th>Clastic Rocks</th>
<th>Carbonates</th>
<th>Evaporites</th>
<th>Organic Rocks</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conglomerate</td>
<td>Limestone</td>
<td>Gypsum</td>
<td>Peat</td>
<td>Chert</td>
</tr>
<tr>
<td>Breccia</td>
<td>Chalk</td>
<td>Anhydrite</td>
<td>Coal</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>Dolomite</td>
<td>Rock salt</td>
<td>Diatomite</td>
<td></td>
</tr>
<tr>
<td>Siltstone</td>
<td>Marl</td>
<td>Potash</td>
<td>Limestone</td>
<td></td>
</tr>
<tr>
<td>Mudstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
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</tbody>
</table>
tetrahedron so that some of the variations between contents of shale, sandstone and limestone can be seen. For example, starting from shale and going toward limestone, increasing amounts of lime will produce calcareous shale, grading into argillaceous (shaley) limestone, then to pure limestone. Similarly, on the other two edges, it is shown how the changes occur from shale to sandstone and from sandstone to limestone. The other three sides show similar variations with chert replacing one of the other constituents. Other valuable classifications of sandstones based on composition were presented by Teodorovich (1965). (e.g., Figure 1.2a,b.)

One of the most important aspects in reservoir characterization is an understanding of depositional environments in the area under study. Depositional environments and facies relationships, diagenesis (physical and chemical changes in sediments up to and through
Figure 1.2b Classification of sandstones on the basis of mineralogical composition. (A) Family of quartz sandstones (1, 2, 3); (B) arkoses (4, 5); (C) two-component mineral-petroclastic sandstones (6, 7, 8, 9, 10, 11) – the latter family can be subdivided into (a) predominantly quartz sandstones (6, 7); (b) predominantly feldspathic sandstones (8, 9), and (c) predominantly petroclastic sandstones (10, 11): (D) three-component mineral – petroclastic sandstones with absolute predominance of one of the components (12, 13, 14); (E) three-component mineral – petroclastic sandstones with relative predominance of one of the components (15, 16, 17); (F) ultrapetroclastic sandstones (18). (After Teodorovich, 1967, Figure 1, p. 76.)

lithification) and catagenesis (physical and chemical changes in the lithified rock) strongly affect the size, shape, pore-space geometry, porosity, permeability, and location of clastic deposits.

Any sediment has originally a terrestrial source (place of origin), created by the life cycles of plants or animals (e.g., shells, leaves, logs, and organic sediments), or by weathering (chemical disintegration and physical breakdown) of parent rocks. Each sediment has a provenance, which is the particular area from which its components were derived and transported by water, ice, or wind into the place of deposition. Sediments are deposited under a variety of conditions or environments, both on land and at sea. Each environment is characterized by specific physical processes and has the particular plants and animals living within it, which contribute such fossils as bones, shells, and plant fragments. Simplified classification of environments of sediment deposition is shown in Table 1.2.

As an example, the depositional environment and stratigraphy of the South Caspian Basin are presented here owing to the geological complexity of the basin and familiarity by the authors with the area.
### Table 1.2 Depositional environments.

<table>
<thead>
<tr>
<th></th>
<th>Delta Group</th>
<th>Intradelta Group</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Continental</strong></td>
<td>Aeolian deposits</td>
<td>Aeolian deposits</td>
</tr>
<tr>
<td></td>
<td>Alluvial deposits</td>
<td>Alluvial deposits</td>
</tr>
<tr>
<td></td>
<td>Delta-plain deposits</td>
<td></td>
</tr>
<tr>
<td><strong>Transitional</strong></td>
<td>Deltaic deposits</td>
<td>Coastal Intradelta-marine</td>
</tr>
<tr>
<td></td>
<td>Prodelta-plain deposits</td>
<td>deposits</td>
</tr>
<tr>
<td><strong>Marine</strong></td>
<td>Normal marine deposits</td>
<td>Shelf deposits</td>
</tr>
<tr>
<td></td>
<td>Slope deposits</td>
<td>Slope deposits</td>
</tr>
<tr>
<td></td>
<td>Deep marine deposits</td>
<td>Deep marine deposits</td>
</tr>
</tbody>
</table>

#### 1.1.1 Geographical and Geological Background of the South Caspian Basin

The South Caspian Basin encompasses water areas of the South Caspian Sea, and together with land areas of Eastern Azerbaijan and Western Turkmenistan constitutes the southern portion of the Caspian Sea region (Figure 1.3a). The South Caspian Basin is separated from the Middle Caspian Basin by the Absheron-Prebalkhan zone of uplifts, which extends NW-SE connecting the Absheron and Cheleken peninsulas, forming a narrow submarine ridge (Buryakovsky, 1974c, 1993a, 1993b; Buryakovsky et al., 2001) (Figures 1.3b and 1.3c).

Azerbaijan borders Russia to the north, Georgia and Armenia to the west, Turkey and Iran to the south, and the Caspian Sea to the east. Aerially, it encompasses the southeastern spurs of the
Greater and Lesser Caucasus Mountains, the Kura Intermountain Depression, and Talysh Mountains (Figure 1.4 and 1.5). Azerbaijan is one of the oldest oil and gas provinces in the world. For more than 140 years oil and gas has been commercially produced onshore in Azerbaijan. The offshore production at the Caspian Sea began about 100 years ago.

Turkmenistan borders Kazakhstan to the north, Uzbekistan to the northeast and east, Afghanistan and Iran to the south, and the South Caspian Sea to the west. The onshore portion of Western Turkmenistan includes the Cheleken Peninsula on the northwest and is bordered by the Kopet-Dagh Mountains to the south.
The offshore region includes the eastern portion of the Absheron-Prebalkhan anticlinal trend and the Chiklishyar-Okarem zone (Turkmenian structural terrace); to the south it is bordered by the Alborz Range in Iran.
Figure 1.3c Regional distribution of oil and gas in Azerbaijan and the South Caspian Basin. (Modified after Aliyev et al., 1985.) Regions: 1–with significant, proved, initial potential resources; 2–highly favorable (offshore); categories of favorability: 3–first, 4–second, 5–third; 6–areas favorable for oil and gas; 7–areas possibly favorable; 8–areas with unclarified prospects; 9–areas with no prospects. Oil- and gas-bearing areas; I–Apsheron, II–Baku Archipelago, III–Lower Kura, IV–Schemakha-Gobustan; V–Yevlakh-Agdzhabedy; VI–Gyandzha, VII–Kura-lori interfluve, VIII–Pre-Caspian-Kuba, IX–deep-water parts of the South Caspian Basin probably favorable areas: X–Adzhinour, XI–Dzhalilabad; areas with uncertain potential: XII–Dzharly-Saatly, XIII–Mil-Mugan, XIV–Alazan-Agrichai, XV–Araks, and XVI–Nakhichevan.

There are several oil and gas regions within onshore Azerbaijan. The main regions are (from north to south):

1. Pre-Caspian – Kuba Region
2. Absheron Peninsula
3. Kobystan anticlinal belt
4. Kura Intermountain Depression.

There are four offshore oil and gas regions that are within the Azerbaijan sector of the Caspian Sea (from north to south):

1. Absheron Archipelago
2. Western portion of the Absheron-Prebalkhan zone of uplifts
3. South Absheron offshore zone