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AN INVESTIGATION OF THE MECHANICS OF OIL
MIGRATION FROM THE SOURCE BEDS
TO THE RESERVOIR BEDS.

by

William Reed Quilliam.

A

T H E S I S

submitted to the faculty of the
SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI
in partial fulfillment of the work required for the

D E G R E E O F

Engineer of Mines

Rolla, Mo.

1928

Approved by

C. P. Forbes

Professor of Mining.

AN INVESTIGATION OF THE MECHANICS
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AN INVESTIGATION OF THE MECHANICS OF OIL MIGRATION
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O U T L I N E.

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2. Origin of petroleum.
3. Importance of geologic history.
4. Summary of some previous theories.
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AN INVESTIGATION OF THE MECHANICS OF OIL MIGRATION
FROM THE SOURCE BEDS TO THE RESERVOIR BEDS.

S U M M A R Y.

From a study of the literature on the subject of the mechanics of the migration of oil, the fact is made clear that many factors have an important influence upon the movement of oil in the rocks of the earth's crust. A brief summary of the outstanding facts as they have indicated themselves follows:

1. Gravitational compaction, a phenomenon due to the progressive increase of weight caused by the accumulation of successive layers of strata, reduces the pore space between the fine particles of mud and squeezes out the liquid content, expelling some or all of the oil which the beds may contain.

2. In deformed strata, anticlines are in a state of tension on their convex sides, and synclines are compressed on their concave sides. Liquids in the deformed strata would have a tendency to move toward the area of tension or toward the concave sides of the anticlines, and away from the areas of compression in the synclines.

3. Water pressure acts as an agent of migration, as here considered, in two ways; (a) due to hydrostatic head, water is forced into the oil bearing pores of the rocks and captures them, forcing the oil out; (b) thermal currents are created by

differences in temperature of water at different depths within the earth. These currents it is suggested may be sufficiently strong to create movement of oil particles contained within the rocks.

4. By the process of molecular attraction movement of oil particles is produced by capillarity, adhesion, cohesion, and possibly by a selective attraction which certain oils seem to have for certain minerals.

5. Chemical reactions set up within the earth are considered as agents in producing migration of oil. Cement deposited in the interstices of the rocks would squeeze out particles of oil. Generated gas mixing with oil lowers its viscosity and makes it mobile; also gas bubbles and oil unite, the oil forming a shell about the gas. The oil then "rides" the gas bubble as far as physical conditions permit the gas to travel. Heat produced by chemical reactions may lower the viscosity of oil, thus increasing its mobility. Ground waters which carry certain minerals in solution may release oil films from sand grains.

6. Ground water circulation in its relation to oil migration is considered as (a) connate water circulation, which is caused by compacting and folding of the strata, and (b) meteoric water circulation, which is produced mainly by capillarity and hydraulic head.

7. Thrust faults up to the present have proved to be of little or no importance in the study of oil accumulation so far as known. Normal faults are associated with many known and prospective oil fields. Fault planes often furnish avenues up and along which petroleum can migrate. Faults may also act as barriers to migration where a permeable sand carrying oil is faulted to a position opposite an impermeable rock mass.

I N T R O D U C T I O N .

STATEMENT OF THE PROBLEM.

That this is a mechanical age is certainly true. That machines, motors, and mechanical equipment of all kinds are destined to fill a larger place, not only in our contemporary life, but in the life of many future generations, is also true. The question of lubricating and fueling the vast number of automobiles alone throughout the world presents an economic problem of major importance. The number of machines for which oil must be supplied, if they are to run, is daily increasing. If the oil industry is to keep abreast of the demands of the consumer, petroleum production must be ever on the increase. Whether production of oil balances consumption will depend to a very great extent upon the success of geological search for a new pool, and upon the accuracy of the geologists' understanding of the processes by which oil is accumulated into pools of commercial size.

The study of the migration and accumulation of petroleum has very naturally been analytic, with the result that we have had a variety of studies of its several features. The generation of petroleum, its migration and its accumulation in reservoir rocks is not a rapid process which may be accomplished and terminated in a comparatively short time, but one of long and almost continuous operation from the time of its inception.

In this study the author is not attempting to formulate a new theory for the movement of oil from its point of origin to its final point of accumulation into pools of commercial size. Rather he is attempting to segregate and then string together some of the essential elements involved in the mechanics of oil movements. The material presented in this paper has not been gotten from laboratory or field observation, but from a critical study of the literature on the subject discussed.

ORIGIN OF PETROLEUM.

The theory that petroleum is generated by natural distillation under geothermal and dynamic influences from organic matter buried in the sediments was first suggested by Newberry and Orton. This theory is known as the Organic Theory, and has received almost universal acceptance. The theory postulated the origin of petroleum from plants, especially those of low orders yielding waxy, fatty, gelatinous, or resinous substance, and from animal

matter. The organic matter was deposited on the sea bottom, in estuaries or not far from shore, and more rarely in lakes. Through the action of anaerobic bacteria it is changed, the cellulose probably being altered to other compounds, and the waxes and fats set free to form petroleum.

Arnold and Garfias (66) in referring to the origin of the oil in the California fields, say that it has been derived largely from the organic shales which are associated with the oil bearing strata in all the fields of the state. The oil, it is assumed, was distilled from the organic matter, both vegetable and animal, once contained in the beds. Diatomaceous deposits are abundant in the Eocene and Miocene formations and are thought to be a major source of the oil. Other organisms that are also thought to have contributed to the oil in this area are plants, foraminifera, bryozoa, and possibly molusca and fish. These investigators believe that all evidence points strongly to the organic origin of the California oils.

IMPORTANCE OF GEOLOGIC HISTORY.

In the various localities where oil and gas have been found, rocks of different ages ranging from Cambrian to Pleistocene inclusive are involved. But as a rule the age of the oil and gas bearing formations in any one province does not extend over many periods. In the search for hydrocarbons, it is very important

to ascertain the geologic history of the region in which the prospect lies. In this way it may be ascertained whether the formation which is looked upon as a prospective oil and gas producer, is old and possibly compacted, or has been cemented or otherwise unfavorably affected before the supposed favorable structure was formed.

The physical condition of the prospective oil and gas rocks at the time of folding would have an important influence on the possible migration of hydrocarbons from their disseminated state to some concentration point where a pool may be formed. If geologically old rocks are to contain oil in commercial volumes, they must have led a quiet and uneventful existence. They must be relatively unchanged, and but little disturbed from their initial state. If highly folded and faulted rocks are to contain much oil, they must be geologically young rocks, and geologically unchanged rocks form only a thin veneer in the makeup of the earth's crust. Rocks as young as Pleistocene carry oil in the Summerland Puente Hills of California (56) and gas is found in the Lake Bonneville beds of Salt Lake valley, Utah, and the glacial drift of the Chicago area. In Roumania, Sumatra, California and the Gulf Coast of Texas and Louisiana, Pliocene rocks carry oil and gas. Except for minor occurrences of gas in the Lower Carboniferous of England, all occurrences of petroleum and gas in Paleozoic sediments are confined to the United States.

SUMMARY OF SOME PREVIOUS THEORIES.

The substance of the Anticlinal Theory as originally proposed is that oil moves up the dip on account of its buoyancy as compared with water. Munn (1) in his studies in the application of the Anticlinal Theory to oil and gas accumulation, called attention to features of movement which did not seem to be explained by the then prevailing theory of segregation due to buoyancy. Experiments proved that no movement of oil takes place even virtually upward through the sands unless moving gas is present or the liquid is agitated in some way. Munn later developed the Hydraulic Theory, which embraces the idea that the location of oil pools is due to bodies of oil becoming trapped and held (partly by capillarity) between advancing water currents.

Johnson (85) suggests that squeezing of water out of the sediments during the process of compacting, as well as the expansion of liquids on account of the generation of gas in the deeper rocks, would cause upward movement of the rock fluids.

McCoy (10) argues from the results of his experiments that oil does not migrate for a great distance, and is mostly accumulated near its source, mainly by capillary forces or their related phenomena.

Daily, in his Diastrophic Theory, has urged that the movement of rock fluids is caused chiefly by deformation of the strata.

The fluids are supposed to be squeezed out of the zones of greatest compression and concentrated further from the sources of thrust pressures in belts where pressure is less intense.

Rich (43) and Park (55) have enlarged upon the ideas of others concerning the importance of the role of circulating waters in the process of oil migration and accumulation. In this theory the principal cause of the migration of oil and gas is the movement of underground water which carries with it minute globules of oil and bubbles of gas, possibly as fast as they are formed.

It is the writer's opinion that no one theory involving a given set of conditions can be applied universally to oil accumulations throughout the world. Most, if not all, of the theories of the migration of petroleum thus far advanced, have some merit and applicability wholly or in part in certain areas. With the thought in mind that many factors are involved, and that their relative significance and association with each other are as varied as nature itself, is this paper undertaken. Since the inorganic theory of the origin of petroleum is disregarded, a fundamental premise in the following discussion is that oil is not indigenous to the reservoirs from which it is now produced; shales are here considered the real source material. As a matter of convenience, and more or less arbitrarily, the movements of oil are differentiated into three groups. The first is a DISPERSIVE PROCESS, that is, the processes responsible for the

movement of oil from the oil forming shales or source beds into the more porous sandy strata or reservoir beds. The second, the DISPERSIVE-ACCUMULATIVE PROCESS, is considered as contributing to both accumulations in the reservoir beds and dispersion of oil from the source beds. The third is the ACCUMULATIVE PROCESS whereby oil is collected into pools of commercial size.

A C K N O W L E D G M E N T .

This paper is submitted to the faculty of the School of Mines and Metallurgy of the University of Missouri in partial fulfillment of the work required for the degree of Engineer of Mines. It is based upon a critical study of the literature bearing upon the subject of the migration and accumulation of oil.

The writer wishes to express his appreciation to Professor E. S. Bastin, of the University of Chicago, for valuable suggestions and criticisms.

D I S P E R S I V E P R O C E S S .

GRAVITATIONAL COMPACTION.

COMPOSITION OF SOURCE MATERIAL: The muds and ooze constituting the source beds of petroleum are assumed to have been deposited in comparatively quiet boggy basins of brackish and marine waters and composed of extremely fine mineral and organic particles.

The mineral composition of the sediments on the average consists of hydrous aluminum silicates of the kaolin group, minerals of the chloride group, hydrous iron oxide, primary and secondary quartz, opal, carbonates of calcium, magnesium and possibly iron, small amounts of sulphate, feldspars, micas, ferro-magnesian minerals, and very small amounts of accessory unaltered minerals.

Intermingled and contemporaneously deposited with the mineral particles are spore and pollen exines and other resistant plant matter. Tests and other parts of animal remains are also deposited with the sediments. Increase in density and reduction of volume by compacting and cementation of the fine mineral and organic particles produced shales. The extent to which cementation and compaction may go in the early life of such sediments is as yet not fully known. However, it would seem that the compacting process begins with or immediately follows the earliest deposition and continues as long as subsequent sediments are deposited..

An inspection of the mineral particles composing the muds and silts will show that all are not of the same degree of hardness. The larger and more brittle grains subjected to a heavy load of overlying sediments would be crushed, the smaller fragments filling the interstices between the more competent grains, thus reducing the total amount of voids in the rock. Some of the grains, such as those of the mica group, possess more or less elasticity. These would be further flattened, and in some cases, bent around the more rigid grains. The quartz and feldspars would have a tendency to become rounded, while the biotites and muscovites would always present a flat surface.

Recrystallization of granulated particles would result in the formation of new minerals like calcite, sericite, and white mica, but chemical analysis shows that this change may occur with little or no addition or subtraction of minerals. The inference may be drawn, then, that recrystallization would be of little or no importance in the matter of increasing or reducing pore space within the shales. But a certain amount of vertical shortening within the beds would undoubtedly occur with the volatilization of organic matter. In the case of peat it is estimated that 15 to 30 feet are required to produce one foot of coal. This reduction of volume is accomplished not wholly by superimposed load, but by decomposition with the evolution of volatile gases.

EFFECT OF SIZE AND ARRANGEMENT OF MINERAL GRAINS ON POROSITY:

In his study of porosity Slichter (75) made a theoretical study of an "ideal soil" consisting of spherical grains of equal size. He states that "if the grains of soil are arranged in the most compact manner possible, each grain will touch surrounding grains at twelve points and the element of volume will be a rhombohedron having angles equal to 60 and 120 degrees. If the grains are not arranged in the most compact manner, the rhombohedron will have its face angles greater than 60 degrees, and each sphere will touch other spheres in but six points, but will nearly touch in six other points. The most open arrangement of the soil grains which is possible with the grains in contact is had when the rhombohedron is a cube -----.

"If we imagine a soil made up of particles arranged so that the lines joining the centers form cubes, the percentage of the open space to the whole space, or the so-called porosity, can be found by dividing the difference between the volume of a sphere and the volume of the circumscribed cube by the volume of the circumscribed cube which gives a porosity of 47.64 per cent. If the particles are arranged as compactly as possible, the percentage of pore space can be found by dividing the difference between the volume of the rhombohedron whose acute angles are 60 degrees and whose edges equal the diameter of the sphere, by the volume of the rhombohedron which gives a porosity of 25.95 per cent."

Thus it is shown that the per cent of porosity of the "ideal soil" depended not upon the size of the grains, but upon their arrangement with respect to each other. Other conditions being the same, a sediment composed of fine particles of uniform size should have the same porosity as a sediment composed of larger particles of uniform size.

EFFECT OF SIZE OF MINERAL PARTICLES ON FLUID MOVEMENT: The ease of movement of fluids through sand bodies is affected by the size of the grain. Slichter proved this by computing the flow of water through simple sands of different diameter and under a uniform pressure of 1 cm of water. He observed that where 2,296 grams of water flowed through sand grains of 2.755 mm in diameter, only 94.8 grams flowed through sands of .5824 mm in diameter.

As a consequence of the extreme fineness of the particles composing clays, muds, and silts, there is a tremendous surface present in a small volume of material. Twenhofel (88) quotes Metscherlich as estimating that a gram of clay might have from 200 to 900 square meters of surface. Consequently in finely divided substances, the effect of surface phenomena such as adsorption and adhesion would become very pronounced. In the process of settling, the finely divided grains would carry down a much greater amount of adsorbed water and air than an equal volume of coarse material and adhesion may go so far as to prevent the grains of powder-like sediments from coming in contact with each other after settling,

that is, they would remain in suspension. Such a condition as the latter could obviously pass by gradations into a colloidal suspension.

Herberg's (64) experiments offer an example of the high percentage of fluids that may be retained in finely divided sediments. In experimenting with a 50 gram sample of white South Carolina kaolin which had passed through a 200 mesh sieve, he found that the clay showed a porosity of 88.8 per cent when dry and loosely aggregated. After shaking and jarring the container, the porosity was reduced to 81 per cent. The sample was then thoroughly shaken in a liter of water and allowed to settle until a condition of equilibrium was reached. The porosity of the water deposited clay was 84.4 per cent. Shaw states that much of the newly deposited material of the Mississippi delta has a porosity of 80 or 90 per cent. These observations by Shaw and Hedberg are interesting in that they substantiate Slichter's experiment previously referred to upon the flow of water through fine and coarse sands. We may conclude, then, that the size of individual particles composing a sediment has an important bearing upon the total amount of fluids retained by the sediment.

FACTORS DETERMINING SIZE OF MINERAL PARTICLES IN SHALES: The size and composition of particles entering clays and shales are dependent on various physical conditions, some of the more important of which are: (a) Nature and altitude of the rocks of adjacent

lands; (b) Depth of water in basin of deposition; (c) Velocity of tributary streams; (d) The extent of the circulation of the water within the basin of deposition; (e) Temperature and climate.

It is a well known principle of sedimentation that the finest particles of rock remain in suspension in water the longest, and are only deposited where circulation is least rapid. Bays with weak tidal action, swamps and land locked bodies of water would favor the deposition of the finest sediments. Such particles would be more or less the same size and would, therefore, tend to settle in the same area of deposition. The larger particles and those with higher specific gravity would sink to the bottom before the quietest part of the basin was reached. Uniformity of size and extreme fineness would favor a maximum of fluid being retained within the beds.

THE FLUID RESPONSE AND RELATION TO COMPACTION: The life history of inland lakes, lagoons and swamps is short geologically speaking, and rather rapid changes in conditions of sedimentation succeed each other. The pore spaces of the initial sediments are entirely filled with water and gases and only by expulsion of these fluids can the porosity be reduced. In coarse sediments gravity would be the controlling factor in controlling the amount of water held in the interstices, but in the case of muds and silts, a fine film of water is held about each grain by adsorption. A progressive increase of weight due to the accumulation of successive layers of strata would cause a progressive compaction to take place. As the fine particles

of mud are drawn closer together, and space between them reduced, there will be a gradual squeezing out of the liquid contents of the muds. There are certain phenomena, however, that resist the forces tending to expel the fluids. These opposing factors are: (1) reduced openings through which the fluids, particularly oil particles, may be squeezed; (2) cohesion; (3) adhesion; (4) surface tension.

If the opposing forces are in a state of equilibrium at a certain moment, such equilibrium would be disturbed by the further addition of sediments at the top of the column, and the equilibrium state can only be restored by the escape of some of the liquids or by their accommodating themselves to smaller space by compressibility. But the compressibility of oil and water is slight, and this taken in connection with the fact that most rocks are of sufficient porosity to permit movement of these fluids before the point of compression is reached, creates doubt whether compressibility is of much importance in its relation to the movement of oil and water. The gas present is more fluid and responds readily to pressure differences. It is not only highly compressible, but may be dissolved in the oil and water; the solubility increasing as the pressure increases. Any gas in excess of that necessary to saturate the fluids at the prevailing pressure would be present in the free condition either intermixed with the fluids, or entirely separate from them. Because of its greater mobility, gas is the

most fugitive of the three fluids within the source beds, and would be the first to escape as compaction of the sediments increased.

In another section of this paper it will be shown that the surface tension of water is about two and one-half times that of oil. The adhesion between water and the particles of mud is greater than between oil and particles of mud. Since adhesion is a function of the surface exposed in the particles of mud, and exposed surface per volume of sediment is greater in fine than in coarse sediments, the forces opposing the movement of water are greater than those opposing the movement of oil. Hence, as compaction progresses, relatively greater proportions of oil will be forced out of the source beds into the more porous adjacent beds, as Van Tuyl's and Beckstrom's experiment discussed below will verify.

EXPERIMENTAL EVIDENCE OF DIFFERENTIAL COMPACTION: Van Tuyl and Beckstrom (60) performed some experiments that throw light upon the inter-relations and actions of oil and water in their response to compaction. The experiment was to determine the effect of compacting on 1000 cc of sand, two-thirds of which passed through a 40 mesh screen and one-third through a 30 mesh screen. The porosity having been determined as 40 per cent, 200 cc of water and 200 cc of Salt Creek crude were added to the sand, the water being mixed in first. The mixture was then placed in a steel cylinder,

the piston inserted, and pressure applied. At first oil came off rapidly and but very little water. At 1000 lbs. pressure (equivalent to about 75 lbs. per square inch) the recovery was 40 cc of oil and only a few drops of water. As the pressure was increased, the porportion of water to oil became larger, and finally at intermediate and higher pressures, the water equalled or exceeded the oil in nearly every measurement. The total recovery at 45,000 lbs. pressure was 137.5 cc of fluid, the water consisting of 43 cc. and the oil 94.5 cc. The reduction in volume of the sand as a result of compacting was 13.75 per cent and the reduction in pore space from 40 to 30.43 per cent.

It should be pointed out here that in nature the proportion of oil to water in petroliferous shales has undoubtedly been smaller than in the mixture employed in this experiment, so that early in the process of compacting, water has probably passed off to some extent, at least, before an appreciable amount of oil has left the beds.

Some interesting data on the relationship between pressure and porosity were obtained by Hedberg (64) in his study of samples taken from the Ransom Well in Hamilton County, Kansas. The information is most interesting because it represents a long vertical sequence and comes from a region in which no evidence of major lateral compression exists. The tabulation below will show that the lowest sample obtained was from a depth of 5440 feet and

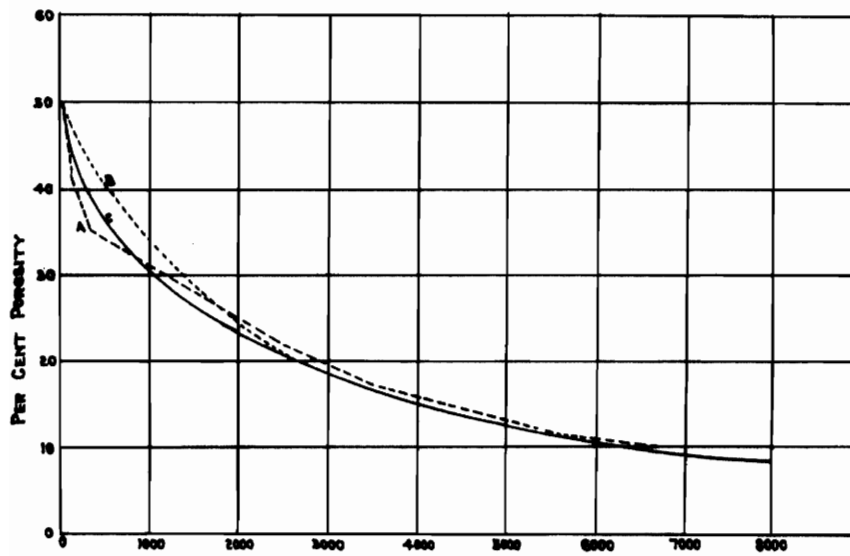


FIG. 1

THIS GRAPH SHOWS HOW THE PERCENTAGE OF POROSITY VARIES WITH DEPTH BELOW THE SURFACE.

Hedberg had reasons to believe that at least 2500 feet of Cretaceous sediments once existed above the surface rock, making the total depth of burial for the cutting approximately 8000 feet.

Using 8 per cent, the porosity of the shale cuttings from the Ransom Well due to a total calculated overburden of 8000 feet, and 50 per cent as the average initial porosity of a hundred feet of freshly deposited mud, and using certain deductions suggested by Sorby, Hedberg constructed an approximate porosity gradient Fig.1. "From the porosity gradient thus determined it is possible to calculate the approximate vertical shrinkage which a bed of mud or clay will undergo during compaction. For instance, a hundred feet of freshly deposited mud, when buried under 3000 feet of sediment, will be reduced to about 50 feet. On the other hand, a shale with a porosity of 8 per cent must have had a thickness of about 180 feet when first deposited." No attempt is made to claim mathematical accuracy for the porosity gradient. It is thought, however, that it may be approximately indicative of the true relation between porosity and pressure for the particular type of shale used and roughly for all dominantly argillaceous sediments.

The tabulation of samples from the Ransom Well referred to above are as follows:

Depth in Feet	Rock Density	Mineral Density	Percentage of Porosity
Graneros shale outcrop	1.983	2.649	25.16
	1.989	2.637	24.57
3,029 - 40	2.388	2.702	11.62
3,945 - 50	2.358)	2.596	9.17
	2.348)	2.637	10.98
4,485 - 95	2.407	2.644	8.96
4,797 - 4, 805	2.523	2.791	9.62
4,994 - 5, 006	2.448	2.683	8.71
5,355 - 60	2.526)	2.744	7.94
	2.523	2.754	8.38
5,437 - 40	2.521	2.743	8.09

ECONOMIC ASPECTS OF COMPACTION: The economic importance of compaction in producing changes in the attitude of sedimentary strata has been recognized. Blackwelder (86) believes that condensation due to differential settling of sediments over granite ridges accounts for the structure exhibited in the central Kansas oil domes. Interpretations regarding the structure of the Eocene clays of Northern Louisiana and Southern Arkansas has been very unsatisfactory; the dips in the clays ranging from horizontality to 20 degrees or more and the dips may change within the distance of a few hundred feet. Dozens of dry holes have been drilled on the evidence of surface dips, and areas which have since proved productive have been condemned by reputable geologists. Teas (89)

explains this confusion in interpretation of the structure as failure to take into account the phenomena of differential compacting and settling of beds.

D I S P E R S I V E - A C C U M U L A T I V E P R O C E S S .

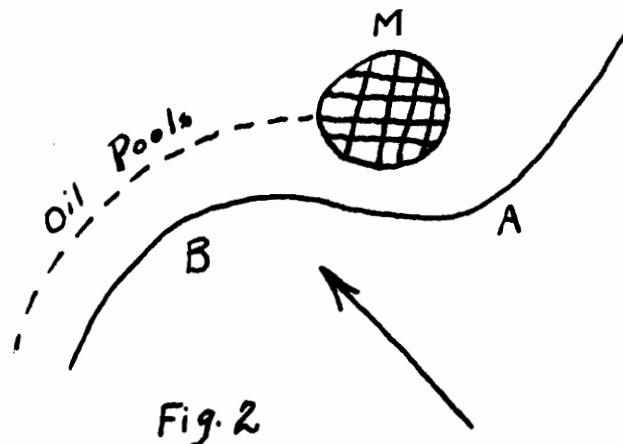
AFFECTS OF DEFORMATION.

Much stress has been laid upon the importance of geological structure as a necessary condition relating to oil and gas accumulations. This is as it should be, for all deposits of these substances, when studied in detail, are seen to be closely associated with deformation in one or more of its many manifestations. Most, if not all, of the oil fields of the world, show a direct relationship between their structure and some of the great periodic movements that have from time to time affected the earth. Ordovician sediments, for example, were deformed by the movements that produced the Cincinnati Arch and Nashville Dome, and large deposits of oil and gas have been found on the flanks of these domes in the Trenton (Ordovician) limestone in Ohio, Indiana, and Illinois. In the Appalachian fields, oil and gas occur in rocks of Devonian, Mississippian and Pennsylvanian age deformed by the great Hercynian and subsequent deformations. Similarly, all the other known fields of the world can be shown to have a direct structural connection with the orogenic and epirogenic movements registered in the rock strata of the area.

When sedimentation ceases and orogenic movement begins, the yielding strata convert sites of deposition into sites of erosion. Although there is no known way of inferring what really happens in a particular case, it would be safe to assume that the thrusts do not occur at regular intervals, that they are not of the same magnitude, that they do not plicate all strata alike, but differently depending on the component parts of each stratum, and that the same stratum is affected differently as its proximity and remoteness varies with the loci of the movement. What happens then is not a simple series of more or less parallel folds elongated in one direction, but a system of folds complicated by transverse folds which create successive elevated and depressed areas along a general line at right angles to the direction of the applied force. In the course of lateral compression and folding, the processes of differential compression begun through the effects of loading alone, and discussed in the preceding section, are continued. If the strata are saturated with liquids, the tendency would be for the liquids to move from the more compressed parts to the less compressed parts. In general this would mean that the fluids seeking relief from pressure would tend to migrate from the more compact mother shales to the porous or sandy members above or below. However, not all the oil is squeezed from the shales even by these forces or by subsequent forces. That there remains behind a very large total amount that is never removed is well

known from the almost universal presence of petroleum in most dark shales and limestones.

Daly (13) brings out an interesting relationship between structures and accumulation in the Pennsylvanian oil belt. He describes the Appalachian Mountains as trending north after crossing the southern boundary of the state. A flexure diverts them to the east before crossing the Susquehanna River where they resume their normal northeast-southwest direction. The flexure, he interprets as being due to the resistance offered by an ancient mass of consolidated rocks which is indicated by M in the sketch Fig. 2. Such a deflection would produce an increased pressure in the concave part of the curve toward A and a tension in the region of B where the curve is convex. This is an interesting comparison, because the principal oil fields of Pennsylvania and Southwestern New York are located precisely in this zone of tension.



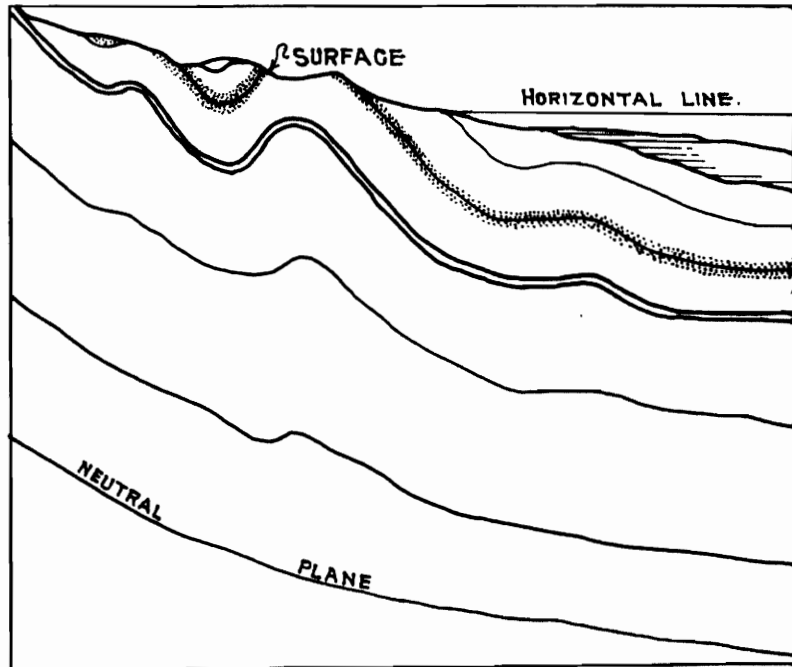


FIG. 3

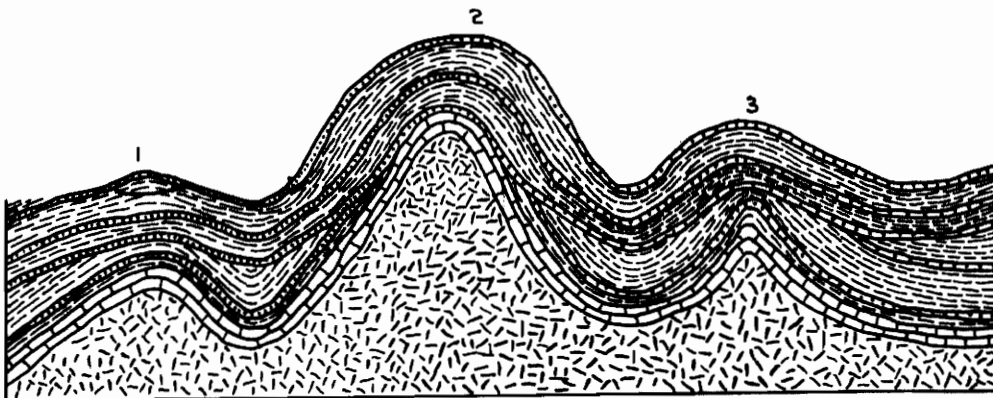


FIG. 4

In analyzing the causes of movement of oil and gas, the geologist is confronted with certain facts that are more or less obvious. He knows from experience that folds, which are possible oil and gas reservoirs, are anticlines or parts of anticlines definitely related to mountain ranges and usually paralleling them. Other facts are not so obvious. For example, in a study of the various oil fields one is often confronted with the question why this structure contains both oil and gas; another only oil with little gas, while a third contains only gas. Does the age of the strata have any bearing on the question; does the time of folding enter the equation and does depth and altitude play leading roles? All these and many others are important questions economically as well as scientifically. In order to arrive at answers with any degree of merit, it is necessary to follow, if possible, some of the movements involved in the formation of a structure and the behavior of the hydrocarbons during the time these processes are in operation.

The problem then is one in earth mechanics. Assuming the strata to have been deformed, the deformation, at first only slight undulations, may be converted with increased force into distinct topographic and structural features ----anticlines, synclines, faults and overturned folds may follow in the wake of the movement. At some depth below the surface, lies a neutral plane, Fig.3, in which there are neither stresses of compression

nor of tension. It is not necessary here to attempt to answer the question as to what started the forces involved in the movement. When such movements take place, whatever the cause, all the strata above the neutral plane are immediately subjected to tension and compression. It has already been indicated that any fluids in the beds would tend to seek relief from pressure, and move from areas of pressure into areas of tension. As the strata are lifted, the neutral plane acts as a hinge while the beds above accommodate themselves to lessened space by (1) compressing and uniformly thickening; (2) sliding over each other (strike faulting); (3) wrinkling up into folds parallel to the strike. All these different phenomena may occur independently or simultaneously, depending upon the magnitude of the forces and the competency or incompetency of the rocks involved.

Fig. 4 shows three folds in cross section; a major fold and two secondary folds. Fold No. 2 having been opposite the point of greatest bending, was probably the first to form. On each side of fold No. 2 appear auxiliary folds. Many local conditions would influence the size of a particular fold or possibly cause its suppression. Faulting and general thickening could relieve stresses to such an extent as to entirely eliminate folding.

Before the movement began, portions of the oil and gas that had been expelled by gravitational compaction from the source beds, would occupy the more porous rocks above or below. When folding

starts, a gradual up-dip creep of the hydrocarbons will begin, influenced by many contributing factors, some of which shall be discussed later. The movement of hydrocarbons simultaneously with flexing of the beds conforms with the previous statement concerning the upper part (convex side) of an anticline where tension gives relief from pressure; oil and gas being trapped in the crests of the folds.

The oil in the strata below folds No. 1 and No. 3 would move upward toward the crests of these folds where it would be trapped, (56). The oil and gas between folds No. 2 and No. 1 and No. 2 and No. 3 would be divided -- a portion seeking the crest of each fold. If the beds down the dip from folds No. 1 and No. 3 should be prolifically charged with hydrocarbons, the migration would continue until folds No. 1 and No. 3 were full down to the high point on the axis of the syncline between the folds (56). Gas would fill the upper portion of the trap, and force an equal volume of oil past the lip of the syncline into fold No. 2. As the process continued, more gas and less oil would fill the top of folds No. 1 and No. 3 until they were eventually gas filled. If the supply of hydrocarbons were limited, folds No. 1 and No. 3 would be left with both oil and gas entrapped. Fold No. 2 might become so completely filled with gas that back pressure would saturate the sands with oil along the east and west flanks respectively of folds No. 1 and No. 3. But as fold No. 2 is a great deal larger than either of the other folds,

it would probably never become completely filled. The development of a similar structure into an oil field, would find that folds No. 1 and No. 3 were highly productive of gas with little or no oil; the possible exception being accumulation low on their flanks adjacent to fold No. 2. Fold No. 2 would be gas filled at its crest with a larger body of oil below. Of course, any number of changes could be brought about by subsequent folding, either before or after the completion of the migratory process of the hydrocarbons.

In appraising the value of such a structure for exploitation Hintze (56) considers that much depends upon the view adopted as to the time when the movement of the hydrocarbons is accomplished following the formation of suitable structure. He suggests that light on the problem may be found by referring to the age of the youngest petroliferous beds and noting the time that can be definitely stated as having elapsed since the beds were laid down and the structures were formed in which oil and gas are now found.

WATER PRESSURE.

HYDROSTATIC: Some rocks of the lithosphere are dry, or at least contain very little moisture. But the great majority of them, particularly those containing oil, are saturated with water. The water is often under hydrostatic pressure which at any point under the surface is equivalent to the weight of the column of water above.

Under some conditions, hydrostatic pressure of the water column and the greater surface tension of water over oil, may be forces sufficient within themselves to force oil and gas from the pores of the finest sands. This general capturing process by the water may be termed "scavenging", the effect of which is to force oil out of the dense shales into less dense sandstones. If there have been plications in the strata, the fluids tend to seek the crest of the structure due to its greater porosity. And if the oil is in quantity, this tendency is materially increased by the propulsive force of buoyancy.

It must be recognized, however, that there are certain limiting factors beyond which hydrostatic pressure as a prime mover in low gravity oil migration would be negligible. Mills (45) proved in his experiment that capillary and frictional resistance to fluid movements through sands increase as the size of the interstices are decreased, and that there is probably a limit to the fineness of interstices beyond which the gravitational migration of oils of high viscosity would not occur under hydrostatic conditions.

THERMAL CURRENTS: The question of thermal currents as a cause, or contributing cause, for oil movement has been mentioned but has received scant attention in the literature on the subject of migration. It seems that there are good reasons for believing that thermal currents may contribute to movements of hydrocarbons in both

the reservoir and source beds.

It is a well known principle of geology that temperature varies with depth and locality within the earth. The normal rise in temperature is approximately one degree Fahrenheit for each 50 feet of increased depth below the surface of the earth. Subsurface temperatures of 150 degrees F. are not uncommon in the vicinity of oil fields, and subsurface temperatures of 120 degrees F. in and around oil fields have been frequently observed. It is not improbable that fluids of abysmal origin may penetrate far through the sedimentary strata and at one time were conceivably at much higher temperatures than those named above. This supposition would find support in the great amount of helium and argon found in some natural gases.

Experiments have shown that thermal currents are created by differences in temperature at different points within a body of water. Good examples of this are the major ocean currents which are caused primarily by a difference in temperature of connecting bodies of water in different portions of the ocean. Experimentation further shows that a drop in temperature from 71.6 degrees F. to 39.2 degrees F. in 24 hours will completely turn over a body of surface water from 30 ft. to 50 ft. deep (69).

Pepperburg (69) in discussing the problem of the relation of thermal currents to the migration of oil has this to say: " By the introduction of geothermal temperature within the basin, which may

be due to increased depth, and locally due to faulting, folding, chemical action, vulcanism or metamorphism, thermal currents should be established sufficiently strong to create a marked movement of the fluid within the sand stratum. This movement should be accelerated in regions where oil or gas is associated with the water bearing formation because if subjected to the same conditions these substances are more sensitive to compression and expansion than water."

Van Ostrand of the United States Geological Survey in a recent study of ground water temperature in wells drilled in various oil fields, finds that earth temperatures are higher near the crests of anticlinal structures than elsewhere in their vicinity, and that in these locations the temperature gradient is in many cases in excess of one degree Fahrenheit for each 50 feet of depth below the surface. That is, at a depth of 3000 feet below the surface, a temperature of at least 60 degrees F. higher than the normal surface temperature may be expected. These figures would indicate that if the mean surface temperature were around 70 degrees F. fluids occurring at a depth of 3000 feet below the surface would be subjected to a temperature of 130 degrees F., and at 4000 feet, 150 degrees F. The difference then in surface waters ^{temperatures} and those at depth is undoubtedly sufficient in large bodies of ground water to produce a constant state of agitation or movement. Oil and gas in the path of the movement would be carried along provided forces in opposition to the thermal currents were not able to counteract their influence.

NATURE AND CHARACTER OF OPENINGS.

Before going into a detailed discussion of the mechanics of molecular attraction as affecting oil migration, let us consider the nature and character of the openings in the rocks which influence the movement of any fluids which they may contain. Openings in rocks may be considered upon the basis of; (1) form and continuity of the openings; (2) the size of the openings, and (3) the percentage of openings or pore space. Van Hise (74) classifies openings in rocks as; (1) those which are of great length and breadth as compared with width, such as bedding planes, faults, joints, and fissility; (2) those in which the dimensions of the cross sections of the openings are approximately the same, as those of mechanical deposits, including conglomerates, sandstones, muds soils, etc.; (3) irregular openings---those of vesicular lavas and the irregular fractures in rocks.

Slichter's (75) investigations into mechanical sediments show that openings have a strong tendency to a regular form and continuity. He found that the openings alternately narrow and widen, the wider taking roughly a polygonal cross-section, while the narrow places assume triangular cross-section. He further showed that in the various systems of packing of spherical particles, there is at least one direction in which the tubes or openings are straight. That is, there is one direction in which a straight wire could be thrust without coming in contact with a grain of rock material.

This being true, the quantity and ease with which liquids flowed through the particles would increase or diminish as the system of packing in the sediments approached or departed from the one system in which the openings are straight and continuous. But continuous straight tubes in any kind of natural sediments seem to be an improbable if not an impossible phenomenon. In deposits of current or wave action, sand grains are not spherical in shape, but occur in infinite variety of form and size. When angular fragments are deposited under water in the process of sedimentation, tabular faces will assume similar orientation and be brought into close juxtaposition.

Small grains will be deposited in the interstices between larger grains thus preventing continuous openings for any appreciable distance. Later deposition of cement would further reduce free openings not influenced by porosity of a secondary nature.

Openings on the basis of size are classified by Va Hise as supercapillary, capillary and subcapillary openings. For water, supercapillary openings if circular tubes, exceed 0.58 mm in diameter, or if sheet openings exceed 0.254 mm. Capillary openings include circular tubes from 0.508 to 0.0002 mm. in diameter, and if sheet openings from 0.254 to 0.0001 mm. in width. In subcapillary openings the solid molecules extend from wall to wall and the openings are less than 0.0002 mm. in diameter for tubes, and sheet openings are less than 0.0001 mm. in width.

Most openings of sand and sandstones, and many of the openings of fine conglomerate are of capillary size. The openings of clays, shales and slates are usually of subcapillary size while the openings between bedding planes, fault planes, joints etc. are super-capillary in size. In capillary openings the resistance to flow increases very rapidly as the openings diminish in size. This is due to the fact that the area of contact between the area of moving liquid and that fixed to the wall increases inversely as the size of the openings. Poiseuille's law (74) states that the flowage is inversely as the viscosity of the fluid. Van Hise (74) has shown that in slow movements in many of the larger bodies of ground water, the viscosity of the water and the friction becomes almost zero per unit area, but the moment the speed of movement becomes appreciable, the resistance promptly runs up.

MOLECULAR ATTRACTION.

ADHESION, COHESION AND SURFACE TENSION: Molecular attraction is considered by some authorities as the dominant force in the movement of hydrocarbons from the source beds into pools of commercial importance. This force works between the particles of water, particles of oil, and particles of rock and is expressed as cohesion, adhesion and surface tension. Cohesion is the force by which molecules of the same substance attract adjoining molecules. Adhesion is the force by which the small molecules of one

substance attract adjoining molecules of another substance, and surface tension is the cohesion of the molecules at the surface of a liquid which tend to make it contract. Surface tension of pure water equals 81.96 dynes per square centimeter. Lord Raleigh found that a water-air surface has a tension of 72.8 dynes per centimeter at 20 degrees C. The surface tension of any liquid may be expressed by the following formula:

$$T = \frac{\pi r^2 h \rho g}{2 \pi r \cos \alpha}$$

Where T is the surface tension; r the radius of the tube; h the height of the liquid standing in the tube; ρ the density of the liquid, and α the angle of contact between the liquid and the tube.

As a result of molecular attraction, water may rise against gravity in capillary openings and saturate rocks at higher altitudes than it would were it not for this force. Van Hise (74) shows that the rise of water above the normal level in capillary openings is due to the attraction between the water and the walls, and the attraction of the molecules of water for one another. The tendency for water to rise along the walls above its normal level is due to the fact that there is greater attraction between the molecules of the rock and water than between the molecules of water. As a film of water is drawn along the walls, and the molecules of this film of water in turn act upon the film below and draw it up, the total effect is to produce an elevation of

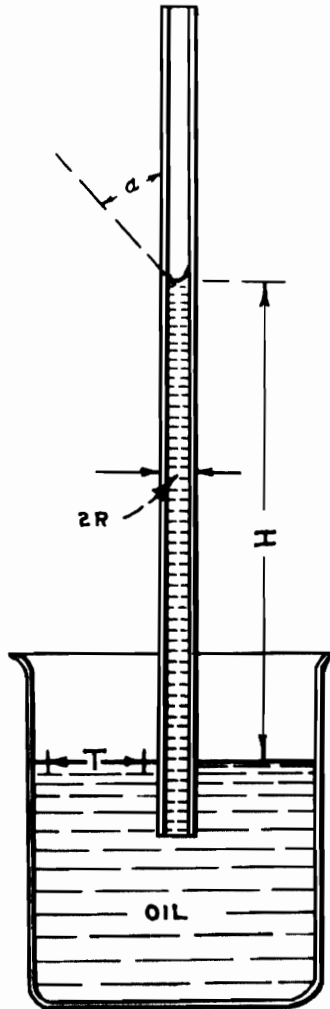


FIG. 5
ILLUSTRATING RISE OF OIL IN
A GLASS CAPILLARY TUBE.

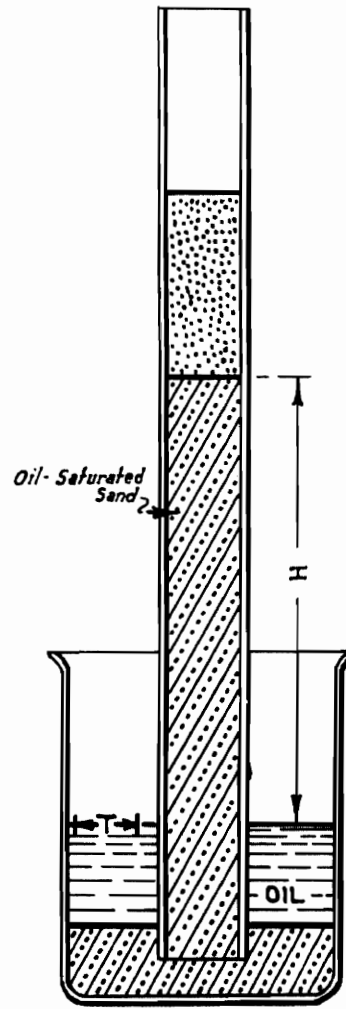


FIG. 6
APPARATUS USED IN MEASURING
CAPILLARY RISE OF OIL IN SAND.

above the normal surface.

In the case of oil in capillary openings a similar effect is produced by molecular attraction. Oil may rise against gravity in capillary openings and saturate rocks at higher levels than it would were this force not in operation. That the capillary rise is directly proportional to the surface tension of the oil, and inversely proportional to the oil density, was shown by Uren, (77). In this demonstration, Fig. 5, Uren used a capillary tube open at each end. The tube was held in an upright position with the lower end immersed below the surface of the oil. The molecular attraction existing between the oil and the glass of the tube, caused the oil to spread up the walls of the tube above the surface of the fluid. The surface tension of the oil opposed distension of its surface, and was powerful enough to lift a column of the oil in the tube. The rising film maintained connection with the reservoir below by cohesion of the molecules, with the result that a column of oil gradually climbed in the tube until a condition of equilibrium was reached.

Convenient means of determining surface tension in an oil, and measuring the height of its rise in a capillary tube is provided by the following formula:

$$H = \frac{2T \times \cos \theta}{A \times R \times G} \quad (77)$$

Where T is the surface tension of the oil in dynes per centimeter; R the radius of the tube in centimeters; G the density of the oil relative to pure water at zero degrees C.; A the acceleration of gravity in centimeters per second; H the capillary rise in centimeters, and a the angle of contact made by the oil against the glass surface.

Uren and El Difrawi (77) in an effort to determine quantitatively the magnitude of capillary force in rock pores of various size performed a series of experiments in which the capillary rise of crude petroleum in accurately sized, unconsolidated sands of known porosity was determined. Sands ranging from 20 to 70 mesh were compacted in glass tubes to various porosities and the ends of the tubes immersed in a reservoir of crude petroleum of known surface tension, density and viscosity, Fig. 6. When a state of equilibrium was reached, the height of capillary rise of oil in the sand above the surface of the oil in the reservoir was measured and the following empirical formula derived:

$$H = \frac{275 \times T \times \cos a}{G \times p^{2.3} \times D}$$

Where H equals capillary rise in inches; T equals surface in dynes per centimeter; a the angle of contact between the oil and mineral composing the grains of sand; G the specific gravity of the oil; P the porosity of the sand in per cent; D the mean diameter of the sand grains in millimeters.

Since surface tension determines the magnitude of capillary force and, therefore, the extent of retention of capillary oil in the rocks, it will be of interest to compare the surface tensions of various petroleumx of the United States. The following show some of Harvey's results with the du Nouy Tensiometer: (77)

Field	Surface tension in dynes per centimeter.
Arkansas-Eldorado -----	30.2
California-Coalinga (east side)-----	34.3
Kansas-Augusta-----	31.5
Illinois-Lawrence-----	30.9
Louisiana-Caddo-----	30.6
Montana-Winnett-----	27.4
Oklahoma-Cushing-----	29.9
Pennsylvania-Mercer County-----	32.9
Texas-Burkburnett-----	30.0
Goose Creek-----	33.6
Somerset-----	29.1
Wyoming-Salt Creek-----	34.3

All the above measurements were made at a temperature of 24 degrees C.

This data indicates that the surface tension of water is about two and one-half times that of crude oil. Water, therefore,

exerts greater pressure in entering capillary openings than does oil. Hence the constant tendency of capillarity is to draw water, rather than oil, into the finest openings. Reversing the conditions, we should expect capillarity to resist any movement of water from fine toward larger pores. This action would result in petroliferous areas in forcing the hydrocarbons from the dense, compact source beds, into the porous sandy phase of the same or adjacent beds.

Surface tension and capillary pressure are independent of direction on the whole, but in general are more effective vertically upward due to two factors mainly, viz; heat gradient and the increase of pressure with depth. Observations by Johnson and Adams (78) is to the effect that capillarity is quantitatively negligible at any considerable depth except in pores of such fineness that the amount of fluid which could flow in them is infinitesimal. It was also proved that capillary forces are effective only when there is a surface of separation within the pores, and moreover that these forces diminish steadily with rise of temperature and vanish at the critical point of the liquid. Washburne (12) argues "that since heat increases more rapidly downward in many oil fields, it is probable that capillary force decreases half at depths of 3000 or 4000 meters, below which it becomes practically ineffective. Moreover the surface tensions of all but the lightest hydrocarbons decrease much less rapidly

than that of water for each increment of temperature, so that the surface tension of water does not have such great excess over that of oil at these depths. Hence, it is probable that the capillary concentration of oil and gas must all be effected within 4000 or 5000 meters of the ground surface. Oil in deeper strata, must remain diffused in the shales, if that were its original distribution."

When oil soaked mud is placed against water saturated sand, it is a well known fact that an interchange of liquids takes place, that is, the oil moves into the sand, and the water moves into the mud. McCoy (76) observed this action to continue over a period of six months. In observing this phenomenon, the immediate question that arises is how does the water and oil pass each other in making this change. The key to the situation undoubtedly lies in the peculiar relations existing at the oil and water contact. We have seen that in contact with air, at 24 degrees C., oil has a surface tension of about 30.0 dynes and water at 20 degrees C. has a surface tension of 73.0 dynes. But McCoy (76) states that water in contact with oil has a surface tension of less than one-half its surface tension when it is in contact with air.

In order to study the forces involved, and the exact changes that took place Cook (79) performed a most interesting experiment regarding oil and water relations. A piece of glass tubing 10 mm.

in diameter was drawn out to capillary size in the middle. In one end of the tube was placed a mixture of coarse sand and water, and in the other, a mixture of fine sand and oil. Within a short time water was observed to flow along the sides of the capillary tube in an opposite direction to a flow of oil which moved along the center of the tube, that is, the water formed a tube through which the oil passed. The capillary opening through which the water passed had its two sides composed of different materials--glass on one side, and oil on the other. The walls of the opening through which the oil passed was composed of water. It has been stated that the various molecular attractions of a liquid in a capillary tube would be expressed in terms of cohesion, adhesion and surface tension. In this case, as between the glass and water, adhesion was stronger than cohesion and between the oil and water, cohesion of the water was greater than adhesion for oil. Hence, the water moved along the oil wall in the opposite direction to the oil. The top surface of the water had a tendency to concavity on one side and convexity on the other, allowing the effective force of surface tension to cause movement as indicated. In the oil, cohesion was greater than adhesion for water. The oil assumed a convex surface with the result that its surface tension caused it to move in the opposite direction to the movement of the water.

In analyzing this sort of phenomenon McCoy (76) believes that in nature the action starts with the adhesion of water for shale. Since the surface tension of the water is materially lessened by being in contact with oil, and as the water creeps against the oil, the pressure exceeds the surface tension of the water. The liquid surface is broken and a drop of oil moves into the water capillary and equalizes the fluid pressure. Thus by breaking the surface tension of the water, and the passage of the oil particles, and repeating the act continuously, it appears that this process would have no actual limit so long as the water-sand and oil-sand contact was maintained.

Probably all the facts contributing to the movement are not as yet known. But in this connection it is of interest to note that flotation methods in ore dressing show that certain oils have a well marked selective action for metallic sulphides, tellurides, and some other minerals. This fact prevents them from being wetted by water which in some cases may be a contributing factor in the movement or non-movement of hydrocarbons. In this connection it may be stated that lubricating oils are not used for flotation purposes and gasoline and naphtha are of value only for thinning the heavy coal and wood oils that are used. The relation of oil and certain minerals is of interest, however, and may prove to be an interesting field of research in connection with the problem of oil migration.

CHEMICAL REACTIONS.

DEPOSITION OF CEMENT: It is conceivable that localization of oil pools in reservoir rocks may be accomplished by lithification of the sands, through cementation. The gradual deposition of cement in the interstices between the grains of sandstone may conceivably produce motion in oil particles and cause them to collect into bodies of commercial size. From an initial porosity of more than 40 per cent, the pore space of sands may be reduced to 5 per cent or less by cementation (64). Indeed, cementation is so vigorous in some cases that where rocks have been long in the belt of cementation, bedding planes, faults, joints and other large openings have been closed; great sandstone formations have been transformed to quartzite.

Van Hise (74) defines the belt of cementation as the area between the bottom of the belt of weathering, and the top of the zone of rock flowage. Since most accumulations of oil that we have any knowledge of is within less than 4000 feet of the surface, we are concerned mainly with the surficial portion of the zone of cementation. In this zone openings in the rocks are relatively large and numerous. The percentage of meteoric water active in this portion of the earth's crust is very great, and cementation to some extent is well nigh universal. Where circulating waters are highly charged with material in solution, and proper conditions

for precipitation are encountered, a gradual building up of resistance to movement of liquids by cementation of the sand particles is the result.

The cementing process aided by friction, adhesion, cohesion and other capillary phenomena may become so great as to prevent the escape of water, oil and even compressed gases.

Some oil and gas bearing sands are relatively free from water. These are the so-called "dry sands". Several explanations have been advanced to account for this condition. Mills and Wells (81) suggest that in view of the fact that these sands are highly filled with cementing material, the condition argues the long continued presence of circulating water, which having completed its work of cementing the sands, has left the oil and gas entombed.

Chemical tests made to determine the character of cementing material in oil bearing sandstones, found that pure silicious sandstones are the exception. The cementing material generally consists of silica and hydrous silicates of iron, aluminum, calcium and magnesium. Petrographic studies made by M. I. Goldman of fragments of certain oil bearing rocks, found quartz as a secondary growth around the original grains. Kaolinite was found in fine crystalline aggregates filling the pore spaces and calcite and other carbonates were particularly abundant. Sulphides were scarce, as were chert and opal growths, but the micas were found to be probably the most significant of the secondary minerals.

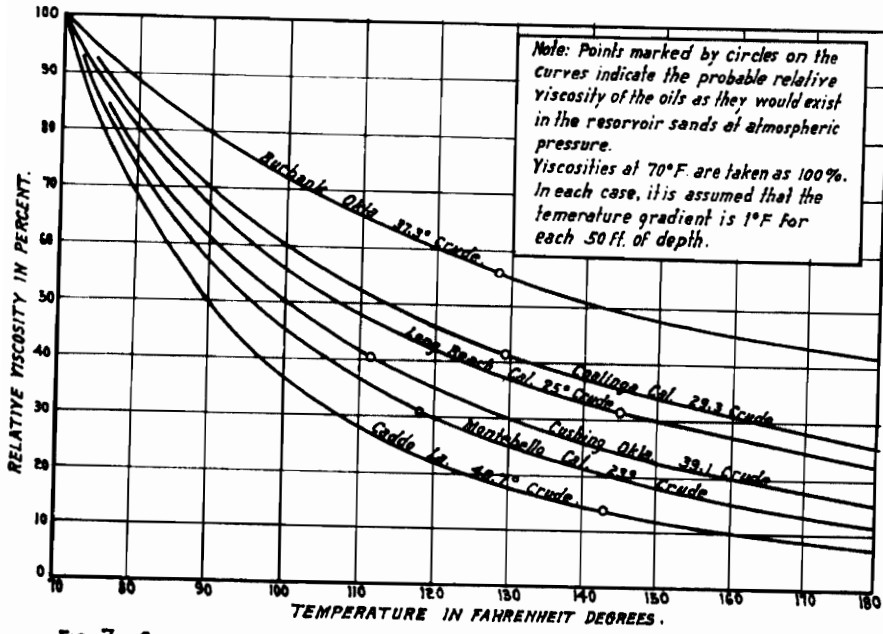


FIG. 7. GRAPHS SHOWING DECREASE IN VISCOSITY OF VARIOUS CRUDE PETROLEUMS WITH INCREASED TEMPERATURES ENCOUNTERED IN DEEP SEATED STRATA.

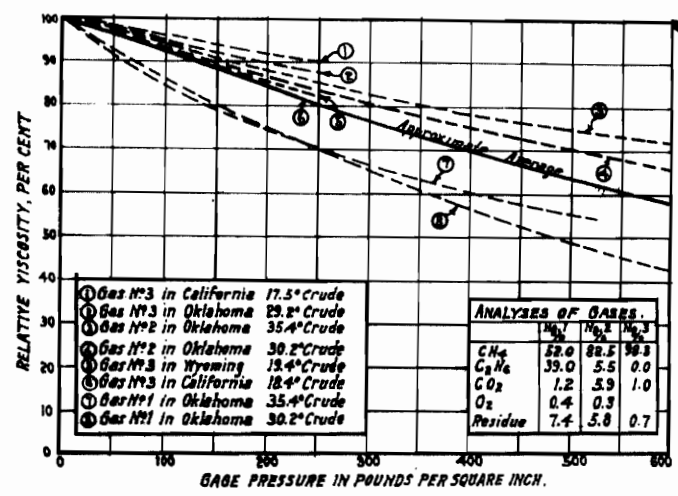


FIG. 8. GRAPHS SHOWING INFLUENCE OF GREATER QUANTITY OF GAS, SOLUBLE IN OIL AT HIGHER PRESSURE, ON OIL VISCOSITY (AFTER BEECHER, PARKURST, DON AND CALKIN)

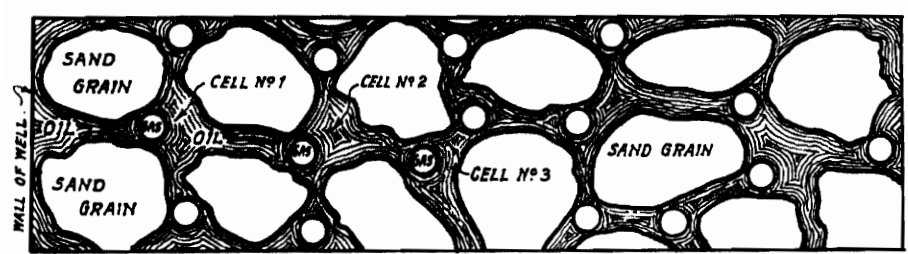


FIG. 9 SKETCH ILLUSTRATING OIL AND OCCLUDED GAS BUBBLES IN PORE CELLS COMPRISING PART OF A DRAINAGE CHANNEL.

FORMATION OF GAS AND ITS EFFECT: From chemical reactions

between certain of the elements composing the rock strata, large quantities of gas may be generated. Natural gas, which in general is associated with petroleum, is a mixture of hydrocarbons and other gases and vapors, the proportions of which vary in different fields. The gas occurs in the reservoir above the oil, or as small globules shut within the oil or dissolved within it. Of this latter condition let us take note. Under great pressure large quantities of gas are dissolved within the oil lowering its viscosity (77a). This fact is made more concrete by referring to Fig. 8. The graph shows that the proportion of gas that can be dissolved within oil is increased under pressure with a proportional decrease in viscosity of the fluid. An increase in temperature is followed by a decrease in gas solubility, but this condition is offset by the fact that there is a decrease in the viscosity of the oil. Fig. 7 brings this idea out very clearly.

If the solubility of gas is proportional to the pressure and inversely proportional to the temperature, it is interesting to note that at 500 pounds pressure and normal temperature, an average barrel of crude petroleum which occupies 5.6 cubic feet may contain 105 cubic feet of dissolved gas (77a). This means that a barrel of average crude oil will dissolve 18.75 its volume of gas under the pressure stated.

Let the reader imagine that this condition has been duplicated by nature and that oil, gas and water in a state of equilibrium are disseminated through porous strata with an impervious capping. If the state of equilibrium should be disturbed by folding, faulting, compaction of sediments or re-adjustments of any kind, changes in the relationship between gases and fluids would begin. Gas bubbles would form in the minute pore cells of the sands and by expansion pass in the direction of least pressure. With the movement of free gas ahead of the oil, and with pressure partly reduced, another portion of dissolved gas would be released assuming the form of minute bubbles in the oil. About each small gas bubble would be formed a continuous shell of oil and as the gas moved forward the oil would be carried with it. Lewis (32) believes that the gas would also carry oil as vapor. Uren states that "the principal factors determining the critical pressure necessary to cause movement of the gas bubbles from pore to pore, are found in the surface tension of the fluid in contact with the gas, diameter of capillary channels between the cells, and the form of approaches to the channels of communication between cells. Integration of the individual resistances to movement offered by the gas bubbles along a channel provides a measure of the minimum pressure necessary to cause movement."

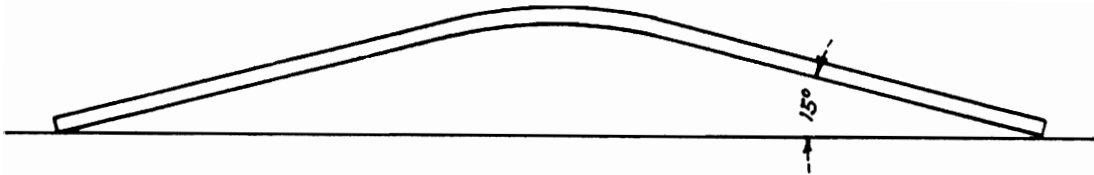


FIG. 10 . GLASS TUBE FILLED WITH OIL-SAND AND SEAWATER, WITHOUT GAS. EXHIBITS NO EXTENSIVE ACCUMULATION OF OIL .



FIG. 11 . GLASS TUBE SHOWING GROUND DOLOMITIC LIMESTONE INTRODUCED AT "A" AND "A'"
THE SYSTEM WAS FILLED WITH OIL SOAKED SAND AND ACIDIFIED SEA WATER.

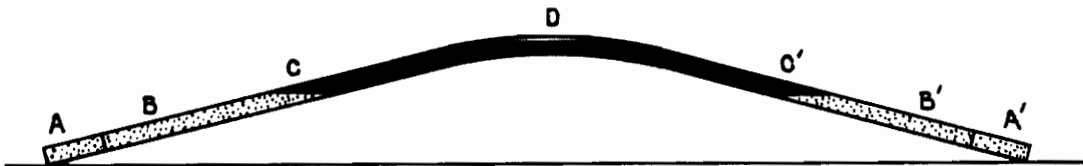


FIG. 12 . GLASS TUBE SHOWING THE RESULTS OF FORTY EIGHT HOURS ACTION ON TUBE AS SHOWN
IN FIG. 2., A AND A', DOLOMITE; B AND B' SEA WATER IN SAND; C AND C' SEGREGATION
OF OIL IN THE SAND; D ACCUMULATION OF GAS IN SAND.

In describing the movement of oil and gas when a well penetrates an oil bearing horizon Uren (77b) used the drawing shown in Fig. 9. The writer believes that this condition may be duplicated by nature where folds and faults provide entrapments above or below oil bearing strata. The sketch shows that the bubbles in cell No. 1 nearest the well escape into the well and carry with them some of the surrounding and intervening oil. Release of pressure as gas and oil pass from cell No. 1 creates a differential pressure between it and cell No. 2. The gas in cell No. 2 immediately expands and a portion of it escapes into cell No. 1 where it undergoes further expansion and escapes into the well carrying with it some of the oil from cell No. 2 and a portion of that left in cell No. 1.

Thiel's experiment (32) is interesting in the light that it throws on the actions of oil, water, and gas in a closed system. It indicates that in some instances the oil in the rock strata of the earth may move toward the source of generating gas and not with the direction of moving gas. In the experiment, a piece of glass tubing 4 feet long with a one inch bore was bent about 15 degrees from the horizontal Fig. 10. Crushed quartzite of 20 mesh was partially saturated with crude oil to which one-third of its volume kerosene had been added. The tube was then filled, except the lower 4 inches of each end, with the oil soaked quartzite sand and sea water acidified to one-half of one per cent with acetic acid.

The lower 4 inches of each end of the tube was filled with fine ground dolomitic limestone and then tightly corked and placed in the position as shown in Fig. 11. Gas pressure was developed when the acidified salt water came in contact with the dolomitic limestone in the ends of the tube. Within 48 hours the separation between the oil, water and gas was most complete as shown in Fig. 12. A similar experiment was performed with the tube inverted simulating a synclinal structure. At the end of 36 hours oil had moved in both directions from the trough of the syncline forming an accumulation in the upper part of the limbs immediately below the contact between the dolomite and quartzite.

Mills (83) in experimenting upon the migration of oil and gas found some very interesting relations and he is quoted at length in describing the phenomena observed. In one of his experiments Mills says, "the cap sand overlying an improvised anticline was disrupted by gas pressure before the cover plate of the experimental tank was bolted in place, and before the oil and gas, which was intimately mixed with water in the sand had segregated. Gas, compressed by the tight tamping of the sands, and accompanied by a little water and oil, escaped violently through the weak spot in the caps and at the top of the anticline. As the gas moved to the point of escape, it propelled oil into the anticline, the oil accumulating around the point where the gas was escaping."

"Other accidents occurred in which the plate glass fronts of the experimental tank cracked because the water and gas pressures exceeded the strength of the glass. In each of these accidents, there was a rush of gas, oil and water to the cracks or crevices of the glass, and in each case oil accumulated in the sands immediately adjacent to the cracks. The migration and accumulation of oil continued so long as gas moved to, and escaped through the cracks. Where there were considerable porportions of absorbed gas, the oil was propelled more effectively than the water. These experiments illustrate the migration and accumulation of oil under the influence of faulting either with or without anticlinal structure."

CHEMICAL COMPOSITION OF GROUND WATER: In the search for the most satisfactory solutions for the flooding of oil sands to increase recovery, interesting information has come to light regarding the chemical effect that underground waters carrying certain minerals in solution might have upon the migration of oil. A series of experiments were undertaken by Beckstrom and Van Tuij (84) to determine the relative efficiency of different solutions in releasing oil films from sand grains. Many different combinations of various compounds were employed such as salts of weak acids and strong bases, salts of strong acids and strong bases, and salt of weak acids and weak bases. In every case of the more active solutions, oil was slowly released from the oil sand and

rose to the surface as small droplets which coalesced to form a film. The tests indicated that salts of strong bases and weak acids were the most effective, and sodium carbonate was found to be the most satisfactory compound for flooding operations. It was further observed that a concentration between one and two per cent at 18 degrees C. released the greatest percentage of oil from the sands. Though at temperatures between 42 degrees and 45 degrees C. the influence of a higher concentration released about as much oil as the lower concentration. The size of the sand grains and the viscosity of the oil played important roles as would be expected. The finer the sand, the greater was the recovery. The heavier crudes that could not be recovered at low temperatures, easily responded to temperatures ranging between 40 and 55 degrees C.

It appears to the writer the inference that may be drawn from this information may be applied to solving the problem of the migration of oil. There is a wide distribution of such metals as sodium in the earth's crust and many of the compounds of these metals are readily soluble in water. With a compound like sodium carbonate in solution, meteoric waters coming in contact with oil bearing sands would release oil from the pores of the sand just as it did in the above experiment. If an entrapment were so situated as to retain the oil as it was released, it is conceivable that disseminated and dispersed oil particles could be

accumulated into larger bodies. With such a start, other natural agencies like buoyancy, capillarity and moving underground water might be brought into action and thus complete the process of migration until there was an accumulation of oil of large proportions.

A C C U M U L A T I V E P R O C E S S .

INFLUENCE OF MOVING UNDERGROUND WATER.

It has been generally conceded that oil migration and accumulation are closely associated with and intimately related to ground water circulation. Water is present to some extent in all rocks within the zone of observation. It is found in large quantities in the more porous zones, and has the power to penetrate even the most massive and impervious layers to some extent. The work of moving underground water in its relation to oil accumulation may be conveniently considered from the aspect of circulating connate water and circulating meteoric water.

There are various hypothesis as to physical state of the oil that could be transported by moving bodies of underground water. According to one view the oil was deposited with shale beds as oil. According to another view, during compression of the beds, the mother material was subjected to critical conditions of heat and pressure and yielded minute droplets of oil, or probably oil in

the form of vapor. Oil vapor under favorable conditions would respond very readily to small differences in water pressure and travel through the minute pore spaces of the strata with ease and for great distance.

If the oil should be in the form of microscopic globules it might move through the pore spaces of the rocks with little or no friction. But if the globules should be relatively large as compared with the size of the openings between the sand grains, as may well be in case the oil is not derived from the shale itself, there would be a lower limit of velocity beyond which the moving water could not overcome friction. However, the velocity of movement which would fail to carry oil globules of one size, would suffice to carry a smaller.

CONNATE WATER. When first deposited, muds and silts contain large amounts of water. Subsequent deposition buries previous deposits and the entombed water is known as fossil or connate water. Connate water to be instrumental in causing oil to migrate must be set in motion. Circulation would be in the direction of least resistance and in general upward, though downward movement would be an entirely feasible conception.

In the early history of connate water, compaction is the most effective agent in reducing the pore space and forcing water from the beds. The course that the water would take in its movement in all probability would not conform to any given direction, but

but would be partially lateral and partially transverse; partly up and partly down. Bedding planes would facilitate lateral movement. Cross-bedding, joints, faults and fissures would encourage transverse circulation, while differences in porosity above and below the water horizon, would localize movements in those directions.

Park (55) thinks that compaction of the sediments and reduction of pore space within the sediments starts the movement of connate water. The final work of accumulating commercial deposits of petroleum, however, he thinks is due to water movement initiated by deformation. It has already been pointed out that convex flexures in the strata are favorable areas as collecting grounds for fluids and open joints and faults of greater or less magnitude become avenues for localized upward movement. Escaping gas from water that has risen from some depth would promote circulation both mechanically and by evaporation. Circulation, as Park suggests, would rise to a maximum during the diastrophic period and then decline.

METEORIC WATER: Meteoric water may be considered to embrace mainly those artesian waters with which all are more or less familiar. Due to differences in head (hydrodynamic pressure) there is a wide and diversified movement of water, the rate of which is as varied as the physical conditions affecting the strata through which it moves. Darton (70) has estimated that in the

Dakota Sand artesian basin of South Dakota, the rate of flow in the sand does not exceed a mile or two per year. Van Hise (74) in referring to the movement of ground water in the Potsdam Sandstone of Wisconsin says, "Since the average lateral movement of the water cannot be supposed to be more than three fourths of one kilometer per annum, the water which enters the artesian circulation at a distance of 150 kilometers from Chicago should, on the average issue from the wells at Chicago two hundred years after it enters the sea of ground water in Wisconsin." As compared with surface water, ground water movements are very slow indeed. But underground water movement such as that in the Dakota basin would be fairly rapid as compared with that in the Potsdam sandstone of Wisconsin. There are cases of more rapid movement of underground water as that in underground channels, caves and caverns, but these we are not concerned with here.

Let us inquire into some of the conditions pertaining to ground water circulation and see how it could produce migration and accumulation of petroleum. Munn (2) has stated that in addition to water moving under hydraulic or capillary pressure being a direct agent of accumulation of oil and gas, it also seals up all the pores of the surrounding rocks and prevents the dissipation of pressure by diffusion. Water travelling along by capillarity, in effect, squeezes itself along. Water under the influence of hydraulic pressure is being pushed along. Open porous beds are

favorable to hydraulic movement since friction in these beds is least, while fine grained rocks, furnish the most favorable avenues for movement by capillarity. It follows then that capillary water would be an effective agent in moving oil in fine grained sandstones or shales. While water travelling from a given intake by hydraulic pressure through porous sandstones would completely saturate the beds as it advanced, and accumulate and push ahead of it the oil and gas encountered, the very nature of the latter beds, if suitable structure were present, would favor large accumulations of oil.

Oil that is being propelled along in a porous bed that suddenly pinches out into a fine grained stratum in the direction of movement, would be screened out and accumulated into a pool at the end of the porous bed. A decrease in the rate of water movement would have a similar effect in producing an oil pool. Anything that decreased the rate of flow until it becomes too small to move particles of oil through the rocks, would tend toward an accumulation of oil.

Munn (2) states that the movement of the fluids through the various strata would not be uniform which would result in zones of conflicting currents of water between which bodies of oil and gas would be trapped. Parker (55) in effect states the same idea though in slightly different terms. He defines the zone of conflicting currents as that ground where the forces of meteoric water

meet and oppose the forces of connate or metamorphic water.

Conflicting currents emanating from different bodies of water would undoubtedly localize circulation, and in the presence of favorable structure result in an accumulation of oil. A fluctuating zone of conflict between bodies of water probably accounts for certain less important accumulations of oil and gas near the rims of structural basins in contrast to the greater accumulations farther from the rims of the basin.

An ideal situation to produce an accumulation of oil under the influence of meteoric water would be an area of high altitudes where porous sandstone strata were well exposed along the borders of a large structural basin from which they dipped steeply, with here and there a reversal, into the deeper parts of a basin 5000 to 10,000 feet below. This condition would result in a general, and fairly rapid circulation of water through the basin. Any oil that the sandstones might contain would be carried along in the general water circulation until conditions were encountered which would cause a selective segregation of the oil particles. Near the intake side of the basin, unusual structural conditions would be necessary in order to have an accumulation of oil since the tendency would be toward "flushing", and not accumulation. Previous accumulations of oil under different physiographic conditions might become dissipated, due to the gnawing effect (flushing) of rapidly moving water (43). In the interior of the

basin, and near the outflow side, the flow of water would be less rapid, due to leakage and general diffusion throughout the basin. With suitable physical conditions in this part of the basin, there would be a strong tendency toward accumulations of oil and gas into pools of economic importance.

F A U L T I N G.

Faulting, which is usually associated with folding, is a most important phenomena in connection with the migration of oil and gas. Indeed some geologists have come to regard it as an essential to accumulation, for without faults, fissures and joints, gas may not be displaced by oil. In sharp folds the oil, if not in the crest of the structure, may be beyond drilling depth, but faulting and its accompanying phenomena often furnish avenues up and along which petroleum can migrate to shallower sands, or in the absence of a suitable reservoir, reach the surface and be lost.

It is significant to note that some of the larger and more productive oil and gas regions owe their origin largely to faulting. Nearly all of the productive domes and anticlines of the Rocky Mountain region are cut by faults, fissures and joints which is evidence that these structures play an important part in the migration and accumulation of oil. Many of the most prolific oil and gas producing areas of the Mid-continent, California and Gulf Coast fields show extensive faulting and fissuring. These

conditions, no doubt, have had a significant part in making the migration and resulting accumulation of oil possible. It is worth while in this connection to consider the famous Tepetate-Toteco-Alamo line of fields in Northern Vera Cruz, Mexico, the unparalleled accumulations along which is also controlled by faulting. The Eldorado, Arkansas field is another excellent example of what faulting will do in the matter of accumulation. This field is practically devoid of any other structure than the severe faults which control the accumulation of the oil.

In the Gulf Coast, faulting is probably the controlling structural feature of all the oil fields in the relatively flat lying Lower Cretaceous to Pliocene beds. In the case of salt dome fields, Pratt and Lahee regard as more important than doming concomitant faulting with resulting fracturing and squeezing as causes for these remarkable petroleum accumulations. The prominent Reynosa Escarpment trending northeast and southwest through Zapata, Webb, Duval, McMullen and Live Oak Counties, Texas, and along which several oil fields have been developed, is undoubtedly a fault scarp subsequently modified by the processes of erosion.

REVERSE FAULTING: Faults may be divided into the two general classes of normal and reverse faults. Reverse faulting in the Rocky Mountain region is of little or no importance in its direct effect on oil and gas accumulations in the known fields. Reverse faults, generally of the thrust type, are, however, closely

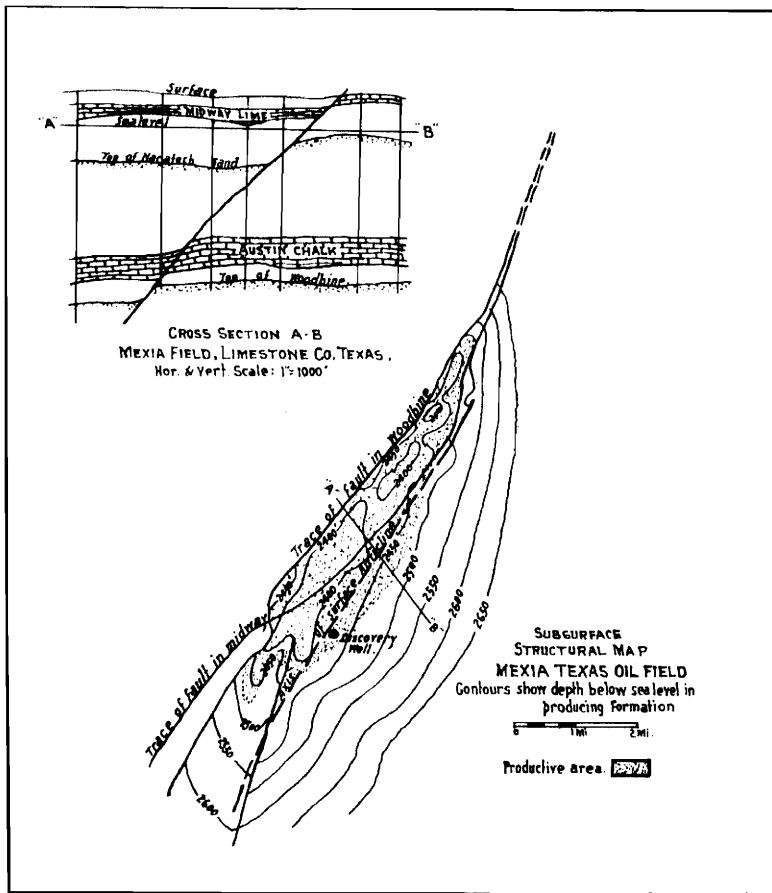


FIG. 13

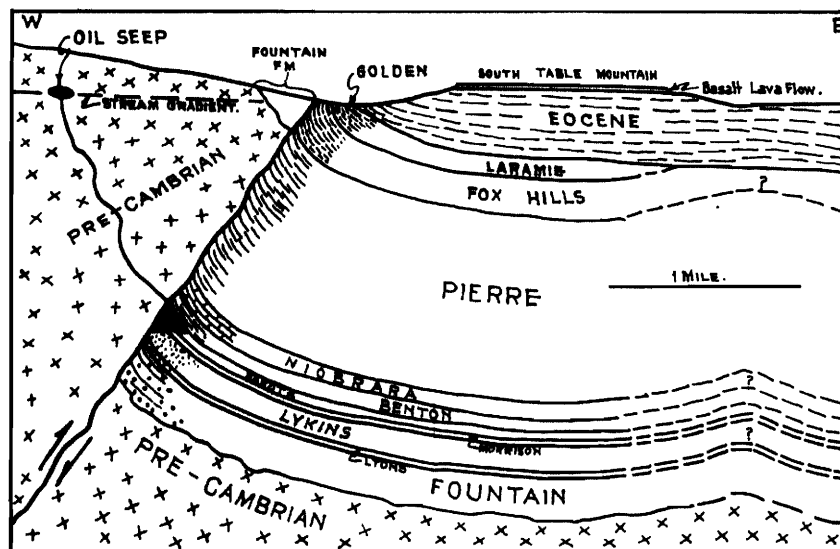


FIG.

FIG. 14 . THRUST FAULT AT GOLDEN, COLORADO. PARTIALLY DIAGRAMMATIC.

associated with certain oil occurrences and prospects, and it is not unlikely that oil accumulations of commercial value may yet be found which are dependent in one way or another on thrust fault relationships.

Irwin, (42) in discussing the Golden thrust fault, Fig.14, near Golden, Colorado describes the probable origin of the structure as a monoclinial flexure passing into an overturned Z-fold which, upon continuation of the thrust from below and from the west, passed into an overthrust fault. The pre-Cambrian igneous and metamorphic rocks have been pushed eastward and upward over the upturned edges of the sedimentary rocks which range in age from Pennsylvanian to Cretaceous. The attitude of the Eocene beds is generally flat to slightly eastward dipping with some rather meager evidence of west dip. An active oil seep in Gold Run Canyon, one and one-half miles north of Golden, emerging from pre-Cambrian gneiss is an interesting accompaniment of the overthrust. The conjecture is that oil originates in the foot wall of the thrust fault, migrates upward across the plate, and escapes to the surface through joints and fissures in the gneiss of the hanging wall. Had the gneisses of the hanging wall been impervious, and had the thrust plane been sealed near the surface, a commercial oil pool might have existed beneath the overthrust.

NORMAL FAULTING: Normal faults which are associated with known or prospective oil fields have been divided by Irwin (82) into epi-anticlinal and fault closures. The epi-anticlinal faults are

those minor faults occurring in parallel or radial systems which are confined to the crests and flanks of anticlines and domes of the mountain type. The fault closures are those faults which, due to their position with respect to folds or to other faults, may be expected to form structural closures suitable for the accumulation of oil and gas. Such a fault as the latter is found at Mexia, Texas, along which is found enormous accumulations of petroleum.

Recognizing the wide evidence of an anticline in the subsurface beds at Mexia, together with small gas production from shallow wells led the Humphreys Oil Corporation to undertake explorations which resulted in the discovery of the Mexia pool. The discovery well was drilled near the crest of the anticline, but the field as finally developed proved to be more closely related to a fault which is situated low on the western side of the anticline. In this part of Texas the major structural feature is the Balcones fault, and it has been suggested that the Mexia fault is a possible en-echelon extension of it. Fig. 13 shows the relation between fold and fault, and also the faulted condition of the Woodbine sand (base of Lower Cretaceous) which serves as the reservoir bed. Pratt (58) in commenting on the situation at Mexia would explain the gas in the shallow wells by assuming that the source of the oil was below the Woodbine and that most of the oil was trapped in the Woodbine sand as it moved up along the fault plane, while gas more readily fugitive, moved along the fault plane to the upper sands.

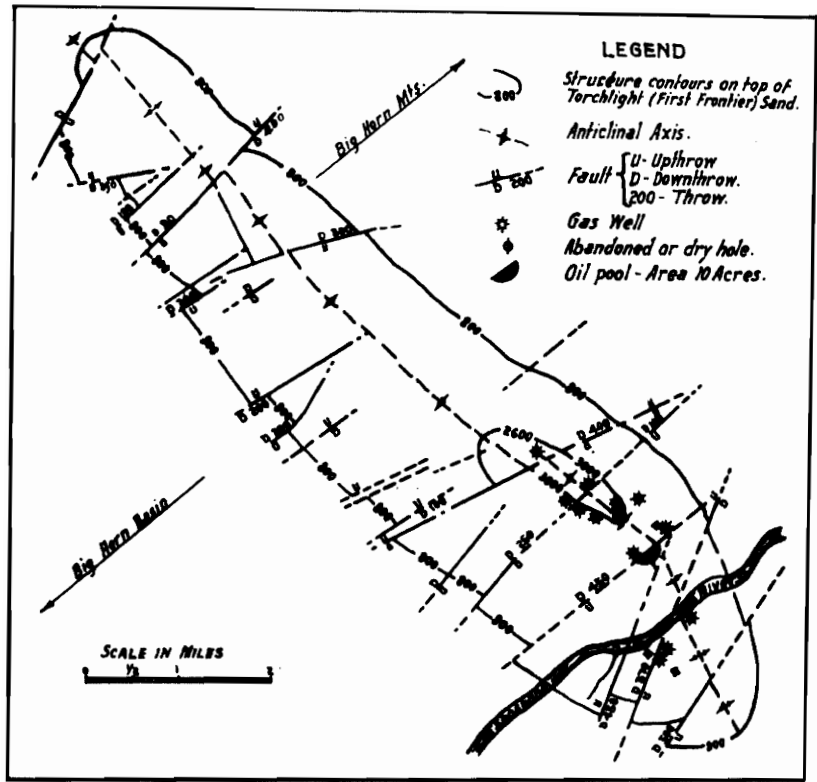


FIG. 15. GARLAND ANTICLINE, PARK AND BIG HORN COUNTIES, WYOMING.

A typical example of an epi-anticlinal fault system is to be found in Garland Dome, Wyoming, Fig. 15, described by Irwin, (82). This dome has at least twenty four transverse faults and one axial fault. The occurrence of a gas vent near one of the faults which could be ignited led to the drilling of a well. Oil was encountered at a depth of 500 or 600 feet, and an area very small, but very persistent in production was developed. The decline curves for the nine producing wells indicated an ultimate recovery of 1,776,000 barrels or 177,600 barrels per acre. Assuming a 15 per cent porosity for the sand which is 35 feet thick, a recovery of 40,730 barrels per acre could be expected. But the production to date has already considerably exceeded this which can only be explained by the accession of oil through faults. The wells are described as being on a relatively elevated block which is a separate closure formed by the convergence of two faults. This is the only oil production on the dome, the other wells being gas. Gas occurs in separate fault closures on the dome 200 feet higher in some cases and 600 feet lower in others. Here, then, occurs within a few hundred feet of each other, faults acting as avenues for migration and accumulation in one case, and as barriers to migration in another.

Irwin (82) pointed out that the longer the fault plane the better are the chances that the fault has functioned as a barrier to the migration of fluids. It is also logical to assume that a

fault is more permeable at the time of formation and that it becomes less permeable with age due to the deposition of mineral water. Obviously then faults have exercised widely variant effects on the migration and accumulation of oil at different periods during and after their formation. Different degrees of porosity along the course of a fault would permit migration at one point and prevent it in another. A permeable sand carrying oil faulted to a position opposite an impermeable rock mass would be the occasion for the accumulation of an oil pool.

CONCLUSION.

The writer believes that any general account of the history of an oil pool, how and when it originated and by what agencies it reached its present position, must take into consideration more facts than are now contained in any one of the known theories of oil migration. More laboratory experiments are needed to test further the observations already made, and to blaze new paths in new and untried directions. From laboratory observations, many physical facts like the composition and temperature of oil field waters, chemical composition and pressure of gas associated with the oil, effect of dissolved gas on the viscosity of the oil, molecular relations of oil, water and gas when subjected to pressure within stratified bodies of rock, etc., should be observed, correlated with, and duplicated by field experiments as nearly

as practicable.

If all false theories on this subject are to be disposed of, as they certainly will be some day, then the investigative spirit must continue to prevail. Mills, McCoy, Munn, Cook, Washburn, Daly and several others have set fine examples in their work that others may follow and enlarge upon. Much, in fact most of what we now know on the subject of oil migration is due to the efforts of these men and to them, not only the oil industry, but the scientific world as well, is indebted.

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