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PREFACE

WHEN the first edition of "Modern Petroleum Technology" was published in 1946, the hope was expressed that it would be possible to issue revised editions from time to time. This first edition was exhausted long ago, but due to the rapid pace at which developments have occurred in the petroleum industry and to the fact that many of the members of the industry best qualified to discuss and explain these developments have been very fully occupied, it has only recently been possible to prepare another edition for the printer.

For this second edition, many of the articles have been revised or rewritten, while some are completely new. The general style of the book has been retained and although it is not possible, in a book of this kind, to be completely up-to-date, every effort has been made to include recent developments. The authors between them have surveyed almost the whole field of petroleum technology and it is hoped that the new edition will be as useful as its predecessor in presenting, at least in outline, the scientific and technical background of a great industry.

The thanks of the Institute and of the industry are due to the authors of the articles and all who have contributed to the preparation of this edition. Special thanks are due to the members of the Abstracts Sub-Committee of Publications Committee who, under the Chairmanship of Mr C. L. Gilbert, have given much thought and time to the arrangement and planning of the book.

E. B. EVANS,
Honorary Editor.

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PART I

EXPLORATION AND PRODUCTION

CHAPTER 1. EXPLORATION FOR OIL AND GAS

By PROFESSOR V. C. ILLING, M.A., F.R.S., F.INST.PET.

IF we are to get a proper perspective of the rôle of the petroleum industry in the world's economy, it is essential to appreciate the importance of fuel as a source of heat, light, and power in modern civilization. This is epitomized by the value of coal, oil, and natural gas, which, on the average, is about three times that of all the other products of mining operations.

During the 20th century the coal industry has endeavoured to maintain its position, whereas the oil industry has endeavoured to increase its usefulness in every phase of life. The adaptability of liquid fuels, their economy in labour, stability in price, high calorific value, and more particularly their expanding supply, have made oil and gas the dominant fuels of the U.S.A. This is in spite of the fact that the U.S.A. holds 60 per cent of the coal resources of the world. Probably the most important material factor which has contributed to the U.S.A.'s present industrial pre-eminence is the influence of oil and natural gas on the nation's industrial economy.

Continuity of supply of essential fuels is vital to the well-being of any community in the civilized world; and the fact that the oil industry has met every demand is not only a tribute to its efficiency but also to its sense of duty.

The use of coal and oil can be traced back into antiquity, but the general use of oil dates from 1859. In fact, it was not until the dawn of the 20th century that there was any clear indication of the immense growth which lay before the oil industry. This is mainly due to the fact that in the 19th century oil was commonly used as a source of light, but not as a source of heat and power. It was the advent of the motor car which gave the great impetus to the expansion of the use of oil. In 1914 coal was responsible for 90 per cent of the total power output of the world, whereas oil and natural gas provided only about 7 per cent. In 1938 the contribution of coal had been reduced to 60 per cent, whereas oil and gas had increased to 25 per cent, and their relative importance continues to increase.

Thus, the struggle between the oil and coal industries, which has already been won for the oil industry in the U.S.A., is world-wide. In countries such as the U.K., France, and Germany, where abundant coal and little oil have created an economy based on solid fuels, the struggle between the two rival fuels is particularly apparent. This is the age of oil, and so long as the oil reserves of the world are plentiful, it is probable that coal will continue to be at a disadvantage in the struggle between the two main sources of heat and power.

One of the advantages which the oil industry has retained in its growth is its control of every phase of every operation with which oil and gas are associated. Exploration, production, transport, refining, and marketing epitomize its motto "From the depths of the earth to the door of the consumer," and its intimate contact with the needs of the community has been a driving force for continuous expansion in order to meet every demand.

This has been achieved in spite of some particular disadvantages. An oilfield is a rapidly wasting asset, and merely to preserve a constant rate of production, new oil reserves must be continually discovered. In the U.S.A., for example, the normal annual decline of proven production from existing wells is equivalent to over 500,000 barrels of oil per day. This has to be made good by the drilling of over 20,000 new wells each year, in order to maintain an annual output of over 2000 million barrels.

Maintenance of production may for a time be achieved by drilling up proven areas, but ultimately all oil produced must be replaced by discoveries of new oil. Therefore, if the industry is to grow continuously it must pursue a far-sighted and vigorous policy of exploration, reaching out into new areas as the proven fields attain their zenith and then decline, for inevitably a producing region must reach a stage when new discoveries can no longer offset the natural fall in production. This decline is affected by economic factors as well as by the efficiency of the discovery technique and production methods. Mexico, Ohio, Poland, and Rumania are examples of producing areas which have declined after reaching their zenith. Illinois, California, and Canada are good examples of other areas which have gained a new lease of life owing to new discoveries.

Inevitably, however, as a region becomes more highly prospected and drilled, the difficulty of making new discoveries increases, so that exploration depends for its success not only on the efficiency of the technique of discovery, and of exploratory drilling, but also on the opportunities for discovery which an area affords. The depth factor alone illustrates this point. In most areas the shallow horizons are developed first, and only when these fail to maintain supplies does exploration extend deeper. The efficiency of modern oil well drilling has increased so remarkably in recent years that it has become economically practicable to drill below 10,000 ft, and wells have been drilled beyond 20,000 ft. Oil production is severely competitive, and unless the yield of these deep wells is proportionate to their cost they are of limited value.

The increased depth of exploration puts a greater test on the technique of discovery, calling for new methods of measurement and a greater accuracy in the old and well-tried tools. There has also been a vast improvement in the technique of exploratory drilling. Potential oil horizons are much less liable to be overlooked now than hitherto. This achievement is due to the collaboration of the geologist, physicist, and chemist with the engineer during the operations of drilling and testing. The normal percentage of success among modern exploratory wells is stated in the U.S.A. to be approximately 20 per cent, which, in the light of the extent to which most of the oil areas have already been tested, is a tribute to the improved technique of discovery.

If such work was left entirely to random drilling it would certainly involve a much lower percentage of success, and only an increase in oil prices could rectify matters by encouraging wildcatting. A good example of such random drilling is instanced by Henneker in the salt-dome region of the Gulf States, for in the period after the obvious salt domes had been discovered, and before the advent of geophysics, the drilling of 675 wildcats between 1917 and 1924 led to the discovery of only one new salt dome. It is not suggested that random drilling does not perform a useful function. It sometimes discovers oil in unexpected areas, and often gives useful stratigraphical and structural evidence, but as a general rule it is wasteful in effort, and is justified only when geological theory in the area has become moribund.

An oil pool is the result of a series of natural processes associated with the deposition and build-up of strata in sedimentary basins. As such, the geologist studies the causes and effects of these processes, and ascertains the conditions which form oil pools and where these conditions are to be found. The geologist must therefore govern the strategy of oil exploration.

The technique of the actual discovery is a somewhat different matter. It has become more and more a question of discovering suitable traps, *i.e.* geological conditions, structural or stratigraphical, which concentrate the oil into commercial accumulations. The technique of discovery involves the use of various tools—geological, geophysical, chemical, and engineering. It is not only the value of these tools in themselves, but the manner in which they are co-ordinated which constitutes the strength of an exploratory team.

History

The discovery of the Drake well in 1859 is sometimes regarded, especially in the U.S.A., as the beginning of the modern petroleum industry. Certainly there is no continuity historically between the modern oil industry and the gas fields produced in China over 1000 years ago, or the oil wells dug in Burma to provide lubricating oil for the European and Asiatic markets, or many other instances where oil was found and used locally for burning, caulking of ships, mortar, or embalming. These are mere examples of the local usage of a substance which can be adapted to many purposes.

The probability is that the modern oil industry did not begin with the Drake well, or with any other well. It started when a means was found to refine crude petroleum into a satisfactory burning oil, and prior to 1859 there were refineries in many countries, including the U.S.A., built to retort oil shale for this purpose, an industry which rapidly died out in the U.S.A. when crude petroleum was found to be an effective substitute.

The early oilfields were developed around the Pennsylvania area, Ohio, and Ontario in North America, whilst in Europe the main sources were in Rumania, Galicia, as Poland was then called, and the Caucasus. Little is known of the basic conceptions on which this oil was sought for and found, but as the wells were shallow it is almost certain that they were drilled close to oil seepages or on the haphazard principle of wildcatting. Even in the U.S.A., where surface oil indications are less common than in many other countries which have smaller oil reserves, it is remarkable how much of the early drilling was guided by reports of oil or gas in the area. Some of this was brought to light by the wells drilled for salt water in Pennsylvania, but some of these oil indications were true surface seepages.

It is probably true that in the first half-century of the oil industry's growth, exploratory drilling was rarely based on scientific principles, and though full use was made of surface seepages as a guiding feature, the main drilling effort was haphazard. In those days the average order of success was one in twenty, but the wells were shallow, drilling was relatively cheap, and there grew up a community of oil drillers famed rather for their rugged individualism and optimism than for their knowledge of the underlying principles governing the distribution of oil pools. It is, however, a remarkable tribute to the acumen of some of the early scientists associated with the oil industry that within a year or two of the discovery of the Drake well, the fundamental conceptions of a reservoir rock and of oil pools were formulated by the Canadian geologist, T. Sterry Hunt.[8] In these conceptions Hunt drew attention to the importance of permeability and porosity in the reservoir rock, the influence of the cap rock in preserving the gas and oil from dispersal, and of the underlying water zones which maintain the oil in the higher parts of the reservoir.

There grew up in these early days two rather different conceptions of the part played by anticlines in the formation of oil pools. According to Hunt, the gas and oil accumulated in the crest of the porous rocks of the structure because oil and gas are lighter than water. E. B. Andrews, on the other hand, suggested that anticlines were zones of fissures, and that the importance of anticlines lay in the fact that the oil occurred in the underground fissures which tended to be more plentiful along the crests of the anticlines.

It is rather curious that Andrews' conception was put forward in the Pennsylvanian oilfields and in a part of these fields where in actual fact the folding is so gentle or non-existent that the so-called anticlines can be appreciated only by careful contouring of the formations. This was the heart of a great regional basin in which the formations are practically completely undisturbed by folding, though it is true it is bordered on the east by a zone of folding which marks the beginning of the Appalachian Mountains. Where, however, folding intervenes, there is practically no oil and only a little gas.

In any case, divergences between the two schools of thought were limited to a small body of scientists. The oil industry went on its way finding pool after pool, with little or no regard to either Hunt's or Andrews' conceptions. It did, however, in the first instance concentrate most of its drilling in the valley areas on the general assumption that the oil occurred in underground streams and that these naturally bore some relationship to the surface topography. There was also a firm belief among operators in the presence of fissures running in a north-east to south-west direction, a feature which was afterwards found to be associated with the trend lines of the main coarse sand bars.

In 1883, I. C. White[15] re-formulated the anticlinal theory, without apparently being aware of the previous writings on the subject, and it can only be surmised that the earlier discussions had been completely forgotten.

White is sometimes claimed to be the father of the anticlinal theory. This, however, in view of the earlier writings, is not justified. He can, however, be credited with the re-formulation of the anticlinal theory in a more detailed form. Most of his work was devoted to the discovery of gas rather than oil. Furthermore, there is no indication that these views of White were generally accepted. Indeed, they were bitterly opposed by the officers of the Second Pennsylvanian Geological Survey. However, so far as the Pennsylvania fields are concerned, there was considerable ground for the scepticism of Lesley [11] and his colleagues, inasmuch as these fields were not developed in true folded country, and practically all of the so-called anticlines were merely slight undulations in otherwise horizontal strata.

Furthermore, there was abundant evidence in this Pennsylvania area of the primary importance of such lithological factors as the coarseness of the rock in determining the location of the individual pools. An unbiased assessor of the evidence in Pennsylvania would probably assert that in these oilfields the most important feature was the coarseness of the reservoir rock, *i.e.* the presence of coarse sands in finer sands, or of sand bodies in shales, though within these coarse streaks the effect of gravitational separation was often apparent in the occurrence of gas over oil and oil over water. These conceptions were ventilated particularly in the writings of Griswold and Munn. In developing his hydraulic theory of oil accumulation, Munn laid great stress on the importance of water levels in determining the position of the oil pools resting on the general water table in the reservoir rocks.

Little detail is known of the theories of oil accumulation in other parts of the world. Writers on the Caucasian fields laid great stress on the presence of underground caverns filled with oil, which appeared to be the most natural explanation of the haphazard local results of drilling. A successful well in the Baku fields was often a gusher, and a well near-by which failed to obtain oil was readily explained by the thought that the successful well had penetrated the oil-filled cavity, whereas the unsuccessful well had failed to do so.

In Rumania, where many of the early wells were dug by hand, the association of oil with sands was more apparent. In Galicia the one large field at Boryslaw was of so complicated a nature that its relationship to structure is still not altogether clear. The early oilfields in Burma were found close to the seepages, where hand-dug wells had previously been made by the inhabitants of the country, but the association of the oil with anticlinal conditions was noted at an early date by Oldham, and this may have been one of the first instances where the anticlinal theory was properly related to true folded conditions.

The beginning of the 20th century saw the advent of the motor car and of a tremendous increase in the demand for oil, not merely for burning purposes, but as a source of power. As a result, prospectors in the U.S.A. transferred part of their attention to the Gulf States, California, and the Mid-Continent, where in many ways the geological conditions were different. In California, for instance, there could be no question about the importance of the anticlinal occurrence of oil, and this was accepted as a basic truth, but in addition the importance of faults and unconformities as local features guiding the distribution of oil, and also determining the juxtaposition of reservoir rock and source rock, were two important conceptions which were relatively new in the theories of oil accumulation.

To the Mid-Continent we owe the development of the conception of closure, of the great importance of such structures as monoclinal domes in forming localized areas into which regional migration would concentrate supplies of oil migrating from the main basins. These monoclinal domes were not necessarily fold features, indeed many of them were afterwards attributed to the effects of compaction around ridges in the basins of deposition, but it was in this area that geology first came into its own as a technique of oil discovery of first-class importance, and large numbers of geologists were utilized by the oil companies to make stratum contour maps of the beds exposed at the surface in order to look for closure, *i.e.* the gentle domes at the surface reflecting deeper structures of a similar type.

In the regions bordering the Mexican Gulf, structural features of a different nature were found to be important in governing the distribution of the oil pools. Among these the salt domes of the Texas and Louisiana coast were the first in order of discovery. These were proved to be oil-bearing by the discovery well of Spindletop. Though, like many other discoveries, the basic theories were wide of the mark, this did not prevent a rapid increase in the discovery of oil in other salt domes which indicated that the oil had accumulated in the dome-shaped strata above the salt and in the porous cap rock which formed the uppermost layer of some of the salt domes. It was much later that the theory of flank production was proven to be true, a theory suggesting that oil would migrate up-dip in the various strata and with its associated gas would be impounded against the flank of the impervious salt or would be trapped by faults and unconformities which tended to occur around such structures.

Other instances of unconformities of a regional nature unrelated to the salt domes were provided by such discoveries as East Texas, the major field in the U.S.A., and due mainly to a single shore-line sand covered by an impervious shale wedged out against the unconformity.

Other examples of lensing of a different nature had been provided by the shoestring sands of Kansas and Oklahoma. These were illustrations of sand bodies, developed as lenses or ribbons in the general mass of muddy sediments. Another group of fields of an entirely different type, which were well illustrated in the regional geology of Texas, were the fault fields along the Balcones line of faulting. Here the oil accumulations were attributed to the presence of faults truncating the porous strata and providing a seal preventing further up-dip migration.

One of the most unusual types of fields found in Texas is probably the group of limestone pools of Permian age found in the West Texas Basin. These are related to the formation of limestone reefs, and form one example of a very diversified series of oil pools, of which there are many different types in the oilfields of the Middle East, of Mexico, and of Canada. Those of the Middle East are true examples of fold fields, wherein the limestone is moulded into anticlines and therefore displays many of the characteristics of an anticlinal accumulation of oil and gas.

In many such areas, however, the permeability of the reservoir rock is normally too small to give commercial wells, and there has to be a high degree of fissuring created by local distortion to render the rock sufficiently porous and permeable to give commercial production.

It would seem, therefore, that the earlier views of Andrews regarding the importance of underground fissures in oil accumulation on anticlines, though possibly untrue in the area of their early application, have a very important bearing on certain types of oil accumulations of which limestones and possibly other cemented rocks are the most common examples. Certain it is that many of the Middle East fields owe a considerable amount of their permeability to fissuring in the rock, and in some of these areas the only economically productive parts seem to be where such fissuring is prevalent.

Although it is true that the porosity and permeability of the limestone fields of the Golden Lane in Mexico were highly variable and in part probably associated with fissuring, elsewhere they appear to be related either to local conditions in the original formation of the limestone or to secondary changes which took place during and after deposition.

It was known at a very early date that in the limestone fields of Ontario and Ohio dolomitization had been an important factor in creating porosity and permeability, and generally such dolomitization plays a considerable part in many reefs, but all porosity in limestone reefs is not due to such secondary changes. There can be detrital limestones or relatively porous reefs where algæ, corals, and other organisms grow *in situ* and the reef mass retains its original porosity. The various factors which may create favourable porosity and permeability in a limestone reef are only just beginning to be understood and form one of the critical studies which is of immediate interest to oil geology.

Considerable comment should be made in any historical study of this nature on the great diversity of oil accumulations in anticlines themselves. The accumulation of drilling evidence has drawn attention to the extraordinary complexity of this subject, and the early simple theories of accumulation need modification to take into account the variety of other structural features prevalent in anticlines. Among these there are, first, the complexities of a stratigraphical nature due to changes in the reservoir rocks, such as the presence of lenses of sand, or the wedges of formations due to unconformable deposition. Such features are in themselves factors that cause oil accumulation, and when they occur, as they often do in anticlinal folds, the resulting accumulations are mainly due to the stratigraphical factor.

Secondly, there are complexities of a structural nature including faulting, thrusting, and the difference in attitude of the various formations. These are due to the changing thicknesses in the original formations and to divergences in the forms of the folds in different strata, caused by differences in the plasticity of these formations. Having regard to all these features and because many folds are the result of movement spread over wide intervals of geological time, no experienced oil geologist would be prepared to prophesy in detail the changing form of a fold at different levels in the earth's strata.

At the extreme end of these categories of folds, there are fields like Boryslaw or Turner Valley, where the degree of folding and fracturing has become so extreme that the field must be regarded as a unique type in itself, displaying the characteristics of both fold and fracture fields.

This broad summary conveys an idea of the great complexity of the types of natural oil accumulations. Indeed, it is probably true that oil in commercial quantities has been found in practically every type of geological structure. None the less, it is also abundantly clear that there are certain types of structure in which oil is more commonly found than in others.

The feature common to all such structures is the fact that they contain reservoir rocks having both porosity and permeability. Such reservoir rocks are protected by cap rocks which preserve the gas and the oil and prevent it from escaping. This, however, is not sufficient to provide commercial oil pools. There must also be a sufficient volume of reservoir available in each separate entity of the oil pool to ensure oil in payable quantities.

It is not always favourable to have too large a volume of porous reservoir rock, otherwise the oil and gas may be dispersed unless they are contained in certain portions of the structure by the presence of water. Thus a commercial oilfield is the result of many different influences, partly stratigraphic and partly structural. Sometimes the influence of one of these features is negligible, but most oilfields are due to a combination of them both.

Among the other large oil-producing territories of the world which have not been mentioned, the oilfields of Venezuela and the neighbouring island of Trinidad are of considerable geological interest. Their development in the second and third decades of the 20th century followed in the first instance the lines of seepages, but considerable guidance was given by geological mapping. Exploration and development have brought to light the great complexities of reservoir conditions caused by faulting, lenticularity, unconformity, and other features. Some of the larger oilfields in the Maracaibo Basin are more properly ascribable to stratigraphic than to structural conditions and the same is true of some of the fields in the eastern part of Venezuela.

In Trinidad lenticularity sometimes plays such an important part that accumulations of oil are found in the heart of the synclines as well as in the anticlines, and faulting also causes such complexities in the fold structures themselves that it is difficult to differentiate in detail between the effects of folding, faulting, and lenticularity in determining the local positions of the oil and gas.

The development of geophysical technique which was first used in geological investigations in Austria and Germany found its greatest practical application, first, in the use of gravity surveys to detect the presence of underground salt domes in the Gulf States of the U.S.A. This was later followed by refraction seismic shooting, utilizing the high velocity of the salt to enable its presence to be detected at depth, but perhaps the most detailed application of geophysics was in the use of reflection shooting for the direct determination of structure in the deeper parts of the sedimentary basins. This had its first practical application in parts of the Mid-Continent area, where the fortunate occurrence of ideal conditions for reflection shooting, associated with simple geological conditions, gave the first practical demonstration of the extreme accuracy of some such surveys.

The success of these methods of attack led, however, to considerable disappointments when the same methods were applied to more complex stratigraphical and structural conditions elsewhere, and later experience suggests that if these methods are to attain their maximum fruitfulness there must be close association between the geologist and the geophysicist in the interpretation of the physical data.

Characteristic Features of Oil and Gas Accumulations

Sometimes the choice of a site for an exploratory well may be a question of land tenure or alternatively the appearance of the surface topography, or proximity to known seepages of gas or oil. More often, the location may be chosen only after years of careful study involving extensive investigations of the stratigraphy of the area, detailed geological mapping of known structures, and geophysical surveys to explore the deeper structural conditions.

The dividing lines between these various methods of approach are to a certain extent artificial, for even though we may claim that modern methods are more scientific, we can be satisfied that experience was fully utilized throughout the early days of the oil industry in oil exploration. Seepages are in any case taken into account in all geological investigations, and the modern geophysical surveys would be of little value unless they were properly interpreted in geological terms.

Nevertheless, referring only to the immediate technique of discovery, whereas random drilling and drilling near seepages played the dominant part in oil discovery in the 19th century, they have been replaced largely by geological and geophysical methods since the first world war. The change has enhanced the efficiency of discovery, and although results differ widely in different areas the percentage of successful discoveries has increased on the average from about 5 to about 15 or 20 per cent. It is also interesting to note that in spite of the fact that the shallower and more obvious fields have been the first to be discovered, and the deeper pools should be more difficult to find, exploratory wells now have a greater chance of success than they had at the beginning of the 20th century. This is due partly to the greater efficiency of modern drilling and testing technique, but mainly to the skill and thought which are expended on the preliminary investigations leading up to the choice of the drilling sites.

The principles which govern the search are based on a knowledge of the natural history of oil in the earth's crust, *i.e.* of all the various phenomena which lead to the formation of an oil pool. This study lies wholly within the province of the geologist. It has therefore been his duty to inquire how oil originates, how and where it accumulates into oil pools, and how such pools can be preserved in the earth's crust against the destructive influences of erosion.

The natural history of an oil pool, its origin, its growth, and its death, are part of the history of the main basins of deposition. Although there may be many possible ways in which hydrocarbons can be formed naturally, the commercial oil pools and gas pools are born in the sediments, and are of organic origin. The nature of the original organic matter is still a topic of discussion, as is also the *modus operandi* of the change from the organic matter to oil. When this change takes place is also undecided; it is uncertain whether it is early in the cycle of sedimentation or after the sediments have been lithified.

These are important matters, and until they are settled our approach to the subject of discovery must lose somewhat in its effectiveness. However, the measure of agreement already reached, that the oil and gas are formed from organic matter within sediments which are called source rocks, is still an adequate basis of attack. It means that no oil pools of importance can occur unless there have been deposits of considerable magnitude from which the oil can be produced. This fundamental concept gives a stratigraphic basis to our preliminary discussions on oil exploration, for it means that the oil possibilities of any area depend in the first instance on the environments of sedimentation which have existed in that area in the past.

Source Rocks

The characteristics of oil source rocks are vitally important matters to the oil geologist. Source rocks can be clays, shales, marls, or limestones, and according to some authors, even sandstones containing carbonaceous material. There is no general agreement regarding the critical features of source rocks. Some geologists are inclined to endow them with special characteristics, such as those of the highly organic black muds found in parts of the geological succession. Others assert that all oil-producing deposits must contain abundant evidence of organic remains, but this need not always be the case, since such evidence may be completely destroyed.

The fact that oil is commonly found in strata of marine origin indicates that a marine environment is the common one in which oil source rocks are produced. However, there are cases where freshwater formations contain oil, and the possibility of large lakes furnishing a satisfactory environment cannot be excluded. The marine rocks in which oil is found do not in many cases display any special characteristics, showing that the deposition of source rocks does not involve highly specialized conditions and that suitable ones are commonly produced naturally.

It is probable, and even to be expected, that the original source rocks may vary considerably in their organic content. The more highly organic may be represented by such examples as the Kupferschiefer of Germany or the Menilite Shale of Poland. The fact that oil from source rocks undergoes processes of concentration implies that clays and marls with a much smaller quantity of original organic matter may also act as source rocks. Some authors,[4] however, stress the origin *in situ* of oil pools, particularly those found in limestones. The principal feature on which stress is laid by most geologists is that the conditions of deposition of source rocks must be in the main anærobic, so that the organic matter is not completely destroyed during the processes of deposition and lithification.

Reservoir Rocks

Most of the accepted source rocks are too fine-grained and compact to yield their oil sufficiently freely for commercial production. It is assumed, therefore, that an essential preliminary to the formation of most oil pools is migration of the oil and gas from the source rocks to suitable storage rocks where they are concentrated. These reservoir rocks, as they are termed, consist normally of sands, sandstones, grits, limestones, or dolomites. They vary considerably in the form and distribution of their porosity. Usually the pore space is provided in the interstices between the constituent grains of the rocks, but sometimes, when the rock has been rendered compact by cementation or pressure, the fissures within the rock, due to jointing and fracturing, are sufficiently important to provide the necessary pore space.

Reservoirs vary in shape and size according to the stratigraphical and structural conditions, but they all have one feature in common: they are permeable, and the contained fluids can flow through the rock easily, making it possible for the oil and gas to be extracted. There are probably enormous quantities of oil distributed through thick masses of fine sediments which will never yield commercial oil wells, because their permeability is too low.

The stratigraphical search for oil is therefore not merely a search for areas containing suitable source rocks; it is concerned still more closely with the investigation of possible reservoir rocks, which are suitable for oil storage and recovery. The proportion of reservoir rock to finer sediments is of considerable importance in deciding the value of potential oil territory. It is possible to have either too little volume of reservoir space, in which case oil production becomes non-commercial, or too large a volume of reservoir space, in which case oil is liable to become dispersed, or at least more difficult to locate. Satisfactory conditions occur when the finer sediments bulk largely in the whole stratigraphic column, but the reservoir rocks are reasonably extensive, and of good thickness and homogeneity. Each reservoir rock should be completely enveloped by good thick sheets of impermeable beds.

Cap Rocks

Gas and oil tend, by virtue of their buoyancy, to rise as high as they can in the permeable reservoir rocks. They are imprisoned within the reservoir by the layer of impermeable sediments, *i.e.* the cap rock, which covers the reservoir. In general, this sealing layer completely envelops the whole reservoir, but as the gas and oil seldom fill more than the upper portion of the reservoir, the oil is usually underlain by similar reservoir rock saturated with brine. This constitutes the edge-water zone of an oil pool.

The liquid and gas contents of the reservoir are normally under considerable pressure, their escape being prevented by the impervious envelope which constitutes the cap rock. Rupture of the cap rock leads therefore to the dispersal of the oil. Nature induces escape by the deformation and fracture of the sealing strata, or by their removal by erosion.

Active oil shows are the phenomena associated with these processes of dispersal, and therefore they herald the destruction of an oil pool. This is one of the several reasons why oil shows may be doubtful guides in the location of exploratory wells. Their evidence may be of great value, but it must be read in the light of local stratigraphy and structure to get its true significance. Clays, marls, and shales make good cap rocks, as does salt, which flows under pressure and becomes highly compact. Sometimes cemented sandstones and limestones are sufficiently impervious to seal off the oil and gas, particularly when these rocks are water-saturated.

The pressure within a pool is commonly ascribed to the loading of sediments, to the effects of lateral pressure, and sometimes to artesian waters from neighbouring areas where the rocks are exposed. In all but the latter case the oil accumulations can be looked on as trapped portions of the migrating fluids, and the pressure within them reflects the pressure which was developed during the processes of compaction and migration. Such conditions are ephemeral, and they last only as long as the seal is effective.

Thus the dispersal of oil pools is just as much a natural process as their formation.

Whilst every oil pool has a source rock, a reservoir rock, and an impervious cover, it also has a history. It is born because the source sediments are laid down and the organic matter is changed to oil. It grows because the ensuing processes of compaction create movements of the oil and gas, and their concentration in suitable reservoirs. Inevitably it will be dispersed when fracturing or erosion ruptures the seal.

The geologist's consideration, therefore, must not be confined to the study of the oil traps in their present form. He must also include the geological history of these structures subsequent to the period when it may be presumed that the oil was originally concentrated in order to determine whether there has been a reasonable chance of the survival of the oil pools.

This careful balance of the possibilities of preservation of oil pools in the crust of the earth is one of the most difficult of geological problems, for it involves a detailed knowledge of the stratigraphic history of the area, and a discriminating assessment of the evidences of seepages and their relationship to the structural elements. From first to last it is a geological study, and for this reason the broad principles governing the search for petroleum are, and must always remain, geological.

Structure

There is one attribute of the oil reservoir which has been deliberately avoided in this chapter, though it is implicit in the statement that a reservoir has shape. This shape is the result of two features, the stratigraphy and the structure, but the relative importance of each of these characteristics may be very variable. A pool can be due entirely to stratigraphical conditions, *e.g.* some of the largest pools are simple sand-bars or sand-wedges on old shore lines.

The most perfect oil-trap is the simple sand lens. It is completely enclosed by impervious strata; the porosity within it provides adequate space for the storage of oil and gas; and the change in texture from the reservoir rock to the overlying cap rock provides an effective filter which distrains the oil and gas from the water during migration and imprisons them within the reservoir.

The sand-wedge on an unconformity representing shore-line conditions is equally suitable as a trap for oil, and no later folding, faulting, or tilting can improve the value of such a trap produced simply by conditions of sedimentation. It is often difficult, when studying some of the more complicated pools, to appraise rightly the relative value of each feature, stratigraphical and structural, in forming the original oil accumulation. There are, however, many cases where the stratigraphical features are relatively less important, and structure is the dominant influence determining the whole oil accumulation.

The consideration that a multiplicity of factors may be responsible for a particular oil accumulation, and that often the more obvious structural features are found on closer examination to have been less important than stratigraphical features which have been overlooked, becomes more and more apparent as we delve deeper into the geology of individual pools.