CHAPTER 1

Introduction and Summary

Petroleum: history – origin, migration, concentration – pool – reservoir – resources and reserves – discovery – prospect.

PETROLEUM (*rock-oil*, from the Latin *petra*, rock or stone, and *oleum*, oil) occurs widely in the earth as gas, liquid, semisolid, or solid, or in more than one of these states at a single place. Chemically any petroleum is an extremely complex mixture of hydrocarbon (hydrogen and carbon) compounds, with minor amounts of nitrogen, oxygen, and sulfur as impurities. Liquid petroleum, which is called *crude oil* to distinguish it from refined oil, is the most important commercially. It consists chiefly of the liquid hydrocarbons, with varying amounts of dissolved gases, bitumens, and impurities. It has an oily appearance and feel; in fact, it resembles the ordinary lubricating oil sold at filling stations, is immiscible with water and floats on it, but is soluble in naphtha, carbon disulfide, ether, and benzene. Petroleum gas, commonly called *natural gas* to distinguish it from manufactured gas, consists of the lighter paraffin hydrocarbons, of which the most abundant is methane gas (CH_4). The semisolid and solid forms of petroleum consist of the heavy hydrocarbons and bitumens. They are called *asphalt*, *tar*, *pitch*, *albertite*, *gilsonite*, or *grahamite*, or by any one of many other terms, depending on their individual characteristics and local usage. The general term "bitumen" has long been used interchangeably with "petroleum" for both the liquid and the solid forms. *Hydrocarbon* is a term often used interchangeably with "petroleum" for any of its forms. This is not strictly correct, since hydrocarbons consist of only hydrogen and carbon, whereas petroleum contains many impurities. Definitions of some of the common forms of petroleum are given in the Appendix.

The nomenclature and scientific classification of petroleum are in a state of uncertainty and confusion. Geologists, chemists, lawyers, refiners, and highway engineers have all made attempts to define the naturally occurring forms, but, for one reason or another, few of their definitions have gained widespread acceptance. Chester, in his dictionary of minerals,[1] defines petroleum and many of the liquid and solid forms as "mineral hydrocarbons." Legally, petroleum has been called a mineral,[2] but this usage does not satisfy the common geologic definition of a mineral as an inorganic substance with chemical and physical properties either uniform or varying within narrow ranges. It has also been called a *mineraloid*,[3] a term also applied to chalcedony and amber, on the ground that it is not definite enough in chemical composition to be called a mineral. Perhaps a compromise term, such as "mineral substance" or "organic mineral," would be most useful, even though mineralogically inacceptable. Because of its association with rocks, petroleum is included among "mineral resources" and is frequently called *mineral fuel*, along with peat and coal; this term raises no fine points of definition.[a]

Because of its wide occurrence and its unique appearance and character, petroleum has always been readily observed by man, and is repeatedly mentioned in the earliest writings of nearly every region of the earth.[4] Oil and gas seepages and springs, and tar, asphalt, or bitumen deposits of various kinds exposed at the surface of the ground, were regarded as local curiosities and attracted visitors from great distances. From the earliest times recorded by man, petroleum is frequently mentioned as having an important part in the religious, the medical, and even the economic life of many regions. Not until after the middle of the nineteenth century, however, when it was first discovered in large quantities underground, did its potential commercial importance become apparent.

The use of petroleum spread slowly in what has been called the "kerosene age" (1859–1900), but the development of the internal-combustion engine, near the beginning of the twentieth century, set off a phenomenal growth of the petroleum industry, a growth that has not yet shown any sign of slackening. We are now in what might be called the "gasoline age," for gasoline is the chief product now being derived from petroleum. More than half of the national supply of energy in the United States is furnished by gasoline, natural gas, and other petroleum products, and the use of petroleum as a source of energy is increasing rapidly in other parts of the world as well. In addition, thousands of chemical compounds, known as *petrochemicals*, are made from petroleum. Petroleum has, in short, become one of the most important natural resources of modern civilization.

Ever since E. L. Drake drilled the first well for oil in Pennsylvania in 1859, and especially, of course, since 1900, the geology of petroleum has assumed growing importance as a special economic application of geology. From the

[1] The superior figures in the text refer to the reference notes at the end of each chapter.

[a] The United States Geological Survey, before 1924, and subsequently the United States Bureau of Mines, included petroleum in the annual reports *Mineral Resources of the United States*, and a number of bulletins of the Survey (for example, 786 and

first, geologists attempted to explain the occurrence of oil and gas in terms of geologic phenomena. Then, as the petroleum industry grew and developed, they were called in more and more to guide the programs of exploration for the raw materials upon which the industry depended. New geologic concepts relating to petroleum were thus developed, and at the same time enormous volumes of new data were made available with which to test and prove or disprove many established principles of geology. As a result, not only the petroleum industry, but the science of geology as a whole, has benefited greatly.

The term "petroleum geology" has come into use to describe the area of common interest between petroleum producers and geologists. It is doubtful, however, whether this is a proper usage. Rather, it is more accurate to say "geology of petroleum" just as we say "geology of iron" or "geology of clay," although the shorter term, "petroleum geology," is commonly used in writing or speaking informally. The geologic concepts applied to petroleum are all established and recognized geologic principles, which are merely put to practical use in finding and exploiting petroleum deposits. A person who applies these principles to finding petroleum, however, may properly be called a *petroleum geologist*.

When a petroleum pool has been discovered, we know (1) that a supply of petroleum originated in some manner, (2) that it became concentrated into a pool,* and (3) that it has been preserved against loss and destruction. The evidence for the speculative theories about the geologic history of the petroleum before it was discovered—its origin, migration, accumulation, and preservation—can come only from a study of the pool. For that reason the logical sequence for study is: (1) to examine the evidence as we find it—that is, the occurrence of petroleum, both at the surface and underground, the geological, physical, and chemical environment of the reservoir and its fluid content, and the phenomena observed and the principles involved during production; (2) to use this knowledge as the basis for speculation on the theoretical phases concerned with the history of the reservoir before discovery. We must say bluntly, at this point, that we do not know just how oil and gas originated, nor how they have moved and accumulated into pools. These problems, if solved, would aid greatly in the *main job* of the petroleum geologist—*the search for new pools*—and we shall discuss possible solutions later. A full discussion of the various elements that enter into the problems of the origin, migration, and concentration of petroleum into pools will be delayed until the reader has studied the evidence concerning reservoirs, their fluid content, and their fluid mechanics.

The fundamental geologic requirements for oil and gas pools are, of course, the same the world over. Whether one is exploring in the Americas, along the

* The oil or gas content of a single deposit is called an *oil pool* or a *gas pool*; if several pools are located on a single geologic feature, or are otherwise closely related,

continental shelf, the Middle East, or the Far East, the essential elements of a pool are simple. *A porous and permeable body of rock, called the reservoir rock, which is overlain by an impervious rock, called the roof rock, contains oil or gas or both, and is deformed or obstructed in such a manner that the oil and gas are trapped.*

Commercial deposits of crude oil and natural gas are always found underground, where they nearly always occur in the water-coated pore spaces of sedimentary rocks. Being lighter than water, the gas and oil rise and are concentrated in the highest part of the container; in order to prevent their escape, the upper contact of the porous rock with an impervious cover must be concave, as viewed from below. Such a container is called a *trap*, and the portion of the trap that holds the pool of oil or gas is called the *reservoir*. The significant thing is that reservoirs can be of various shapes, sizes, origins, and rock compositions.

Any rock that is porous and permeable may become a reservoir, but those properties are most commonly found in sedimentary rocks, especially sandstones and carbonates. A trap may be formed, either wholly or partly, by the deformation of the reservoir rock, which may be accomplished by folding, faulting, or both, and in either a single episode or in several episodes. Or a trap may be formed, either wholly or partly, by stratigraphic variations in the reservoir rock. These may be primary, such as original facies changes, irregular distribution of mineral particles, or diagenetic solution and cementation. Or they may result from secondary causes, such as fracturing, solution and cementation associated with erosion surfaces, or truncation and overlap along unconformities. Likewise, the direction and rate of flow of the fluids within the reservoir rock may influence, or even dominate, the position of the pool within the structural or stratigraphic trapping feature. Many traps are the result of complex combinations of structural, stratigraphic, and fluid variations that are difficult to unravel and evaluate from the data available before the pool is developed. The geologic principles involved in the formation of traps are fairly simple, but the variations in their application are almost infinite in number and complexity.

We have yet no direct method of locating a pool of petroleum. We know no physical property of underground petroleum that we can measure at the surface of the ground. The petroleum geologist's approach to the discovery problem must therefore be indirect. Each pool is unique—we may think of a pool as the end result of twenty or twenty-five variables of which only a few can be ascertained in advance. Test wells are located where an underground trap capable of trapping a pool of oil or gas is inferred from the available geologic data, and where it is believed that a pool of petroleum, if present, can be produced at a profit. Since new geologic conditions are discovered during the drilling of the test well, the petroleum geologist's interest persists until a discovery has been made and until the well begins to produce oil or

gas or both. During the drilling of the test well the interests of the geologist merge with those of the petroleum engineer.

Both the amount and the location of undiscovered petroleum are, of course, unknown. The petroleum must be discovered before it can be of any use to society. For broad geologic reasons we are fairly certain that petroleum deposits will eventually be found in some regions that are not now known to contain them. We cannot say in advance, however, at what depth or at what exact location these deposits will be discovered. The actual location and size of a deposit in the earth are determined only by drilling test wells into the deposit and by producing the content of the reservoir. A test well drilled in the hope of discovering a new pool is called a *wildcat well*. The person or organization drilling a wildcat well is called a *wildcatter*.* If the well taps a deposit of petroleum, it is called a *discovery oil well* or a *discovery gas well*, according to which kind of petroleum is found. If it produces neither oil nor gas but only water, it is called a *dry hole*, a *duster*, or a *wet well*. Wells drilled into the same reservoir after a discovery has been made are called *development wells*. The next well drilled after a discovery confirms the discovery and is called a *confirmation well*.

The fundamental need of the petroleum industry is an adequate supply of its raw materials—crude oil and natural gas. Each year the "crop" of oil and gas is completely destroyed by consumption; no "seed" is left with which to start a new supply. Renewal of the domestic supply for any country depends almost entirely on the continuing discovery of new deposits. At any time the recoverable petroleum in sight, which is known as the *producible reserve*, or the *proved reserve*, is only that which has been discovered and developed but has not been consumed. For a number of years the known reserve of oil in the United States has ranged between eleven and fifteen times the annual consumption; for the rest of the world it has ranged from thirty-five to forty times. The gas reserves of the United States are eighteen times the annual consumption, but a rapid increase in the use of gas may reduce this ratio in the years to come. In the absence of a new source of energy to replace petroleum, the past steady increase in the consumption of petroleum products is creating a growing need for new deposits, which, in turn, means a continuous increase in the need for petroleum discovery.

The petroleum *reserves* of any region should be distinguished from its petroleum *resources*. The reserves consist of the oil and gas that are now available for use. The resources, which are always far in excess of the reserves, include the reserves, the prospective undiscovered reserves, and any substances

*In the early days of the oil industry in the United States, drillers working on wells back in the hills said they were drilling "out among the wildcats"—hence were called "wildcatters." The term "wildcatter" is an honored title in the petroleum industry; it corresponds to "prospector" in mining or "inventor" in manufacturing, and carries none of the distasteful connotation of "wildcat strike," "wildcat land boom," or "wildcat stock."

from which petroleum could be derived, either by one or by both of (1) present or improved technology and (2) present or more favorable economic conditions. Technology implies ideas, "know-how," concepts, machines, methods, and principles; economic conditions imply availability of adequate capital, incentive, profit, skilled labor, and political climate. Here is a comparison between the petroleum resources of any region and their relation to the petroleum reserves:

RESOURCES	HOW TRANSFORMED INTO RESERVES
1. Known and recoverable oil and gas deposits.	Now available.
2. Oil and gas known to have been left behind in pools but not recoverable at present.	In part by secondary recovery methods, but chiefly by new technology and more favorable economic conditions.
3. Undiscovered and undeveloped petroleum pools.	By discovery and development through present and improved technology, with present or more favorable economic conditions.
4. "Tar" and asphalt deposits, inspissated deposits, outcropping oil pools.	By present and improved technology, together with more favorable economic conditions.
5. "Oil," or kerogen, shales, torbanites, and coals.	By present and improved technology, together with more favorable economic conditions.

This book is concerned with the first three of the above resources, but our chief interest will be in the third—undiscovered petroleum deposits. This is the resource that has supplied the oil reserves of the past, and it may be expected to supply much of the reserves for a long time to come. Improvements in technology are steadily bringing the day closer when large reserves now locked up in the nonrecoverable oil, inspissated deposits and the "tar" and asphalt deposits will enter the supply picture. These resources are large and the question as to when they will become available in large quantities is primarily a matter of cost.

When the science of geology is applied to the petroleum industry, an economic element is inevitably introduced at some point. The skillful petroleum geologist translates an idea or concept into barrels of oil or cubic feet of gas at the surface of the ground. And these products must be worth more in money than they cost to produce. Some geologists may be working in a laboratory far removed from the oil fields, doing work that seems to be completely academic, but someone in the chain of discovery, sooner or later, must translate their work into terms that can be entered on the record as producing lands and finally as profits. Every geologist working in the petroleum industry

should bear in mind, therefore, that the ultimate objective is *to find oil and gas that are profitable to produce*. He may find such petroleum through the discovery of new pools, or he may find it through the better development of known pools, either by extending them or by increasing production from them.

A petroleum geologist does not physically see an oil or gas pool any more than a meteorologist, for example, sees a low- or high-pressure area, though both commonly use contour lines and maps to describe the ideas they intend to convey. Both are presenting mental concepts of the conditions they believe exist. Any undiscovered oil or gas field can be mapped only as an idea or a concept in the mind of the petroleum geologist. He may, by careful mapping, judge that the rocks and the structure are favorable to the trapping of petroleum under a certain area, but until a discovery well has been drilled he does not *know* whether that area is an oil pool. Imagination, then, is an indispensable quality of the petroleum geologist. The world's future supply of petroleum is as dependent upon the imaginative powers of the petroleum geologist as on the presence of favorable rocks—of which there appears to be an abundant volume.

The actual discovery of a pool is made by the drill, but the proper location of the wildcat well to test a trap, the depth to which it should be drilled, and the detection and outlining of the oil or gas pool from what is revealed by that well and others, are wholly geologic problems. They constitute the essence of the geology of petroleum and are the most important work of the petroleum geologist. He may need to consider only a simple combination of stratigraphy and structural geology, or he may have to take account of a complex combination of data, involving such various fields as stratigraphy, sedimentation, paleontology, geologic history, fluid flow, structural geology, petrography, geophysics, geochemistry, and metamorphism. In addition to all this, he may have to draw on his own and other people's knowledge of many related sciences, such as physics, chemistry, biology, and engineering. He must do his best to work out the geology of an area from what is visible or what can be mapped at the surface, and from all available well and geophysical data for depths ranging up to three miles or more below the surface. His prediction, however, may often be based on the most fragmentary data, some of which are obtained by specialists or experts who may or may not have a working knowledge of geology, or by geologists who have worked with no thought of the petroleum possibilities of the region. This information is assembled on maps and cross sections, and fitted together in the mind of the petroleum geologist, where it is interpreted and translated into the best place to drill a well that will penetrate a trap below the surface of the ground and thereby enable the well to test the trap's content.

As the search for petroleum gets deeper below the surface, the geology becomes more complex and uncertain, and the data upon which the geologist must base his conclusions become progressively fewer. As drilling is costly, there are never as many test wells as the petroleum geologist would wish.

Every scrap of information must therefore be squeezed out of the record and put to use, and the data from each record must be projected outward in all directions. The geologic, geophysical, and engineering data must be assembled on various maps—structural, stratigraphic, facies, thickness, paleogeologic, potentiometric, productivity, isopotential, and geothermal. The aim of academic geology may be said to be the accurate correlation of formations, the detailed working out of the geologic history, or the making of a carefully contoured structural map. That of exploration geophysics, on the other hand, is to measure various physical properties of the rocks underground, such as their reflecting power, their magnetism, their electrical properties, and their relative densities. The job of the petroleum engineer is to determine the reservoir data—the pressures and pressure changes, the fluid mechanics—and to produce the oil and gas efficiently. Yet all these maps and data do not, of themselves, tell the whole story. If they are to be fully used in the discovery of petroleum, they must be interpreted, correlated, and integrated. This interpretation of the combined basic geological, geophysical, and engineering data, for the purpose of finding new oil and gas pools, is what constitutes the special province of the petroleum geologist. It results, first of all, in locating an oil and gas *prospect*, which is the set of circumstances, both geologic and economic, that will justify the drilling of a wildcat well. The petroleum geologist's work does not stop, however, when he has located a prospect; it continues during the drilling of the wildcat well. He must relate the new facts encountered in the drilling to the problem of identifying and testing the potential producing formations and of completing the well in the producing formation if the well becomes a discovery well. The petroleum geologist thus spans the gap between geology and the related sciences, on the one hand, and the oil and gas prospect and the pool, on the other. This relationship is graphically shown in Figure 1-1.

The chapters that follow attempt to show how the petroleum geologist uses the evidence of the rocks to help him discover petroleum. He obtains his evidence directly by observing outcrops, well cuttings, and well cores, and indirectly through geophysical measurements, logs, core analyses, and fluid data. He obtains additional evidence from the producing history of pools that have been discovered in the past. The techniques and methods for obtaining this evidence are many and varied, and they are constantly being improved and made more accurate. Since they have been described in many books and articles,[5] they will be only briefly mentioned in this book. It is the purpose here, rather, to consider how the evidence may be interpreted *after it has been obtained*, so that we can better predict the location of new petroleum deposits or extend old ones. What evidence is significant? And how is it to be translated into discovery?

Petroleum prospecting is an art.[6] It requires combining and blending many geologic variables in varying proportions, since each pool, field, or province is characterized by a unique combination of many different geologic

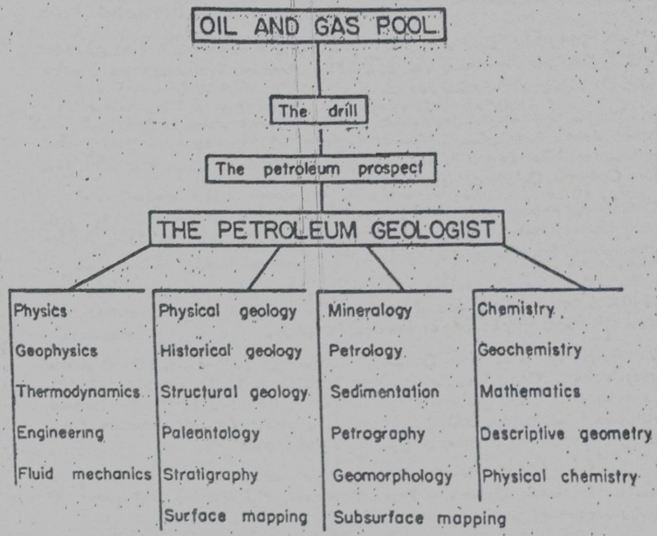

FIGURE 1-1 *Relations among the various sciences and specialized fields that are utilized by the petroleum geologist. He stands between these sciences and the oil and gas pool; his chief job is to interpret them so as to locate a prospect that, when drilled, will yield commercial oil and gas.*

conditions. Some of these conditions can be known in advance, but most cannot, and the most successful geologist is the one who can visualize the pool or locate the extension with the least advance information. He may be likened to the artist who can draw the picture with the fewest lines, or to the paleontologist who can identify a fossil vertebrate from the least number of bones. The chief objective of this book, then, is to point out the kinds of evidence, the principles, and the ideas that should prove to be the most helpful in the discovery of petroleum.

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