Part I

Seismic Theory Background

1

Introduction

1.1 Introduction

Oil and gas are important natural energy resources, since they are used in nearly every aspect of human life from fuelling cars and generating power to producing plastics and fertilizers. Their impact on human civilization is such that continuing and improving the success of the overall production process is vital. Even with the forecast decreasing use of, for example, gasoline in cars, oil and gas products will still be extensively used. Oil and gas exist in reservoirs located thousands of metres below the Earth's surface and ocean floors. Such reservoirs only exist in certain locations, dependent on the geological history of the area. An increasingly essential precondition for successful extraction of gas and oil is the accurate determination of the subterranean geophysical structure. The knowledge obtained is not simply that of knowing where to look for oil and gas; it is also relevant to the management of the production process after the crude oil is found and extracted. But first, the geological strata need to be imaged. Imaging of subsurface layers is done by a method known as reflection seismology. This geophysical technique relies on the generation of artificial seismic waves and the recording of their reflections from different geological layers. However, the acquired seismic data do not reveal an accurate image of what lies beneath the surface, unless appropriate signal processing methods are carefully employed. In fact, the seismic signals acquired are among the most challenging geo-signal data to process and interpret, since more than 80% of them have extrinsic sources, or are simply noise. In the case of land-based seismic data, for example, the primary seismic reflection signals sought are overwhelmed by surface wave noise (known as ground roll), wave scatter, and so on. The signals of interest in marine exploration seismology are usually masked by multipath waves (multiples).

Digital signal processing (DSP) has long been widely accepted as the primary tool for data conditioning and information extraction. It plays an important role in many applications in science and engineering, including seismology. The actual application of DSP theory to the exploration of subterranean layers began with the work of the Geophysical Analysis Group at the Massachusetts Institute of Technology (MIT) between 1960 and 1965, which proved to be a significant milestone in the history of seismic data processing. This book deals with the application of DSP to the processing of reflection seismic data that are used for hydrocarbon exploration (otherwise known as Seismic Exploration). This type of seismic data has been successfully used for hydrocarbon exploration for approximately 100 years, where measurements can reach a depth of up to 10,000 m. This geophysical method does not assist in showing oil and/or gas (sometimes gas can be seen in time-migrated data) as such or even in terms of quantity. This is due to the low resolution of the seismic reflection data, where in order for the seismic waves to travel deeper in the subsurface, fewer frequency components are acquired. The normal seismic data frequency bandwidth is only between 15 and 60 Hz. However, the idea of processing seismic waves that are reflected from various geological interface layers of the strata will result in clearly identifying such interface boundaries between the layers. In addition, as will be explained in this chapter, oil and gas are usually trapped and accumulated in certain geological structures. Hence, petroleum reservoirs are most likely to be found in such potential geological structures, and reflection seismic will certainly identify those structures.

Geophysics students, particularly applied geophysics students, would normally have covered the subject matters that are related to oil and gas formation, types of petroleum reservoirs based on their geological classification, seismic theory and seismic reflection theory, seismic data acquisitions and processing essentials, and so on. DSP students reading this book, however, would be lacking such important knowledge and background. Therefore, this chapter will provide brief background information for DSP students about how oil and gas were formed and accumulated. This is followed by a basic description of the geological classification of petroleum reservoirs. Exploration geophysics and the basics of geophysical surveying methods will then be briefly explained. The seismic surveying method, the seismic convolution model, and an overview of seismic data processing are then given. At the end of this chapter, readers will have the opportunity to meet seismic data, probably for the first time, and, as an overview, see various effects of processing on data. Note that the necessary seismic reflection theory background (that will hopefully lead to the understanding of the physics behind seismic events and the accompanying noise) will be covered in Chapter 2.

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1.2 Oil and Gas Formation and Accumulation

It might be interesting to note that some evidence exists that millions of years ago ancient seas covered much of the present land surface of the Earth including the Arabian peninsula and the Gulf of Mexico. Rivers flowing down to these seas carried large amounts of mud and sedimentary materials into the sea for many years. The sea floors slowly sunk and were squeezed due to the creation of accumulated mud and sedimentary materials layers. Such layers were the direct result of the distribution and deposition of mud and sedimentary material layer upon layer. Eventually, these formed rocks (where oil and gas are found) such as sandstone, shale, and carbonate rocks, all of which belong to the sedimentary category. The source of petroleum was constituted mainly by two organism resources: (a) a very large amount of small plants and animal life, which came into the sea from the land with the river mud and sedimentary materials, and (b) small marine life that existed in the sea already. These organisms died but were buried by the depositing silt, which kept them protected from ordinary decay. Many reactions such as pressure and temperature have over the years caused the dead organisms to change into oil or gas, depending on the temperature conditions.

Rock structures contain pore spaces that oil, gas, or even water can occupy. For example, oil, gas, and water can occupy the pore spaces between the grains of sandstone rocks or the pore spaces in addition to the cracks and vugs of other rocks like limestone and dolomite. These rocks where oil and gas were formed are known as *source rocks*. If they were sealed by a layer of rocks that is impermeable (known as the cap rock), then the accumulating petroleum within their pore spaces will be trapped and form the petroleum reservoir. When the pore spaces in the source rocks are not trapped, then under the effects of pressure and gravity, oil and gas will migrate from the source rocks until they are trapped in other capped rocks. Within the trap rock, oil and gas as well as water are segregated because of their density differences, with oil coming between gas and water. A *petroleum reservoir* can then be defined as the geological structure in which petroleum has been trapped and has accumulated. A petroleum reservoir can be a source rock or a rock to which petroleum has migrated.

1.3 Geological Classification of Petroleum Reservoirs

Petroleum reservoirs are usually classified according to their geological structure and their production mechanism. However, for an applied geophysicist and, hence, a DSP reader, it is sufficient to know about these reservoirs' geological structures. The reservoirs come in various sizes and shapes, and they are geologically classified according to their formation conditions. Structural-based reservoirs exist, which are physical arrangements of rocks, where traps result from deformation of the rocks by outside forces (Sheriff, 2006). Examples include but are not limited to:

1. Anticline- and dome-shaped reservoirs[1]: These are formed by the folding of the rock as shown in Figure 1.1. An anticline is considered as a fold in stratified rocks, where the rocks dip in opposite directions from a crest and the corresponding layers are, therefore, convex upward. A dome, on the other hand, is a structure where all of the rock beds dip away from a central area. While the anticline is long and narrow, the dome is circular in outline. Oil and gas are migrated upward through the pore spaces in the rocks and they are trapped by the cap rocks and the shape of the structure. Examples of such structures are Dammam and Bahrain domes.
2. Faulted reservoirs: Shearing and offsetting will cause faulting of the strata. Movement of impermeable rocks opposite rocks with pore space formations, which contain oil and gas, will create the trap. Both the tilt of the petroleum-bearing rock and the created fault trap the oil and gas in the reservoir. Figure 1.1 shows an example of a normal faulted reservoir. In this case, the faults drop one side down and push the other side up to place the reservoir rock against impermeable sealing rocks, forming a structural fault trap. An example is the Dunvegan gas field in northwestern Alberta. Another example of a faulted reservoir is the thrust fault. In the foothills of Western Canada, east of the Rockies, the original limestone layer was first folded and then thrust-faulted over itself. An overlying seal of impermeable rock completes the structural trap. Examples include the Turner Valley oil and gas field and Jumping Pound gas field, both in south-western Alberta.
3. Salt-dome reservoirs:[2] Such reservoirs are shaped like a dome and are formed due to the upward movement of a large and impermeable salt dome that has deformed and lifted the overlying layers of rock. Oil and gas can be trapped between the cap rock and the underlying impermeable rock layer or in between two impermeable layers of rock and the salt dome, as can be seen in Figure 1.1.

On the other hand, stratigraphic reservoirs exist, where traps are formed by variations within the sedimentary rocks themselves. Rock classification is organized according to different schemes, which do not have one-to-one correspondence. In other words, lithostratigraphic and geochronologic or chronostratigraphic

[1] In 1885, I. C. White, an American geologist, was the first to associate the existence of organic matter, the presence of reservoir rocks, and an anticlinal trap with the successful location of oil and gas (Shoup et al., 2003).

[2] In 1900, P. Higgins (a businessman and self-taught geologist) started drilling on Spindletop Hill, Texas, which is located on a salt dome, with the salt capped by a fractured dissolved limestone, which acts as a reservoir, producing in 1901 100 K barrels/day. This has led to exploration of salt structures along the US gulf coast region (Shoup et al., 2003).

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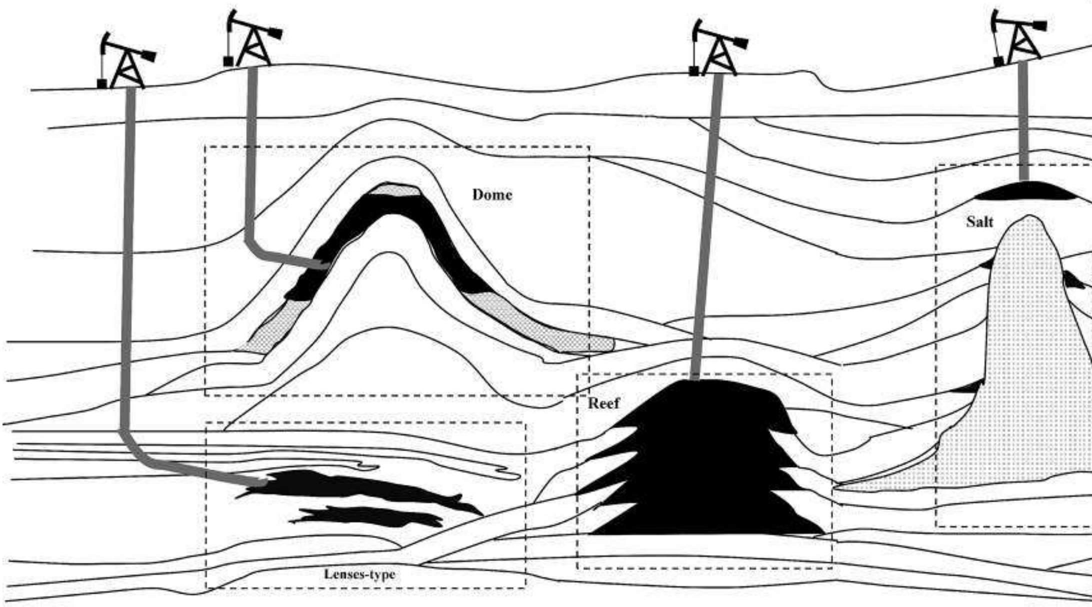

Figure 1.1 Common structural and stratigraphic petroleum reservoi

subdivisions sometimes cross each other (Sheriff, 2006). Examples of stratigraphic reservoir types are listed as follows:

1. Unconformity reservoirs[3]: Figure 1.1 shows an example of this type of reservoirs. Such reservoir types are formed as the result of an unconformity, where the impermeable cap rocks lay down across cutoff surfaces of lower geological beds.
2. Lenses-type reservoirs: Pore space rocks that contain oil and/or gas are surrounded in these reservoir types by impermeable rock formations, probably due to irregular deposition of sediments, leading to the creation of shale rock types. An example of a sandstone lenses-type reservoir is shown in Figure 1.1.
3. Reef-type reservoirs: in this type, hydrocarbon is trapped in the core of the reef, with fore-reef talus and back-reef lagoonal muds acting as lateral seals, and basinal mudstones as top seals.

Note that combination reservoirs exist, which can be formed based on a combination of folding, faulting, abrupt changes in the pore spaces, and so on. Such types are common. For more details on petroleum reservoirs, the reader is recommended to see, for example, Onajite (2013); Gluyas and Swarbrick (2014); Dow and Magoon (1994); Selley and Sonnenberg (2014); Miall (2008).

1.4 Oil and Gas: From Exploration to Production

It is important to understand that the process of extracting oil and/or gas is not straightforward. It basically requires a great deal of effort emerging from different areas of expertise from both engineering and science disciplines, and consumes a lot of time and money. The process of extracting oil and/or gas involves, in principle, three main stages:

1. Geological and Geophysical Surveys: Such surveys are the most important step toward extracting oil and gas. The aim of geological surveys is to examine the surface geology, formation outcrops, and surface rock samples. On the other hand, geophysical surveys aim to generate approximate maps of the subsurface structures by measuring various physical properties of rocks such as their densities, velocities, resistivity values, and many others. The data collected from both survey types are usually combined together, and without them, particularly the geophysical ones, it is difficult to claim the existence of oil and/or gas. More light will be shed on geophysical surveying methods in Section 1.5.
2. Drilling Exploratory Wells: The data collected from the geological and geophysical surveys are extremely useful in formulating probable definitions and

[3] In 1934, the American geologist A. I. Levorsen suggested that unconformities and changes in sedimentary environments control the trapping potential for hydrocarbons (Miall, 2008).

realizations for geological structures that might contain oil and/or gas. That is, they greatly assist in the determination of possible rock caps (traps) and, hence, potential petroleum reservoirs. The question that comes next is, does oil and/or gas exist? If so, then is it economical to develop oil and/or gas fields based on their quantity? The answer to such questions is determined only by drilling exploratory wells, called *wildcat wells*, in locations that are identified by geologists and geophysicists. During the drilling of wildcat wells, rock samples are extracted and used for further analysis. Once drilling is completed, various well logs are taken using logging techniques. Such tools are attached to electric cables know as *wirelines*, and as they are lowered they transmit and receive signals that are recorded, processed digitally, and then further analyzed to produce maps of the rocks and fluid properties versus depths, initial reservoir pressures, reservoir productivity, and many other important data to petroleum engineers.

3. Development of Oil and Gas Fields: The data collected from the previous steps, under the condition that the discovered reservoirs are economically productive, are combined and used to generate many important subsurface maps that will be of great importance to petroleum engineers. Examples of such maps are porosity maps, permeability maps, contour maps, and all are used to construct, through computer simulations, conceptual models that describe details of the subsurface structure and the oil/gas location within the subsurface structures. This is followed by integrated efforts of geologists, geophysicists, and petroleum engineers as one team to plan for developing oil/gas fields and the remaining operations that should ultimately lead into commercial production of fossil fuel. This includes drilling production wells, casing and cementing them, reservoir management, and so on.

Figure 1.2 summarizes the process described previously.

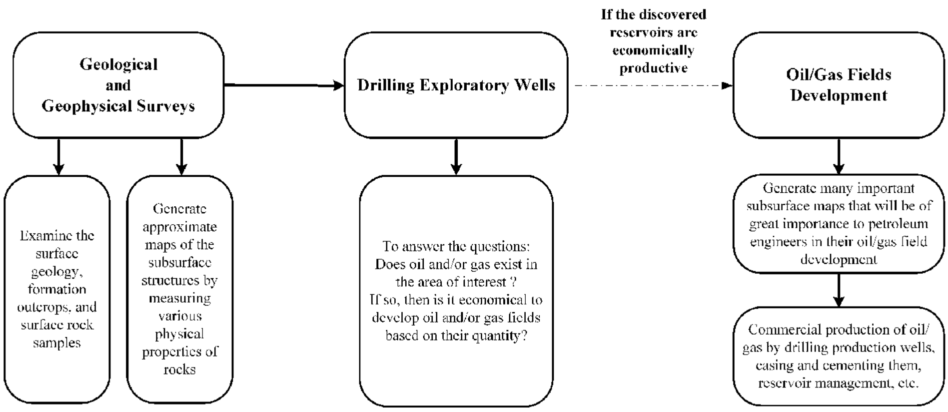

Figure 1.2 Oil and/or gas: From exploration to production.

1.5 Geophysical Surveys

In simple terms, exploration geophysics can be defined as the branch of geophysics that uses geophysical surveying methods to measure various subsurface rock properties in order to somehow infer the presence of oil and gas using various analysis and processing techniques (Sheriff, 2006; Telford et al., 1990). Rocks come with many physical properties and, hence, various interesting geophysical surveying methods exist that ultimately infer some of these properties that can assist in identifying the rock types accurately. Geophysical surveying methods can be applied to a wide range of investigations at various scales, such as studying the Earth. The main aim of geophysical surveying methods is to perform measurements within geographically restricted areas, seeking knowledge of the distribution of physical properties at depths that reflect the geology of the subsurface location of interest. For the sake of completeness, the following commonly used geophysical surveying techniques for hydrocarbon exploration are briefly described:

- **Gravity survey**: This method is considered among the least expensive surveying methods for locating a possible petroleum reservoir. This method involves the use of an instrument called a gravimeter that picks up a reflection of the density of the subsurface rock. The gravimeter can detect, for example, the presence of salt domes, which may indicate the presence of an anticline structure. In places where the gravimeter detects stronger or weaker than normal gravity forces, a geologic structure containing hydrocarbons may exist. The depth of investigation using this method is almost unlimited.
- **Electrical and electromagnetic surveys**: Such surveys can be defined as measurements that are made at or near the surface of natural or induced electric fields and can reveal information of up to 2 km of depth. They aim to map mineral concentrations and/or to map geological basements. These measurements can be made in many ways to determine various results. Electrical conductivity between different rocks makes such measurements feasible. Examples of electric measurements include self potential, magnetotellurics, and resistivity.
- **Magnetic survey**: This surveying method involves measurement of magnetic pull, which is affected by the type and depth of the subsurface rocks. It is usually used for determining the existence and depth of subsurface volcanic formations and basement rocks, which contain high concentrations of magnetite. This information is useful in identifying the presence of sedimentary formations above the basement rocks. The measurements are usually made more easily and cheaply than most geophysical measurements, where corrections are practically unnecessary. It basically can cover depth locations from the surface to the Curie isotherm. It basically infers magnetic susceptibility and remanent magnetization. However, they lack uniqueness of interpretation.